The colours of energy

Essays on the future of energy in society

Edited by Gert Jan Kramer and Bram Vermeer at the initiative of Shell

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Introduction

Energy and climate change are defining challenges of this century.

Foreword

More than a century of operating around the world has taught those of us at Shell some vital lessons about how to do business – about collaboration, innovation and the importance of taking a long-term strategic view.

We have also learned the value of listening to external voices. As CEO of Shell, I have found the wisdom and insights of the people I meet around the world enormously helpful. While we at Shell may not agree with all opinions expressed in this book, they give my colleagues and me fresh insights, which help us make long-term strategic decisions.

Getting those decisions right matters to Shell – but it also matters to the world at large. Why? Because energy is essential to so many of the things we take for granted in our daily lives: commerce, communications, transport and food production, to name just a few. And because the world is experiencing the start of a transition in the way it produces and consumes energy.

The fact is that we all face a number of energy-related challenges – among them rising population, urbanisation and, of course, climate change. It's essential that we, together, get the response to those challenges right. As Gert Jan Kramer, Chris Laurens, Jeremy Bentham and Bram Vermeer ask in their introductory essay to this volume: how can we "marshal ever more energy in the service of human progress and simultaneously make that energy use more sustainable"?

For all these reasons, I'm delighted that Shell has been able to initiate and publish this book: a collection of essays that demonstrate diverse thinking about the many challenges the energy system faces. These essays contain views that do not (and are not intended to) necessarily reflect those of Shell. They do not seek to predict likely future events. But they challenge our thinking, certainly. And they are designed to offer plausible, if perhaps at times remote, possibilities of what the future could hold.

Inside these pages you will read the thoughts of some of the world's leading energy thinkers. You will find essays on subjects as varied as the geopolitics of energy, prospects for a net-zero emissions world, carbon capture and storage, religion and sustainability, the geology of climate change, mobility and transport, and energy efficiency. And while there is a good deal of discussion about oil and gas, and their place in the energy future, there are also many pertinent explorations of the prospects for solar, wind, biofuels, hydrogen and nuclear power.

For all their diversity, the essays share some common threads: a sense of urgency and a sense of optimism; an understanding that, while remaking the global energy system will not be easy, it can be done if we work together.

In fact, when I read these essays I am reminded of why three decades ago, as a young chemical engineer in search of a career, I decided to go into the energy business. It is as exciting an industry to work in now as it was back then – while companies like Shell have proud histories, our gaze is to the future, and the role we can play in the transition to a world of cleaner energy.

I would like to thank the contributors for the breadth, depth and quality of their work. I hope you will find this book as informative, eye-opening and inspiring as I have.

Ben van Beurden
CEO of Royal Dutch Shell plc
November 2015

Preface

Energy is the enabler of all human activity in modern societies. This makes affordable and environmentally acceptable energy one of the defining challenges of the coming decades. The 21st century will be decisive in the transition to a civilisation that lives within the boundaries of our one common planet.

The Club of Rome put the finitude of our resources on the international agenda with its first report in 1972, as one of its original authors incisively remembers in this book. Since then, the urgency of the challenge has only become more pressing. Humankind has already surpassed some planetary boundaries and is approaching others. There is hardly any room left for business as usual. We need to come to grips with the scarcity of resources, surging demand and the impact of climate change. Pope Francis in his recent Encyclical *Laudato Si'* has urgently expressed the same point of view.

Solving these challenges requires that all reasonable ideas are considered and debated. Answers may be found in the full extent of the issues surrounding energy technology and energy in society. It is, therefore, refreshing to read the analyses of the 55 experts in this book. They give a long-term view and take quite different angles. Their views are thought-provoking and sometimes counterintuitive. They question established truths and explore new paths. Their diverse backgrounds – from academia, industry, governments and NGOs – ensure a multi-faceted approach that bridges the gap between industry and environmentalists.

The number of pages and kilobytes and the variety of subjects in this book already indicate that there are no simple answers. Yet the challenge is not impossible, as will become clear from the essays in the book. And I believe the time is ripe for getting broad support for the necessary changes. The global financial crisis of 2007-08 and the long stagnation in its aftermath have made many people aware that growth cannot continue indefinitely and that humankind may not be able to maintain the conditions we have come to take for granted. Development and growth are increasingly discussed in relation to planetary boundaries. This realistic mindset puts us in an excellent position to set change in motion.

Challenges differ locally, as this book shows. Germany works to integrate an increasing share of renewables in its energy system. Balancing the intermittency of solar and wind power requires new connections between regions and with neighbouring countries. At the same time, the country needs to come to grips with its dependence on coal and gas, intertwining the issues of climate change, economics and geopolitics. In another part of the globe, China is fighting the pollution from its coal-based energy system. That has already triggered an energy transition that may bring profound changes. Meanwhile, small communities in Nepal are leapfrogging into modernity with solar-powered lights.

The transition is not just a concern of the energy industry. It is not a matter of exchanging one energy supply for another. We also need to reduce energy demand, decoupling wealth creation from energy and material consumption. Fascinating options exist to do exactly that, as the essay of Amory Lovins in this book ineluctably demonstrates. In essence, houses can be retrofitted to use passive solar energy for heating. Household appliances and lighting can be developed to use less power. Exciting efficiency gains are also available for cars and trucks. Such measures have a huge advantage over supply actions: they remain valid year after year, while new supplies are gobbled up as they are developed. What is more, in a world of rising demand, energy efficiency becomes a strategic factor for a country's competitiveness. It will help companies survive and expand.

At the same time, we need to create a decent living for all those hundreds of millions who live near or below the poverty line. Eventually, this might well mean that the well-to-do must learn to limit their demands and face up to the limits of the Earth. In this respect, the concept of sufficiency, which Thomas Princen explains in this book, is a valuable guide for our aspirations for the future. We need to learn to enjoy a high-quality life, without added resource consumption; and even if efficiency improves, sufficiency is still something to aim for.

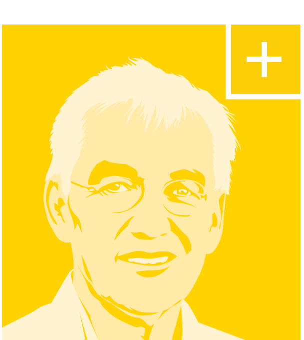
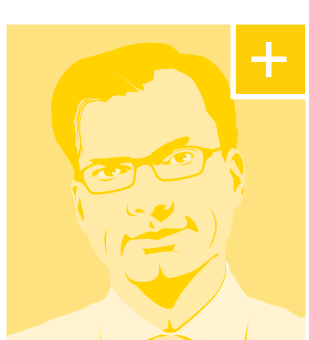
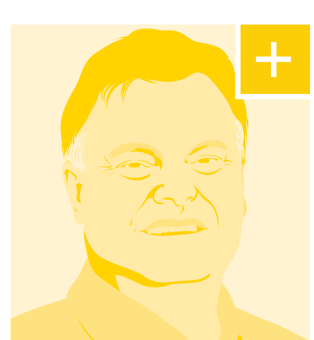
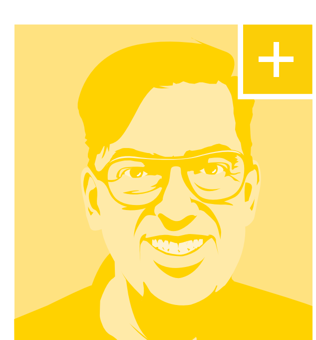
In the real world, renewable energies, energy efficiency and sufficiency don't grow fast enough. Policy interventions will be needed to allow both new, sustainable technologies to make quicker inroads into the energy system as well as to foster different behaviours in relation to energy consumption.

During this century, the business of the energy industry will change completely. This book was made out of the desire to get to grips with this dynamic outlook and to look far ahead – as far as the authors dare. It is a true venture to debate the future of energy on the basis of what the best experts in the world have come up with. The book offers an inspiring glimpse of the future and invites debate and action.

Ernst Ulrich von Weizsäcker
Co-President of the Club of Rome

Energy, sustainability and progress
A long-term perspective

Two of the defining and interrelated challenges for this century are energy and climate change. As the world grapples with them we will see a fundamental change in how energy is produced and consumed. Only continued change and innovation can reconcile the desire for human progress with the need for environmental sustainability.

> *Gert Jan Kramer, Chris Laurens, Jeremy Bentham and Bram Vermeer*

This is a book about the long-term future of energy and it is a good companion to Shell's scenario publications.[1] As with the scenarios, we will in this book try to look as far ahead as we can meaningfully do – one or two decades at least, and, if possible, beyond. It is therefore inescapably also a book about human progress and environmental sustainability.

The defining problem of our generation is to deliver a step change in energy provision with a view to giving billions of aspiring middle class people in the developing world access to modern energy, keeping climate change in check, and retaining a relevant share of high-quality reserves of fossil fuels for the benefit of later generations. If the first two points are commonly acknowledged, the latter is markedly less so; but fossil hydrocarbons are a precious endowment.

Energy is a prerequisite for life. Since life emerged on our planet, its metabolic processes have driven global chemical cycles, changing the environment over the geological eons.[2] *Homo sapiens* has immeasurably accelerated these changes, starting by his use of fire. No wonder that the ancient myths associate fire with the gods, and – as the Prometheus myth illustrates – its use by mankind wasn't necessarily sanctioned by them. The innovations and adaptations that fire brought along improved lives, but also created new challenges, propelling us forward to ever more complex technologies and ever more advanced use of energy.

Indeed, 'modern energy', the technical forms of energy such as electric power and various fuels, is still under a Promethean spell. On the one hand, modern energy is indispensable for modern life, and more of it will be needed to bring billions of the less privileged into the fold of development. But at the same time some of humanity's greatest challenges are a direct consequence of our use of it, the climate challenge especially. In this manner, progress and sustainability frame all innovation in energy and also the collection of essays in this book.

Progress and sustainability – not a trade-off

How then can we continue to marshal ever more energy in the service of human progress, and simultaneously make that energy use more sustainable?

Whereas the word ‘energy’ has a well-defined meaning – at least so long as we stick to joules and kilowatt-hours – ‘sustainable’ and ‘progress’ are words whose meanings are more subjective. Both are laden with moral meaning and highly sensitive to context.

Progress, for all the elusiveness of its generic definition, can be straightforwardly defined in relation to energy. It is for humans to have access to somewhere between 100 and 150 gigajoules of primary energy per person per year. This might seem strange at first: wouldn’t continuing progress mean an ever increasing need for energy? Actually, not necessarily: the Canadian geographer and prolific writer Vaclav Smil, in his book *Energy at the crossroads*, has found that a variety of indicators of human progress (food intake, life expectancy, literacy, political freedom, etc.) show a correlation with annual energy use up to levels of 50-100 gigajoules per capita and no correlation above that level.[3]

Another empirical observation is that energy consumption in virtually all developed nations has been shown to level off at income levels above about €18,000 ($20,000) per capita per year.[4] The level of energy satiation varies, though, from about 175 gigajoules per person in energy-efficient Japan to more than 300 gigajoules per person in the USA and Australia. The differences are related to differences in energy efficiency across the economy, which are embedded in infrastructural choices (building standards, city layouts, transport modalities) as well as ingrained behaviours. But in none of the developed economies do rising incomes inexorably lead to rising energy use.

From this combination of empirical findings we can conclude that, in round numbers, 100-150 gigajoules per capita is the energy required for people to participate fully in modern life. If we multiply this per-capita energy requirement by 8 to 10 billion, the number of people on the planet by 2050, we arrive at a future energy demand of around 1,000 exajoules per year, almost double what we use today.

If this is what human progress requires, how do we square this with environmental sustainability? Which brings us to the second definition question: What is sustainable energy? To answer that, we can probably not escape the deeper questions: What is sustainable living; what is sustainable development; and what is a sustainable society?

The Oxford Dictionary gives as the first definition of sustainable: “able to be maintained at a certain rate or level, as in ‘sustainable economic growth’”. As a second meaning it has “conserving an ecological balance by avoiding depletion of natural resources, as in ‘our fundamental commitment to sustainable development’”. We recognise in these definitions how sustainability is interwoven with progress.

The Brundtland definition of sustainable development has that element as well, by requiring that we meet the needs of the present generation without compromising the ability of future generations to meet theirs. But as the political theorist Melissa Lane, of Princeton University, has argued, needs are no more self-evident than wants.[5] For needs, even basic needs, are interpreted within social and technological contexts and conceptions of the good. And these are obviously evolving over time, making the condition of sustainability inherently dynamic and evolving. Lane therefore favours the definition of sustainable development put forward by the Forum for the Future, a London-based think-tank: “a dynamic process which enables people to realise their potential and improve their quality of life in ways which simultaneously protect and enhance the earth’s life support systems”.[6]

Adaptation, innovation and mitigation

The attraction of this definition is that it describes sustainable development as a dynamic interplay between the three different means by which humans can cope with change: adaptation, innovation and mitigation. Adaptation, the instinct to continuously and dynamically adapt to external circumstances and thereby our ‘fit’ with the environment; innovation, the process that seeks to improve our lives and our external environment; and mitigation, the foresighted response to protect (and enhance) the vital life support system of our planet.

These three modalities of change can at the same time be connected to how we look at and speak about the future: what *will* happen, what *can* happen and what *should* happen. The primary colours, will, can, and should, get inevitably mixed into a rich palette of secondary and tertiary colours. Together, they can give a white colour, but only if all primaries are in perfect balance. We can probably only really appreciate the full meaning of sustainable development when we consider the full spectrum. That is, when we develop awareness and appreciation for how each of us, from our respective backgrounds, assesses the task of sustainable development and human progress that is before us.

This is what inspired this book, a collection of essays where fifty-odd contributors hope to add colour to the debate about how the future of energy will, can or should unfold.

Human progress and environmental sustainability obviously form a discourse with an impressive pedigree. We cannot possibly do justice to its history here, but since this collection of essays can in aggregate be read as a status update of this debate in so far as it pertains to energy, we want to place our book in this historic context by giving three snapshots of it: one of two centuries back; one of four decades ago; and a glimpse of today.

Malthus, neo-Malthusians and anti-Malthusians

The Reverend Thomas Malthus remains the patriarch of the school of thought that approaches sustainability from a perspective of limits, and of the need for mitigating action to stay within these – his famous 'preventive checks'. Writing in 1798, Malthus' definition of a good life, that "[t]here should be no more people in a country than could enjoy daily a glass of wine and piece of beef for dinner", is both modest by today's standards and also unfulfilled for a significant fraction of humanity.[7]

How many that is was first guesstimated by the Dutch scientist and inventor Anthonie van Leeuwenhoek. The question presented itself to him not from moral reflection, but from scientific curiosity. It was inspired by his observation that there were 150 billion "little animals" in the milt of a cod, more – obviously – than the earth would support humans. So how many could that be? Van Leeuwenhoek multiplied the population density in his native Holland, arguably the world's finest and best-farmed agricultural land, with his best guess for the global total acreage of good farmland to arrive at … 15 billion. A number as good as any respectable estimate today.[8]

What neither man factored in was technological advance – that what we *can* do tomorrow might be more than what we can today. Of course technical progress and 'growth' were imperceptibly slow at the time of Malthus' writing, but that began to change rapidly thereafter. Ever since then, humanity has been able to overcome barriers and move frontiers in an unprecedented and previously unimaginable manner.

Confidence in the dependability and beneficial character of scientific progress probably reached its apogee with Vannevar Bush, when he called science the 'endless frontier' in his famous 1945 report to the President of the USA.

In his committee's report Bush argued that science in the form of basic research is "the pacemaker of technological progress". "New products and new processes do not appear full-grown," Bush wrote. "They are founded on new principles and new conceptions, which in turn are painstakingly developed by research in the purest realms of science!"

This attitude did not just inform and inspire government approaches to technology in the post-war period. In industry the same unalloyed optimism reigned supreme. Monroe E. Spaght, a chemist who was President of Shell Oil in the 1960s, said in 1954: "[W]e are moving into an age of truly remarkable scientific development. [...] Given enough progress in scientific investigation we can be sure of progress in practical results, in the development of new energy sources. The outcome will be more than staving off of trouble. It will be a spreading of productive power, a lifting of much of the distress that has over-shadowed man all his years on earth, a chance for all men to find life a more comfortable and, perhaps, a more satisfying experience."[9]

What perhaps unites Malthus and Bush is the timing of their remarks, which were both made towards the end of a time when what they said was *obviously* true. Just as Malthus' vision didn't allow for technical progress, which soon started to change the basic arithmetic of his argument, so Bush's didn't take into account the public backlash against the ever more overpowering presence of science and technology. From the 1950s and 1960s onwards, scientists were made responsible for the abstract threat of the atom bomb and the all-too-real nuisance and harm of pollution from expanding industry and industrialised agriculture. To the extent that science was still moving the frontiers of technological possibilities, it was no longer obvious to the public at large that this was always desirable. The price science paid was that blue-sky research gave way to mission-oriented research, subject to the fiat of its financiers – be they public or private.

It was also the time that science again took up the Malthusian theme of limits. Two best-sellers mark the entry into this era of new consciousness. First in 1967, Paul Ehrlich's *The population bomb*, and five years later *The limits to growth* by Donella and Dennis Meadows, Jorgen Randers and William Behrens (also known as *The report to the Club of Rome*).

That's not to say all of academia bought into the idea of limits. While many scientists may have been concerned and perhaps shaken in their optimistic beliefs, many economists on the contrary embraced a powerful, if rather abstract, belief in the magic of technology. For instance, in a thoughtful paper about sustainability, the economist and Nobel laureate Robert Solow writes: "There is no reason for us to feel guilty about using up aluminium as long as we leave behind a capacity to perform the same or analogous functions using other kinds of materials".[10]

This set the stage for one of the notable intellectual battles of the last decades, between the aforementioned biologist Paul Ehrlich and the initially little known professor of business administration Julian Simon. While Ehrlich predicted that "by the year 2000 the United Kingdom will be simply a small group of impoverished islands, inhabited by some 70 million hungry people", Simon countered by stating that "we now have in our hands – really, in our libraries – the technology to feed, clothe, and supply energy to an ever-growing population for the next seven billion years".[11]

If there is one thing we can learn from this, it is that whatever we may think of the environmental debate today, it is more nuanced and better informed than it was a generation ago. Collectively, we seem to have found a certain degree of intellectual accommodation for the idea of finitude, even if we haven't fully accepted the consequences, nor necessarily agree on what they are. And this, not because we do not agree on the fact of finitude, but because we differ in our assessment of future technology to allow us to adapt to it.

Towards the future

Adaptation and innovation have arguably been humanity's main survival strategy so far. They brought us to where we find ourselves today: unprecedentedly (yet not uniformly) prosperous, but living dangerously close to the limit of what the planet can sustain.[12] Our approaching of the 'planetary boundaries' is what makes the present different from all previous times. For humanity to navigate through this century will require self-awareness and self-control at levels that are psychologically quite difficult to attain.

Sustainability will require first and foremost a measure of economic security. It is no use telling a squatter not to cut down a tree if it means he can't fix his roof or cook dinner. Perhaps we would have evolved the mitigation gene long ago if we had needed it. But until now, most problems could be solved by adaptation and innovation because we hadn't reached the planet's limits. There was always room to explore and exploit, either in the literal, geographical sense, or by opening up new resources, say switching from wood to coal.

The energy and climate challenge will require us to use our skills to adapt, innovate and mitigate to the full. The good news is that we started with energy innovation for what we now call carbon mitigation as far back as the 1970s. Active government support of the agenda of technology innovation in energy has made renewables a practical reality today. The bad news is that it may not be enough if we are to meet the 2 degrees Celsius trajectory, because the task before us is so huge and therefore the changeover will take significant time.

This makes for the narratives that each of us weave about what can, will and should happen. The transition of the energy system will be driven by the interlocking and dynamic forces of growth, innovation, adaptation, mitigation and the unavoidable time frames of climate and technology. The essays in this book provide snapshots of the next stage of this process of ongoing evolution.

A brief guide to this book

The first section of this book looks at the social, economic and political context of energy. Cho Khong discusses how the energy and climate challenge might play out in geopolitics. In particular, he emphasises the importance of China and the USA and their evolving relationship in setting the direction of future developments in energy.

Next, Coby van der Linde addresses energy security, one of the perennial drivers of energy policy. Her essay makes clear that even as the global energy portfolio incorporates a greater share of renewables, energy security concerns remain, changing in character and possibly in gravity.

Sam Fankhauser and Mallika Ishwaran's contribution deals with affordability, and the relation between energy, energy policy and competitiveness.

Three essays in the section 'Futures past and present' illustrate our fascination with stories of the future. This fascination does not stem from the desire to *know* the future, but to explore it. We publish the essay, 'Some thoughts on the year 2000', which James Lovelock wrote in 1966 at the request of Victor Rothschild, then research director of Shell. This was before Lovelock developed his famous Gaia theory – in fact, as he has acknowledged, this work was instrumental in setting him off on the intellectual journey that led to the theory. It was also before Shell started its scenario planning. Lovelock reminds us that modesty and humility are virtues when we start out on the treacherous path of long-range forecasting. He follows this advice himself admirably, focusing on broad trends rather than specific developments.

This is followed by an essay by Jorgen Randers. Like Lovelock, he focuses on broad trends, but is bolder in asserting that in important aspects we *can* predict the future. He starts from demography and its connections to economic growth and energy consumption. There is a saying that you can only look forward half a century when you also look back half a century. This should make Randers one of the most credible forecasters around, as he has been in the forecasting business for about that long, ever since he co-authored *The limits to growth* in the early 1970s.

If Randers looks mostly at socioeconomic determinants of the future, Chris Anastasi, who worked in Shell's scenarios team in the 1990s, looks back on what he and his colleagues were thinking about technical change back then. It is fascinating to see that in this work some long-term developments – for instance on very efficient cars and on distributed energy – were foreseen with clarity.

With the technologies we have today and their ongoing development in the decades ahead, it is now possible to envision what a world with net-zero emissions would look like. This is the contribution of one of us, Jeremy Bentham. Many energy outlooks stop at mid-century, which is either part way through the transition, or mechanistically forces an end point in a manner that stretches the bounds of what seems feasible in the real world. Yet Bentham explores the later phases of transition, when the world will be approaching net-zero carbon emissions from energy. He concludes that this is feasible, in a world where 10 billion people prosper.

Not solely driven by utility, but also by necessity

This section includes a further three essays that look at developments in energy from an ethical perspective. After all, what makes this one unique is that it is not solely driven by utility, but also by necessity; more specifically one driven by the ultimately ethical considerations of what is sustainable, and respectful of planetary limits. Thomas Princen, an environmental writer and scientist at the University of Michigan, considers these questions in the light of the ecological and environmental sciences tradition. As a sequel to this, Jan Boersema of Leiden University traces the roots of our thinking on energy, growth and environment to our ancient, religious traditions of thought. In the third essay, Herman van der Meyden and Maaike Witteveen, two young professionals working for Shell, discuss the energy/climate challenge from a personal, intergenerational perspective.

The changes in the energy mix that we will see over the coming decades is the backdrop of the subsequent two sections in this book (see Figure 1). The first of these, ‘Oil, gas, carbon and rock’, explores the future of the incumbent – fossil fuels. Clearly there is more to oil and gas than just phasing them out!

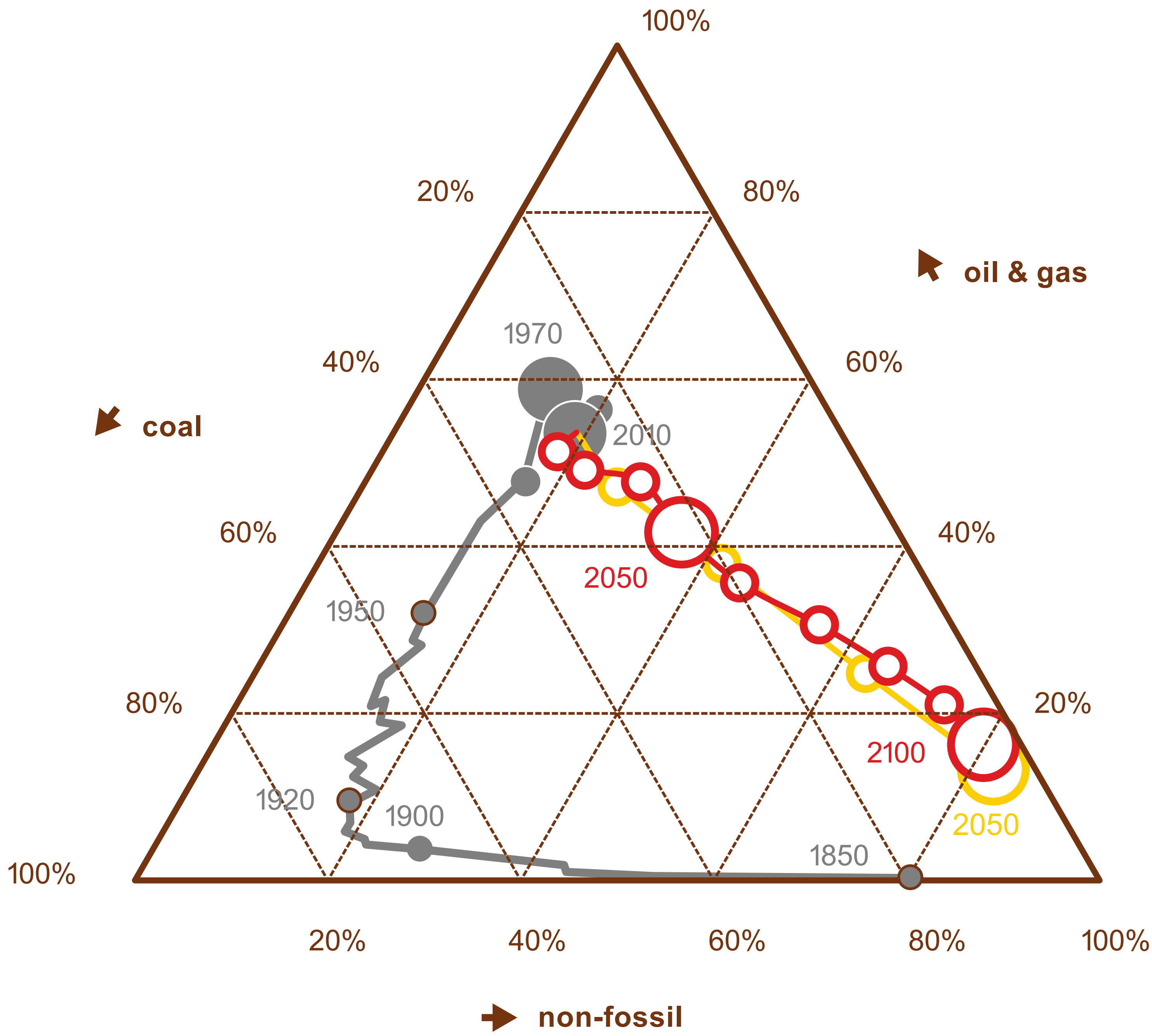


Figure 1: This diagram, adapted from Riahi and Roehr (2000),[13] shows the decomposition of world energy since 1850 into coal (lower left corner), oil & gas (top corner) and 'non-fossil' (lower right corner). Before the industrial revolution most energy was non-fossil, i.e. renewable; in 1920 it was 75% coal; and from 1970 to 2010 composition was more or less constant with 55-60% of energy coming from oil and gas, some 30% from coal and 15-20% from non-fossil, which consists of both renewable and nuclear energy. The forward projections with 10-year intervals are based on Shell's Oceans scenario (red, to 2100) and on Greenpeace's Energy (R)evolution (yellow, to 2050).

The opening essay in this section by Oliver Inderwildi provides a perspective on how the changing mix of remaining and accessible oil resources poses a challenge to CO_2 mitigation efforts, which is best met by giving CO_2 a price.

As José Bravo makes clear in detail in his essay, useful energy means *concentrated* energy. The sources of fossil fuels – the reserves – become progressively less concentrated over time, but are still much more concentrated than renewable resources. In fact, concentrating energy is *the* challenge for both fossil and non-fossil energy resources.

Carl Mesters follows up on this theme in his contribution by showing how quality improvement has been the driving force in refining for a very long time. Because the world will continue to rely on fossil fuels for many decades to come, and probably longer still in such sectors as aviation and heavy-duty transport, technological advances in refining are as relevant today as they were in the past.

In view of the desire and the need to continue the use of fossil fuels, it will be necessary to get serious with the deployment and further development of carbon capture and storage. For this, Ron Oxburgh, a member of the House of Lords, makes a strong plea in his contribution to this book.

Exploration

When speaking about the energy challenge to a general audience, people at Shell are often asked why – in full awareness of the challenge – oil and gas companies keep exploring for more. The answer is that exploration and production of oil and gas is a much more dynamic business than most people realise. The production half-life of most sources is a decade, which is thereby also the timescale over which the upstream part of the business rejuvenates itself. This simple fact explains that to simply stop exploring is not an option because the drop-off of production could not be replaced by alternatives. That may change over the decades to come, which is why preparing to 'Start stopping' (Thomas Princen's essay), is as far as we can sensibly go. At the same time it makes clear that much of the current talk about a 'carbon bubble' on the stock market is misplaced.[14]

So even if on that account geologists and geoscientists will not find themselves out of a job very soon, Dirk Smit points out that the advances in geoscience will continue and will increasingly find applications beyond oil and gas. These include the assessment of water reserves and of carbon sequestration potential.

A more classical geological contribution comes from Bruce Levell, who analyses what the geological record can tell us about the 'experiment' that mankind is presently conducting by raising the carbon dioxide levels far beyond what the world has known since human settling and culture developed.

Renewables and more

We then switch to 'Renewables and more'. We do want to include the prospects for nuclear energy in this book. Nuclear is not properly renewable, and whether it is 'sustainable' is a matter of definition. But nuclear fission has been the most significant form of carbon-free power for over a generation, and it has the advantage of being the most concentrated form of energy. (One of us (GJK) recalls a discussion on future energy with a Chinese academic in Shanghai a few years ago. He waved his arms around and said "This place needs concentrated energy", meaning nuclear. Looking outside to the landscape of skyscrapers that extended beyond the hazy horizon, it was hardly possible to contradict him.)

Chris Anastasi discusses the prospects for nuclear fission, and Niek Lopes Cardozo with Guido Lange the prospects for nuclear fusion. Their two very different stories have one thing in common: the absolute necessity for solid institutions and institutional frameworks to monitor and secure (fission) or to finance (fusion) nuclear energy.

The contrast could not be greater with renewable energy, in particular solar photovoltaics, and where that finds itself at this point in time. Reaping the benefits of decades of research, photovoltaics and a host of related technologies are now close to a 'docking point': for many consumers, investment in their own personal power generation has become a profitable proposition. The revolutionary consequences of this are explored later in this book, in 'Consumers at the gate' by Jurriaan Ruys and Michael Hogan and, further on, in the piece on the German *Energiewende* by Michael Weinhold and Klaus Willnow. Wim Sinke highlights the robustness of technological progress in photovoltaics and the broad front over which this is still proceeding.

Still, no matter how high our hopes for photovoltaics, a mix of energies will be needed. Ideally, as Wim Thomas argues, a full mix of renewables, clean fossil and nuclear. Relying on renewables alone presents a formidable challenge. Even in the very windy corner of Europe around the North Sea basin, it will not be easy to get energy production from wind energy to the scale that would be needed, but doable when the Dutch get to work with the same determination they used in building their defences against the sea. He illustrates this by considering what it will take for the Netherlands to develop offshore wind to produce an energy equivalent of one million barrels of oil per day, roughly the current level of production from the Groningen gas field.

Last, we come to renewable fuels. We cannot get by with electricity alone, and fuels will always be needed, and so far renewable fuels – biofuels and potentially hydrogen – have proved to be more difficult to scale up than was previously thought. Iris Lewandowski and Angelika Voss discuss the topic in a broader context of biomass production, agriculture and land use, and the need to balance the demands for food, feed and fibre with the desire to (co)produce energy.

The potential for agricultural and forestry-based bioenergy is ultimately limited by the availability of fertile land and fresh water. As discussed above, it is part of human nature to resist limits and to seek technological ways to circumvent such natural constraints. Noting that fuels need nothing else but sunlight, carbon dioxide and a small amount of water, Huub de Groot looks at the potential to combine the emerging capabilities of nanotechnology with the insights of life sciences to create ‘the artificial leaf’.

Energy use

Moving to ‘Changing patterns of use’, ‘Consumers at the gate’ looks at the potential impact of energy consumers turning into prosumers, who not only consume, but also produce energy. If this is a novel phenomenon, there is an equally important, evergreen item, namely efficiency. There is probably no better person able to articulate its potential then Amory Lovins, who has been advocating a ‘soft energy path’ since the 1970s. His essay ‘Energy efficiency: the rest of the iceberg’ has plenty of recent insights – how, for instance, a different approach to engineering delivers an almost zero-emission house, while minimising its construction costs.

The third essay in this section discusses hydrogen as a transport fuel. Touted as the ultimate fuel, the future fuel and – during the George W. Bush years – the Freedom Fuel, hydrogen has suffered more hype and consequently more despair than any other future fuel. However, the logic for its introduction, in tandem with fuel cell powered cars, still stands. Seven authors who were the lead proponents for their organisations to realise the next step for hydrogen rollout in Germany relate their story in ‘Hydrogen – Getting the fuel of the future on the road at last’.

If energy production is a more or less orderly topic, allowing us to cover the bases of the dozen or so forms of primary energy in a systematic manner, energy consumption is less so. It has myriad forms and shapes and any selection may feel somewhat arbitrary. So with that disclaimer, this section has three more contributions that cover very different aspects of energy consumption.

Tom Graedel, Ayman Elshkaki and Ester van der Voet discuss the connections between energy and the consumption of other major resources: water, metals and land. Here we return to the broader aspects of sustainability and planetary boundaries. Even if a specialist can convince himself that in his particular area of technical expertise there are no limits to growth, the linkages between sectors give us pause to reconsider.

In the last two essays in this section, Tali Trigg and Grahame Buss cover transport in two unusual ways. The first shows how distances vanish in cities that attract creatives and innovative industries. The latter demonstrates that, when all related agricultural emissions are taken into account, walking can sometimes be as carbon-intense a way to get around as is car driving.

Regional perspectives

The future of energy will be determined by a myriad of decisions taken all over the world. The final part of this book shows how different countries are going in different directions. The importance of China and the USA was highlighted in Cho Khong’s essay on the geopolitical aspects of the energy transition. Here we look at the evolving energy systems of these countries in detail. Jiang Kejun and Alexander van der Made start from today’s incongruous fact that China is not only the world’s largest carbon dioxide emitter but also the leading manufacturer of solar panels and – in recent years – the leading installer of green technology. They hypothesise how this may impact on the build-out and transformation of energy in China.

What makes China's energy transition different from that of the West is the fact that the pressures of growing energy demand, clean air and decarbonisation are all playing out at the same time – now – whereas in the USA, for example, the energy growth spurt happened in the post-war period, clean air legislation followed from the early 1970s and now the country is adopting low-carbon and renewable energy. In this light, Michael Eckhart describes the USA as halfway through a century-long path of transformation. Having reshaped its energy scene through market innovations, deregulation and policies to create demand for new energy technologies, he sees financial innovation as one of the shaping forces of the future energy transition.

What about Europe? It is the continent which was early in initiating the transition – both as a moral force and as an early adopter of greentech through a patchwork of lavish incentives. As one might expect, elements of national character are recognisable in the national energy transitions: the *Schaffensdrang* of the Germans, the economic rationality of the British, and the tradition of *polderen* in the Netherlands. First, Michael Weinhold and Klaus Willnow tell the story of how the *Energiewende* has made Germany the first country that can sometimes produce all its electricity requirements from just sun and wind, an accomplishment that brings its own challenges. Then Jo Coleman and Andrew Haslett show how early preparations in the UK can create a low-cost pathway for decarbonisation, opening up a global marketplace for low-carbon technologies. The two subsequent essays deal with the Netherlands. Wiebe Draijer describes how he led a 40-party negotiation leading to an *Energieakkoord*, which should help the Netherlands accelerate the cleaning and greening of its economy. Ed Nijpels, who is in charge of overseeing the implementation of the *Energieakkoord*, gives his impressions and the lessons he has learned as the plan is brought to life.

The book ends with a wonderful essay by Bennett Cohen and Anya Cherneff, who relate how the latest solar and battery technology and LED lighting can be packaged as a sturdy, low-cost device that brightens life in Nepali villages.

That ends our brief tour of this book. We hope that the essays make clear that while the challenges surrounding energy, progress and sustainability are daunting, there are myriad ways in which these can be addressed – the full spectrum of *The colours of energy.*

Gert Jan Kramer is Manager Energy Futures at Shell Technology Centre Amsterdam. A physicist by training, he joined Shell in 1988 where he initially worked on classical oil industry topics such as catalysis and reactor engineering. In 1998 he became involved in research relating to hydrogen as a future fuel. Over the years his activities broadened to technology assessment across the full spectrum of alternative energies. In addition to his role at Shell he is professor of sustainable energy at Leiden University and a member of the Technical Committee of the Energy Technologies Institute in the UK.

Chris Laurens is Vice President of Future Energy Technologies at Shell where he oversees the Shell technology programme in the areas of renewable energy generation, hydrogen and the future electricity system. Prior to Shell, he spent 15 years at McKinsey & Company in Europe, Africa, the Middle East and Asia where he served clients on energy, technology, finance and economic sector development. Laurens holds a PhD in Physics from Groningen University and lives in The Hague.

Jeremy Bentham is Vice President Global Business Environment at Shell, head of the Shell Scenarios work, and a member of the corporate strategy leadership team. He has more than 30 years' business experience in Shell and has studied at Oxford University, California Institute of Technology, and Massachusetts Institute of Technology.

Bram Vermeer is a science writer and publisher. He has written several books, including works on the future of technology, energy and the role of science in policy and public debate. Vermeer is a co-founder of Oostenwind Press (Amsterdam), which publishes books by Dutch journalists. He was educated as a physicist and did several years' research on superconductivity. Vermeer lives in Amsterdam and Berlin.

References

1. Shell scenarios at www.shell.com/scenarios.
2. F. Niele (2005). *Energy, engine of evolution*, Elsevier Science: Amsterdam.
3. V. Smil (2003). *Energy at the crossroads*, MIT Press: Cambridge, MA, chapter 2.

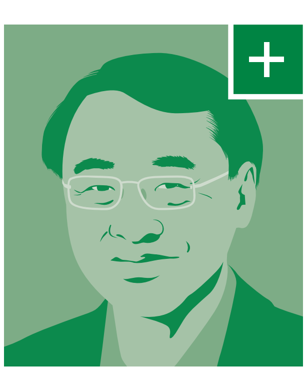
4. See for instance: A. van Benthem & M. Romani (2009). Fuelling Growth: What Drives Energy Demand in Developing Countries?, *The Energy Journal, 30*, 91-114.
5. M. Lane (2011). *Eco-republic: Ancient thinking for a green age*, Peter Lang: Bern.
6. T. Chambers, J. Porritt & P. Price-Thomas (2008). *Sustainable wealth creation within environmental limits*, Forum for the Future.
7. J. Cohen (1995). *How many people can the earth support?,* W.W. Norton: New York.
8. J. Cohen, *vide supra*.
9. M.E. Spaght, *Energy and economic development*, address before the Western Area Symposium of Stanford Research Institute, San Francisco, November 17, 1954, reproduced in M.E. Spaght (1965), *The bright key: Thoughts on the relation of business to research and education* (Appleton-Century-Crofts: New York). The authors wish to thank Rutger van Santen for bringing this reference to their attention.
10. Robert M. Solow (1991), *Sustainability: An economist's perspective*, Vol 18 of J. Steward Johnson lecture in marine policy.
11. P. Sabin (2013). *The bet: Paul Ehrlich, Julian Simon, and our gamble over earth's future*, Yale University Press: New Haven.
12. J. Rockström et al. (2009). A safe operating space for humanity. *Nature, 461*, 472-475.
13. K. Riahi and R.A. Roehr (2000). 'Greenhouse Gas Emissions in a Dynamics-as-Usual Scenario of Economic and Energy Development', *Technological Forecasting and Social Change, 63*, 175-205.
14. See e.g. the report: *Unburnable carbon – Are the world's financial markets carrying a carbon bubble?* by the Carbon Tracker Initiative, www.carbontracker.org.

Energy and society

A new sustainable global order can bring new prosperity. The geopolitics and economic structures will change. The transition will create new dependencies and security concerns.

A new order
The geopolitics of the energy and climate challenge

Globalisation may slow as a result of the energy transition. Yet a global climate agreement may bring new prosperity.



> *Cho-Oon Khong*

Dealing with energy transition and climate change puts humanity at a critical inflection point. Does it rise to the challenge and manage to unlock the immense benefits that a new sustainable global order might possibly bring? Or will it fail and plunge the world into unprecedented upheaval and loss? As Brutus chides Cassius in Shakespeare's Julius Caesar,

> There is a tide in the affairs of men
> Which, taken at the flood, leads on to fortune;
> Omitted, all the voyage of their life
> Is bound in shallows and in miseries.
> On such a full sea are we now afloat;
> And we must take the current when it serves,
> Or lose our ventures.[1]

It is on this full but uncertain sea that we abide. The global geopolitical landscape is on the threshold of fundamental change. The old order, with its narrative of the 'end of history', the USA with unchallenged global hegemony and big global deals on trade and security, is looking increasingly outdated. The Washington Consensus, with its liberal prescriptions for the crisis-stricken countries, that this old order promoted, has proved to be double-edged. On the one hand we have seen China's remarkable rise in living standards and economic power, with other developing countries following on; on the other hand the inequalities within countries have intensified, underpinning a new politics of anxiety and insecurity and laying the seeds of ecological implosion. While old certainties no longer appear viable, what takes their place has still to be fashioned.

One possibility is of a more pluralistic international system and a return to geopolitical rivalry. There may be a heightened risk of conflict (though not the industrial-style warfare of the 20th century). But this does not preclude the great co-operation in power that will be needed to deal with the challenges of the 21st century.[2] Those challenges, particularly the interlinked problems of climate change and of transitioning to more sustainable energy sources, suggest another possibility – a more co-operative international system, with collective action based on a recognition of shared common interests.

At present the international geopolitical system is under strain from two transformations happening at the same time. First there is the long-term shift of economic and geopolitical power from West to East, which is gradually reshaping the global system. This shift will take time to play out, but it will have profound long-term consequences. Second, there is the political impact of the financial and economic crisis which began in 2008. This may be making a tentative recovery, but its consequences will play out over the longer term. Both transformations are expected to leave their mark on energy transition and the way we deal with the climate challenge.

The USA and China need to co-operate

The USA's relationship with China is central to this West-to-East shift, and it remains to be seen how contentious this might turn out to be. The USA itself is no longer able to play a global role on its own terms, setting and maintaining the rules of the global system and enforcing its will on others. Instead, it will have to feel its way towards a *modus vivendi* with other powers. So dealing with energy transition and the climate challenge requires both the USA and China to agree to co-operate with each other. In this area of action, the state of their relationship will be decisive.[3]

Europe's significance as a global geopolitical player has steadily declined over the course of the 20th century and is now marginal. So in trying to establish global co-operation on energy and on dealing with climate change, Europe has only a limited tangible impact, though she may seek to take a moral lead.

Meanwhile, existing international organisations have proved incapable of dealing with global problems and have largely been sidelined. They appear to be largely disconnected from the urgency of the problem, and this limits what we might expect from international efforts to deal with the climate challenge.

Just as 2001 marked the beginning of a shift away from the post-Cold War order of global unipolarity centred on the USA, 2008 marked a second turning point in this structural shift. It marked the end of the 'unipolar moment' and gave us hints as to how the global landscape might evolve over the longer term. While we may get a smooth transformation of the system, political transitions are inherently unstable. We are moving into a more fluid geopolitical environment, with greater political uncertainty and an increasingly confrontational world. The global order may well be heading into a period of *disorder* before the system gels again to establish a new order.

Just how much disorder there will be in this transitional period will depend on the choices that peoples and governments make. Rising powers are asserting their interests against established powers whose authority has been damaged by the crisis. With every country looking to defend and advance its own national interests, the key players in the international system will need to take a broader view. They will need to co-operate over the course of the transition if they are to avoid potentially damaging consequences.

The geopolitics of the 21st century

While globalisation carries on for now, there are question marks over the direction it will take in the future.[4] In one possible scenario we would see a geopolitical context similar to that of today, but one which might change if there were compelling reasons for international co-operation. So national rivalry could morph into adaptation and finally into co-operation, in order to deal with the challenges of energy and climate.

We begin in the familiar world of competing nationalisms and geopolitical rivalry, a world in which power is concentrated in the hands of global elites who drive policy. Global growth slows down, with many countries trapped in stagnation.

Then, as the international system becomes more pluralistic, the USA remains pre-eminent but can no longer dominate, and other leading states see no reason to emulate US norms. As one Chinese scholar has remarked, when commenting on China's role in the international system, China is being invited into the casino to play and is offered a seat at the roulette table, but the West retains ownership of the casino and sets the house rules.[5] Beijing naturally prefers to operate to its own priorities.

States initially confront each other, in the South China Sea, in Eastern Europe, in the Middle East and elsewhere. Globalisation slows as state control and nationalist tensions increase. Countries are more concerned about the security of their energy supply than about climate change.

Civil society will drive change

From the late 2010s and into the 2020s, however, states move to a more adaptive world. They accommodate each other's interests through hard bargaining, and retain 'sharp elbows' in dealing with each other. States will co-operate with each other, including on climate change, provided they see this as being in their own interest. But any co-operation is against a backdrop of continued rivalry and heightened risks.

As the world moves further into the 21st century, this geopolitical order of great power rivalry will need more and more to accommodate the concerns that are already being voiced, of people power and a more vocal politics, with civil society driving the change. People power is already a potent force today, with existing regimes concerned about its destabilising potential. But it has yet to prove it can establish new forms of secure and stable governance that will address the deficiencies of today's world, and it lacks the leadership to do so. It will have ample opportunities in the future to prove it can be a potent positive force to build a stable geopolitical order, and it is likely to gain increasing traction. Indeed, we will need radical 'grass-roots' action, driven from the bottom up by individuals and local communities with new populist concerns, to address the failures of the existing powers to deal with the climate challenge. Some early signals suggest the seeds of such action are already in place.

For effective action the bottom-up pressures and top-down drivers need to coalesce, so that the leading powers of the 21st century geopolitical order form a de facto equivalent of the Concert of Great Powers that sorted out Europe's problems in the 19th century. Just as those great powers of the past were motivated by the need to sort out the problems of Napoleonic disorder, so their 21st-century equivalent will need to work together to manage their rival interests so they can tackle the big problems of energy transition and climate change. They will also need to learn to work with the increasing public pressures for change within their own societies. By the 2030s and 2040s, new technological opportunities should start to make a significant impact on the climate challenge; and business interests and leading figures across the wider society may well be first to recognise the new opportunities for sustainable growth that these new technologies will make possible.

Geopolitics and the climate challenge

The crux of the problem lies in the nature of climate change itself. It is a linking of deeply interconnected threats with a common origin – the rising levels of carbon emissions as a consequence of human activity. That human activity itself is the foundation on which global economic growth has been built, but these positive forces threaten the very existence of human civilisation. In turn the human imagination finds it difficult to connect the two sides, to recognise that the positive forces driving progress are inherently perilous. Thus we tend to keep the two separate. There is also the timescale of the problem. The most harmful consequences of climate change will happen in the second half of this century, while the need for action is in the next two decades. In any case, today's governments are more concerned to stimulate economic revival in any way they can.

The default position of governments, in turn, is to remain on automatic pilot, even though they are increasingly aware that a crash is inevitable unless they change course. Add to the mix a growing rejectionist politics, with people feeling that the democratic political process is dominated by out-of-touch elites who no longer understand and reflect their interests. This populist backlash is gutting for political leaders who lack any ability to rethink the fundamental assumptions on which they base policy. And there is the danger it will extend to energy companies, as climate disruption starts to hit home.

One might have thought an effective worldwide governance body to steer the global order would make all the difference. But the international community is too divided, despite a vague awareness of shared long-term interests. We see this in the limited track record of climate negotiations.

The need for a multilateral approach to deal with the climate challenge was recognised in the United Nations Framework Convention on Climate Change, ratified in 1994. The Kyoto Protocol followed in 1997, but it had few adherents and covered an increasingly smaller percentage of carbon emissions, particularly as emissions grew rapidly in the large developing countries, and the USA and Canada withdrew. The Protocol expired in December 2012.

The Copenhagen Accord, intended as a successor to Kyoto, followed in 2009, but it too failed to generate substantive agreement, as countries, concerned about costs, shied away from binding commitments. In the wake of the 2008 financial crisis, all countries were strapped for cash and had to deal with an immediate system-threatening challenge. This left the international approach at a dead end. So countries are stuck on a course which they know is inherently unsustainable over the long term.

The Montreal Protocol, to eliminate the use of ozone-depleting chlorofluorocarbons and hydrochlorofluorocarbons, is often held up as a successful example of international action to deal with a global challenge. The Protocol was successful, however, because it focused on a targeted problem, to deal with the thinning stratospheric ozone layer, with clear scientific evidence. People could be motivated to change their behaviour at little or no cost, and governments faced a clearly defined set of benefits that far outweighed the cost of change. Climate change, by contrast, is a more variegated long-term problem with complex interdependencies, and is less amenable to global agreement.

The way forward – carrot and stick

The basic problem in dealing with the climate challenge is that the price of carbon-based energy must rise to take account of externalities, in particular the follow-on costs from carbon emissions. Emissions must in some way be made to cost.

The question at this point is how to move forward in a way that recognises this problem. Given the stalemate in international negotiations, is unilateral action the answer? Unilateral action is when countries act at a national level to deal with the climate challenge, but do not co-ordinate with other countries. Some countries have already taken limited measures in this regard, setting targets and objectives to lower carbon dioxide emissions. But their targets have been patchy, and inadequate to deal with the scale of the climate challenge. Nor are there any real penalties should national governments fail to meet their own goals. Nevertheless, these limited, tentative actions at the national level have constituted the only approach we have seen so far to deal with climate.

The focus of democratic countries is short term

The problem for democratic countries is that they are driven by the immediate concerns of voters, and so their focus is short term.[6] The challenge for them is to think long term. This requires a broad consensus across the political spectrum, so that plans are not overturned by changes of government, and are deep-rooted enough to be sustained despite the vicissitudes of day-to-day politics.

At the international level there have been many proposals for agreements that would require all countries to set binding regulatory and tax measures to deal with the climate challenge. These agreements would be co-ordinated at the international level and be subject to global monitoring and accountability. As we have seen, the track record of success at the international level has so far been modest. But given the nature and scale of the problem, a multilateral approach is essential for a long-term solution. What geopolitical conditions could enable such a multilateral approach to be built?

At the heart of the problem is the need for governance. Markets alone will not solve the problem. On the one hand, national governments find it hard to play an enabling role within their own economies and societies.

On the other hand, the major countries obviously need to work together. But there is no legal mechanism to prevent free-riding and to force countries who take a narrow self-interest to shoulder joint responsibility with others and to act for the common good.

The use of a ‘stick’ of some kind, forcing governments to act by threatening penalties, would be difficult. Indeed, compelling governments to act against their will would be counterproductive. It would certainly be ineffective if the aim were to persuade countries to work co-operatively rather than to ride free.

In an environment of geopolitical rivalry, however, where governments look mainly to their narrowly defined national interests, it is hard to see how the ‘carrot’ of positive inducements might be enough to encourage action on climate change. Governments are naturally concerned to protect their national sovereignty and domestic policy prerogatives, and democratic governments, by definition, stand or fall by the decisions of their electorates. In this day and age, even autocratic regimes require some popular consent if they are to survive.

One way forward towards an international agreement on climate strategy might be to combine carrot and stick. Such an approach, motivated by national self-interest and combining inducements with penalties, could see a group of leading countries committed to energy reform. They could seek to protect themselves from cheaper high-carbon-emitting economies, erecting trade barriers against the latter. The leading countries might, for instance, agree to a carbon cap with border tax adjustments that imposed heavy penalties on high-carbon-emitting economies. Alternatively they might choose to impose a uniform percentage tax on imports. The idea would be to wield a stick in a way that incentivised countries to become part of the solution, while dangling a carrot that would seem more attractive than remaining outside the tent of reforming countries.

In such an approach, leading countries would set standards to encourage laggard countries to raise their game. The objective would be to impose a cost on carbon emissions, and to harmonise these costs to approximate equivalence for all countries.

There may be other routes to a multilateral agreement, and we should remain open to all possibilities. But it is hard to conceive of a solution that does not involve both carrot and stick, to incentivise action and to penalise free-riding.

Such an approach might be regarded as consonant with a geopolitical environment of slower globalisation and national rivalry, where governments aggressively deploy renewables to meet concerns such as energy security, and play a greater role in national economies. If this approach could stimulate the innovation and investment needed for a sustainable energy transition and cheaper non-carbon energy sources, popular support might grow. Eventually a virtuous cycle would be created, with support feeding the impetus for energy reform. Change will not be driven by global altruism, but by people who have come to believe it will improve their personal circumstances.[7] This is a world order which would be driven more and more by popular bottom-up pressures, with rising aspirations pushing for reform and change. It could possibly set off a new wave of globalisation.

Leading governments will themselves require popular consent in order to act. There is clearly a role for fashioning solutions at local level, bringing in the private sector to work with others in order to achieve positive endorsement. As various commentators have noted, change driven only by top-down decrees cannot be sustained. Ultimately, it does not work. Genuine reform will depend on top-down directions built on a foundation of grass-roots pressures, bottom-up initiatives and enlightened self-interest.[8]

China turnaround

In looking at the geopolitical order of the 21st century, the one big question that commentators ask is what we might expect China to do. There is much discussion about the need to avoid the 'Thucydides trap', in which a rising power upsets the balance of power set by an older waning power, with mutual suspicion leading eventually to conflict.[9]

Many in the West ask if 'we' should be worried that China invests heavily outside its borders. Asking the question in the first place shows that there is a subconscious fear of China which reflects how the West sees itself. The rise of China comes at a time when the West is deeply mired in self-doubt, questioning the strength of its own institutions and systems of governance.

But there is another view of China – not of China as threat, but of China as hope. This is most evident when it comes to dealing with climate change. Fearing that the West will do too little, and that it will do even that too late, some pin hopes on China to lead the way. This appears as the modern counterpart to the 18th-century European Enlightenment obsession, as pronounced by Voltaire and others, of China as the ideal model state, wisely governed by learned emperors. Equally then, as today, this idealised view was more a critique of the West than any realistic grasp of China's circumstances.

China will of course act in what the regime believes to be its own interests, but it faces fundamental adjustments as its model of growth becomes increasingly unsustainable. The regime expects that gradual economic reform will maintain consensus around the ruling regime. History has shown, however, that a scenario of crisis and swift radical change is possible. The challenge for the regime is to implement radical reform while maintaining stability.

The continuation of China's current development strategy is impossible, given its impact on global imbalances, its rising domestic inequality, other social stresses, environmental damage, and an increasingly restive population now more interconnected and empowered by social media. Economists agree that China needs to move to a more sustainable growth model with a shift to domestic consumption and non-industrial investment. It is a moot question whether such a transition would also require wide-ranging social and political reform. Reform, in any case, would challenge vested interests and be difficult to implement.

The new leadership recognises the need for economic rebalancing, but is equally concerned to maintain control over the reform process and not endanger stability. The direction of reform needs to be set clearly, so as not to open up a contentious debate on where it should go. China's window of opportunity to reform is now. Its dependency ratio will start to rise from the latter 2010s, as the proportion of its working age population shrinks. The effects of an ageing population will start to become noticeable in the 2020s, leading to slower rates of growth. So reform *now* is crucial to maintain growth and stability over the longer term.

China's greatest environmental concern today is water security, which it attempts to deal with through big engineering projects. These have proved controversial and may well bring unforeseen consequences and costs. But the question now is, how will she deal with the climate challenge? Hope that China will take the lead is based on a belief that the Chinese government is able to think and plan long term, and to push massive investments into green technology. Whether or not the regime is able to think long term,[10] there are a whole suite of reasons for it to act on climate.

The Chinese urban middle class is increasingly empowered and restive

One of them is an increasingly empowered and restive urban middle class which is concerned about local environmental pollution. Effective action by the government that would noticeably cut levels of urban pollution would greatly strengthen its legitimacy among a key constituency of support – those very people who have most benefited from the economic growth of the last two decades. At the same time, China's taking the lead on climate action would confer enormous legitimacy on the regime in international public opinion, strengthening its status in the global order. Meanwhile, ramping up investment in green technology and pushing energy efficiency measures will help to address China's growing concerns for energy security.

Energy reform is also an inextricable part of the broader imperative of economic reform which China faces as she shifts away from heavy energy-intensive industry towards lower energy-intensive manufacturing and services. Successfully pulling off such a transition would both retain stability and maintain the legitimacy of the regime. The nature of that legitimacy will surely change, however, moving from a justification based solely on economic growth to one that encompasses other measures such as quality of life and accountability.

USA turnaround

Climate change will have an impact on both developed and developing countries. Indeed, it is not at all clear that its impact will be any less in developed countries or that, despite greater resources, the developed nations can deal with it any better than the others. Developed countries characteristically have a more extensive and vulnerable infrastructure and higher costs all round. They also have populations who are used to a higher standard of living and assume a certain level of provision of basic services. US vulnerabilities were first shown up by hurricane Katrina, even if there was little impact on American climate consciousness.

Today an increasing flow of shale gas production is dramatically reducing US carbon emissions, with power stations substituting gas for coal for economic reasons. This suggests that the main thrust in dealing with the climate challenge must be based on market incentives. Regulation has its place, though the history of regulation in the USA shows a propensity for regulatory capture based on the extensive lobbying power of special interests within the political process.

So the USA may be expected to deal with the climate challenge when political elites or key constituents become conscious of the need to act. One trigger could be a hit to asset prices caused by disruptive weather events. Private insurers are currently absorbing some of the economic costs of increasing climate variability, but they are already warning that this cannot be expected to continue.

The authorities will find it difficult to act, however, if there are no votes for the necessary measures. As long as there is an appreciable cost to dealing with climate, it will always be a challenge to shift US public opinion in order to get agreement. We may well find that it is cities and states directly hit by climate events (and their concomitant growing economic costs) that take the initial lead while the federal government prevaricates.

Regulation at the federal level will follow local action, although such progress may require pressure by leading opinion shapers and business figures. New 'super PACs'[11] could emerge, fed by Silicon Valley money and focusing on environmental action. Such developments could unleash strong commercial and entrepreneurial powers, through supportive regulatory and market frameworks, in the same way that the shale gas revolution was driven by the private sector and enabled by a supportive state legislative framework. At the same time, national action on climate would be strongly reinforced by increasing international competition and by the fear that the USA was falling behind. If China were seen to achieve a breakthrough in green technology, whether real or imagined, it might prove to be a new 'Sputnik moment' and energise the USA to catch up with its geopolitical rivals.

The promise before us

The urgency with which we need to tackle the climate challenge and the scale of the effort required suggests that the nature of governance and also of the global order may well be on the brink of change. Reform by its nature is likely to prove turbulent, but disorder can be managed and limited if governments are alert to the need for change and adapt accordingly.

China and the USA will be driven to reform by pressures which their respective regimes, different as they are from each other, cannot avoid. Similarly, a Middle East faced with a world moving away from hydrocarbons will need to diversify economically, even if the global demand for carbon fuels remains strong for a long time to come. It is *relative* importance that matters in the global order, and as hydrocarbons predominate less in the world's total energy mix, so the centrality of the Middle East to the security of the global order will also begin to marginalise.

The parameters of this future geopolitical order are unclear. As we have seen, however, the trends which are shaping this future can be identified and delineated. Globalisation, for instance, may slow in a period of transition, especially if change proves to be somewhat rough-edged and disorderly. But globalisation may well pick up again as responses to the climate challenge set a new direction of change, and it will need to evolve to fit with the world order of the future. The promise before us, if the climate transition is successfully negotiated, is for a stable geopolitical order. In this governments will recognise the need to work synergistically with bottom-up pressures from within their societies, as they co-operate with each other to deal with the challenges they commonly face.

Related essay

The greening and cleaning of China
Low-carbon pathways for the world's largest energy consumer
> *Jiang Kejun and Alexander van der Made*

Cho-Oon Khong is Chief Political Analyst in the Global Business Environment team of Shell. He was educated at the University of Singapore and the London School of Economics. He did post-doctoral research at Cambridge, then taught Politics and International Relations at the National University of Singapore and the University of Bath. Cho is a member of the advisory panel of the Evian Group at IMD, Lausanne, and teaches on the Oxford Scenarios Programme at the Said Business School, University of Oxford. For Shell, Cho has been involved in developing Shell's Global Scenarios since 1995 and advises on political trends and country risk.

Notes and references

1. William Shakespeare, *Julius Caesar*, Act IV, scene ii, 218-224, The Oxford Shakespeare (1984), OUP: Oxford.
2. John Gray, What is going to happen in the next hundred years?, *New Statesman*, 15 May 2013.
3. Jorgen Randers has argued that the US-China relationship is decisive on dealing with the climate challenge. See Jorgen Randers (2012). *2052: A global forecast for the next forty years,* Chelsea Green: White River Junction, VT.

4. The geopolitical contexts described here are derived from Shell's New Lens Scenarios. See Shell (2013). *New Lens Scenarios: A shift in perspective for a world in transition*, http://www.shell.com/global/future-energy/scenarios/new-lens-scenarios.html.
5. Philip Stephens, Rising powers do not want to play by the West's rules, *Financial Times*, 21 May 2010.
6. As many writers have noted. See for instance Anthony Giddens (2008). *The politics of climate change: National responses to the challenge of global warming*, Policy Network: London.
7. Gwythian Prins and Mark Eliot Caine write in *The vital spark: Innovating clean and affordable energy for all: the third Hartwell paper* (LSE Academic Publishing: London, 2013), "Only general prosperity can produce widespread consent for emissions reductions, and only affordable energy for all can deliver prosperity."
8. See most notably: Gwyn Prins & Steve Rayner (2007). *The wrong trousers: Radically rethinking climate policy*, James Martin Institute for Science and Civilization: Oxford; and also Shell (2008). *Shell energy scenarios to 2050*, http://s00.static-shell.com/content/dam/shell/static/future-energy/downloads/shell-scenarios/shell-energy-scenarios2050.pdf.
9. See for instance: James Steinberg & Michael O'Hanlon (2014). *Strategic reassurance and resolve: US-China relations in the twenty-first century*, Princeton University Press: Princeton, NJ; The term 'Thucydides Trap' was coined by Graham Allison. See: Ben Schott, The Thucydides Trap, *New York Times*, 31 January 2011.
10. Shaun Breslin argues in an unpublished paper for Shell, May 2014, that the idea of 'environmental authoritarianism' needs to be heavily qualified when applied to China.
11. A Political Action Committee or PAC is an organisation in the US political process that pools contributions from members in order to fund campaigns for or against candidates, ballot initiatives or legislation. A Super PAC cannot make contributions to candidate campaigns or parties, but may engage in unlimited political spending independently of campaigns, and can raise funds without any legal limit on donation size.

Energy security New forms of energy create new dependencies

The intermittent nature of wind and solar power creates new challenges for the security of energy supply. This requires a rethink of the technological, economic and political demands of the energy system.

> *Coby van der Linde*

New energy sources such as solar and wind promise what seems like an impressive combination: an infinite energy supply, which can be produced domestically. Particularly in Europe, where the prospect of new fossil fuel production is low and support for nuclear energy is declining, countries are embracing the development of renewables in the hope that this will secure energy supply and solve environmental issues.

Yet we still need to worry about the security of energy supply. In the transition towards a renewable energy system all kinds of new dependencies and unwanted side effects might arise. This could make energy supply less secure than it is today. New issues will arise that will make energy security more complex. The many different side effects can't be solved with the traditional toolkits. A broader political approach is needed to control the patchwork of new dependencies and guide society securely through the energy transition.

The priorities of energy policy

Shocks in energy demand or supply can radically change the economic viability of large companies and hit small consumers. Shocks affect the stability of the economy and affect the competitiveness of countries, weakening their strategic position in the world. As a result, the quest for predictability and stability drives many energy policies. Energy security is important to policymakers at all levels.[1]

Security is, however, only one of the three priorities of energy policy. The other two are a relatively low price – or affordability – and protection of the environment. It is hard to pursue these three priorities simultaneously. Over time, one or two of the three policy goals gain prominence while the other receives less attention. A relatively low price for coal or oil, for example, could compromise climate change policies. A preference for domestically resourced energy to increase security could affect both affordability and the environment. This can be seen in the German taste for solar, wind and coal, the last of which is not the most logical from an environmental point of view, but is the result of concerns over security and competition.

Energy policymaking often reflects the concerns of the day.[2] Usually a seller's market focuses policymaking on the cost of energy, while geopolitical uncertainties – particularly when there is a large dependence on a small number of exporting countries – bring security of supply to the fore. In a buyer's market, concerns about disruptions and the cost of energy disappear. The focus then shifts to creating a good balance between imported and domestically produced fuels, as well as environmental concerns.

Policymaking is further complicated by the fact that states are often deeply entrenched in energy markets, even in so-called market economies. State companies operate roughly three quarters of global oil and natural gas reserves (excluding shale). Government income also relies heavily on the energy sector through ownership or taxation, even in importing countries. As a result, 'the market' is more often a forum for competing energy policies than a place where energy is traded as a commodity.

One way to secure energy supply is to diversify imports in terms of both energy sources and geographic origin. Technology may also allay security concerns if previously inaccessible reserves of energy, such as shale oil and gas, can be exploited or other energy technologies can be introduced. In the 1970s, for instance, nuclear energy was a means to diversify. Today renewables, such as solar and wind power, may help countries to manage their energy dependency. Yet diversification doesn't automatically bring more security.

New dependencies

For a start, renewable energy supply is almost never completely local. Sunlight and wind are more evenly distributed over the world than fossil fuels. Yet that doesn't automatically give more independence. Biomass for energy is often imported. Even hydropower is not purely local, as the energy stored in reservoirs may originate far away and affects water availability across national boundaries.

For renewables, such as wind and solar, production chains often extend beyond borders. If China stops exporting rare earth elements, serious problems will temporarily arise with the production of solar cells, batteries or wind turbines, until new production sites are opened elsewhere. With wind turbines, the iron needed to build them is usually not mined on the spot. However, once they are installed this argument no longer holds and the production of wind and solar energy does indeed become domestically produced.

So even with renewables, we will have worries about security of supply because of bottlenecks in access to the raw materials necessary to generate renewable energy. It is a romantic and false idea to think that renewables give self-sufficiency. It might be tempting to think that, because they solve the issue of high dependence on fossil fuel imports. Yet renewables don’t remedy all dependencies, they are currently just less visible because of the relatively small scale and their different nature.

Balancing

These new dependencies are only part of the story. Security of supply will be far more complex than merely exchanging one dependency for another. During the build-up of a renewable energy system, the security of the traditional supply still needs to be managed. Oil, gas and perhaps also coal (with CCS) will all be needed to balance the fluctuating supply of sun and wind.

Many other solutions to balance these fluctuations have been proposed. This book is full of interesting options to manage supply and demand. There is potential storage capacity in water; there are geothermal approaches and batteries. Excess electricity may be stored in the form of hydrogen and transported through the extensive pipeline systems that many countries have. Hybrid passenger cars may store energy, provided sufficient connections are available for charging vehicles during peak production hours at night and midday. Additionally, the management of demand through dynamic pricing and lifestyle changes could in time smooth out many of the issues surrounding short-term security of supply.

While these technical innovations may balance intermittent energy sources in the longer term and may eventually provide a secure supply, the economics of such systems remain unclear. As the capacity for solar and wind power grows, the costs of balancing supply and demand will become higher unless a breakthrough is reached with a variety of new technologies to store electricity being developed at various levels in the system.

As long as these new technologies remain insufficient to balance the system, we will need to combine the old and the new. This means that the energy system must deal with fluctuations almost daily, which will test its technical and economic flexibility. In Germany solar and wind power provide a fluctuating baseload, while other sources are used to service the rest of the demand. With intermittent renewables given grid priority, the traditional thermal baseload becomes – awkwardly enough – intermittent also. This has implications for affordability and the environmental performance of these technologies.

Interruptions and price spikes are the new normal

As the share of renewables increases, such as for heating, the demand for traditional fuels will decrease and will be less predictable. It will be increasingly determined by fluctuating daily and seasonal demands. Investments in capacity to supply these markets will become more uncertain. Interruptions and price spikes were the nightmare of policymakers in the post-1973 world. In the post-2020 world, these might be part of the new normal.

The current infrastructure for coal, oil and gas is sized to meet a continuous, high demand. But as the call on these resources declines, and the economic logic to run them disappears, some of the conventional power generation plants and oil and gas production and transportation infrastructure will atrophy. Although the decline of coal-fired plants without carbon abatement technologies is an expected outcome of policymaking, gas-fired power plants are still needed to balance demand and supply in an energy system with more intermittent sources while lowering carbon emissions. The business models underlying the conventional capacities that are still needed to fill in the gaps will thus deteriorate in a shrinking and less predictable market. It will also be increasingly uncertain what rewards may be realised for investing in them. Already in some countries, utility companies with a large traditional or nuclear portfolio are struggling with both the declining proceeds from their existing plants and their diminishing elbow room for future investments.

Yet to continue the flow of fossil fuels, new investment will be necessary. Maturing infrastructures will require large future expenditure, but with much more uncertain investment horizons. In some countries, power plants need to be replaced or renovated. Ships, pipelines, refineries and power stations require long lead times for building and depreciate over many decades. The lifespan of new installations often already extends beyond 2050, the target year in Europe for a mainly renewable energy system.

This is not only a problem of energy importers. Countries that rely heavily on their export of fossil fuels may see their budgets and employment levels shrink. Although the International Energy Agency predicts that global demand will continue to grow over the next few decades, it is unclear how trade will develop when some regions rapidly increase their share of renewables. Producing countries may find it harder to diversify markets and manage their investments. This may be exacerbated if North America becomes largely self-sufficient through shale oil and gas. As a result, the international energy market may become less integrated and involve more bilateral agreements, in which political issues may play a bigger role.

So part of the new reality for energy policy is a more complex operational adequacy. Securing supply will be more difficult than it is today. This is not a technological issue. Renewable technologies have already advanced further than we can handle economically and politically. The challenge is one of how to continue investments in renewables while at the same time sustaining the extra costs of a double infrastructure to maintain energy security. The energy transition is often debated in terms of its final goal. Yet we need a discussion about the costs of balancing intermittency and how to share them.

The path chosen

Much will depend on the path chosen through the energy transition.[3] The options depend on the availability of national resources, but also on industrial needs, government policies relating to subsidies and taxes, and many other factors.

Winding as the path through the transition may be, each turn we take will cut off some possibilities while favouring others. That is what history teaches us. At the end of the 19th century, a higher percentage of cars were electric than today. Gas motors were well developed at that time. Yet as cheap liquid fuels became available, electric and gas options were no longer pursued. It was purely accidental that transport became oil-based. That other energy technologies developed a century ago didn’t make it was equally coincidental. The choices we make now will likewise determine the outcome, and will be crucial for future energy security. When we pick up the thread of old ideas again, this, in turn, means that some other options have fewer opportunities. We should be more aware of this contingency. Choices we make at an early stage, creating a pathway through the transition, may well determine if we ever reach the goal of a renewable energy system, and at what cost.

Electrifying energy demand (especially for heat and transport) before coal has been sufficiently backed out of the power system is counterproductive. It is simply a matter of getting the most out of each tonne of carbon dioxide emitted. There is a wide difference among fossil fuels in their carbon footprint. Using electricity for heating and transportation is less efficient than natural gas, when electricity is generated by coal. So using electricity for these purposes should not be the first choice during the transition.

Ignoring the crucial roles that oil and gas play may also undermine the position of some industries. You can’t make things from just electricity. The industry needs feedstock to derive the molecules for their products. Those molecules are often made from fossils, but biobased feedstock may also be used. The molecular energy needs of industry may require more specific fuel flows than currently stream into the market. Industry may need carbon capture and storage (CCS) or other technologies to reduce the carbon emissions associated with their molecular needs. Yet the public debate, focusing on electricity from sun and wind, completely misses the security of molecular energy supply. Failing to secure these streams will fundamentally change the structure of industry.

Globalisation and retreat

Our ability to solve these issues determines if we will ever reach the goal of a fully renewable energy system. Failing to do so will get us stuck halfway. Yet at what level should these issues be solved? Which coordination mechanisms best match regional needs with both international developments and the structure of international markets? France and Great Britain already pay utilities to have back-up power available. This is one way to secure an uninterrupted power supply and is an example of central planning at the national level.

At the same time, international coordination is necessary to prevent damaging levels of international competition. In Germany, solar capacity is projected to become twice as big as the current peak demand, which would result in more power being exported to neighbouring energy networks. Already, German solar projects and wind production are squeezing projects in neighbouring countries out of the system. Any form of innovation in Poland or the Netherlands is, depending on support divergences, in danger of being killed by the low price of German surplus electricity.

International coordination is also a matter of how to share the burden of climate change. A debate about the distribution of carbon space has gripped international climate negotiations. It has also influenced energy policymaking in certain consuming countries. A ‘climate cap’ seriously challenges producing countries and companies involved in this sector. The dissimilar interests of industrial sectors, companies and countries have prevented the development of an overarching agreement on managing carbon dioxide emissions. Instead, all players have begun to carve out their own strategies and technological solutions. Such competition is not necessarily bad for the environment, but the differing costs of the strategies could become crucial for the competitive position of these companies, sectors and countries in years to come. In many countries, climate change policies are evolving as new industrial policies.

Some security of supply issues evolve around the organisation of the energy sector and the choice at which level in the energy system the intermittency of production is managed. The logic of centralisation is less clear for a power sector dominated by dispersed wind and solar power generation. To accommodate solar power and land-based wind at the level of suburbs, towns and cities, small-scale balancing is needed. That will require the downsizing of backup facilities. Yet industrial-sized wind and biomass facilities require balancing at a more regional level. The companies servicing these different market segments may be diverse. Smaller companies and regional network companies may become the main players in regional markets, where sizing the facilities to satisfy local needs is crucial to the management of supply and demand. Large companies will still be needed to service the larger, industrial-sized facilities and markets.

If some European countries choose to decentralise, that decision could clash with the choice of others to adopt a centralised policy. Organisational legacy may play a role too. It is not clear whether this will converge into a coherent international and secure energy system.

Socio-economic dynamics

Energy security will not just require a new policy toolbox for international relations and continuing the necessary infrastructures. The patchwork of new dependencies is even messier. It also comprises social relations within a society.

An increasing number of people take their own measures to balance the system. I might be among them. I am in a position to improve the footprint of my own house. I have recently finished my insulation project and I’m now going for renewable energy production. I want to make sure I can at least keep the basics in the house running. Eventually I may want to go off-grid if the benefits and costs of this connection incentivise me to do so. I am not the only one. In a mixture of idealism and distrust, a growing number of people and industries are exploring the possibilities of cutting the cords to the grid. With the combination of a changing lifestyle, solar cells, a solar boiler and batteries in the basement, a house can power itself.

Subsidies, tax advantages, and a distrust of larger foreign companies have motivated households to invest in solar panels. This can be seen as a reaction to the increase in scale of the preceding period. Many consumers suspect that the downside cost of managing a dual centralised energy system will transfer to them, while the upside remains elsewhere in the system. In order not to be exploited by the evolving system, there is a growing movement among industrial and household consumers to reduce their dependency on the grid and perhaps ultimately go off the grid completely. They want to avoid the payments and invest instead in stand-alone options.

Those who have their own roof can retreat from the energy system

So the question is whether an integrated energy system can be maintained, allowing for exchange and optimisation. Or will people withdraw in self-contained units? Formulated differently: should the costs of fluctuations be socialised or do we allow them to be privatised? Will people put a diesel generator in their shed to balance the intermittency of sun and wind, or can we agree on more efficient ways of balancing at a system level?

It is worth remembering that not everyone can go off-grid. Only those who have their own roof and can afford the initial auxiliary investments can retreat from the energy system. If many of the well-off go off-grid in their own energy haven, the power to invest in the energy system as a whole decreases. As the pool of contributors shrinks, the group of consumers who have few alternatives pay. If continued, this will undermine the system. Those who can’t afford a zero-energy house will have to bear the ‘socialised’ cost of energy security, leading to social inequalities.

Energiewende

This inequality is already clearly visible in Germany,[4] where consumers pay a surcharge on their electricity bills to facilitate its investment in wind capacity and the grid. The *Erneuerbare-Energien-Gesetz* (Renewable Energy Act) imposes an extra fee of €0.06 per kilowatt-hour, which is more than 20% of the total retail price of electricity for a three-person household.

Yet not everybody needs to pay this extra fee. Energy-intensive users, including an important part of the German manufacturing industry, have received partial exemptions to maintain their international competitiveness. This benefits manufacturers of paper and paper products, chemicals and chemical products, pharmaceuticals, non-metallic minerals, iron and steel, and non-ferrous metals. For Germany, this includes companies such as chemical company BASF, aluminium producer Trimet and technology company Thyssen Krupp. Moreover, some of these energy-intensive industries do not have to pay for access to the grid, shifting some of the cost of connecting supply and demand onto other parts of society.

The vast majority of Germany, however, does not qualify for exemptions and therefore pays a higher price for its electricity, since total costs still need to be covered. This includes many citizens and the motor of the German economy: the *Mittelstand*, the SMEs.

This gives rise to a growing division in Germany; those that are exempt face shrinking energy bills, as the wholesale price of electricity decreases. This is a result of the growing overcapacity while new solar panels and wind turbines are being installed. The SMEs and citizens who remain in the system must now carry the burden of €22 billion per year. And these 'socialised' costs may rise, as the cost of balancing increases, with the increase in, for instance, offshore wind capacities.

Many households and small businesses may feel they have been left with more disadvantages than advantages by the energy transition. Their chagrin will fuel the urge to become energy-independent, that is, to go off-grid in order to avoid the payments for the transition. For renewables trying to break through as the mainstay of the electricity system, this will test the boundaries.

Already a large group is in energy poverty, which means that they need to spend more than 10% of their income on energy. The share of German households in *Energiearmut* rose from 13.8% to 17% between 2008 and 2011, an increase of 1.4 million households. German power providers have noticed a rise in disconnections. This means that a growing group has become unreachable by the energy system and that basic needs are not being met.

Ultimately, energy security is a matter of reaching society as a whole. It is the socio-economic issue of including the vulnerable.

The challenge of the current transition is that it coincides with a declining economy. During the period of economic growth in the 1990s, when energy was relatively cheap, pain could be massaged away. But now there is no surplus to fund the necessary innovation or to compensate for the attrition of the old system. These asymmetric costs and benefits within the European Union will challenge policymakers in managing the changes in the energy system at the various speeds.

The dynamics of future energy markets create a lot more uncertainty about the energy mix, the technologies that will break through and the market organisation that may facilitate these changes. Nevertheless, such transitions have also been experienced in the past. The challenge is to make this transition at a very high level of energy service, and to maintain the motivation of stakeholders to adopt and adjust.

Many elements of the policy toolbox are needed when dealing with these new faces of energy security. Policies need to deal with more than foreign relations and international security. The current transition also needs to be addressed with industrial and socio-economic policies.

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Coby van der Linde has been the Director of the Clingendael International Energy Programme since September 2001. In 2004 she was appointed Professor of Geopolitics and Energy Management at the University of Groningen. She is also a member of the international advisory board of KAPSARC, Saudi Arabia, and is a non-executive director of a Dutch energy distribution company and an upstream natural gas company. She is based in The Hague, the Netherlands.

References

1. R. Scott (1995). *IEA: The first 20 years,* vol. II: *Major policies and actions,* pp. 37-52.
2. BP Outlook 2035, slide pack, www.bp.com.
3. *Transition? What Transition? Changing Energy Systems in an Increasingly Carbon Constrained World.* Clingendael International Energy Programme (CIEP), 2014.
4. Daan Rutten, *The Energiewende and Germany's Industrial Policy.* Clingendael International Energy Programme (CIEP), 2014.

Low-carbon prosperity The value of forward-looking policy in the face of uncertainty

It is possible to protect the environment and deliver economic growth and prosperity. Understanding the underlying economics is essential to ensure a smooth transition to a low-carbon economy.

Sam Fankhauser and Mallika Ishwaran

Climate change poses clear risks to human prosperity over the long term. They are significant enough[1] to make low-carbon development, which mitigates the causes of climate change, the only credible option for long-term growth. If the worst climate risks were to materialise, high-carbon growth would be inimical with continued prosperity.[2]

In rare agreement, business representatives and green activists have both questioned whether low-carbon economic growth is possible. The former have warned that rapid decarbonisation might cripple the economy, while the latter have argued that environmental stewardship may ultimately require zero growth.[3]

Yet it is possible to have both steady decarbonisation and continued economic growth. The challenge is clearly significant. The degree to which economic activity has to be decoupled from greenhouse gas emissions is unparalleled, but it is a challenge that can be met technologically, economically and financially. It does, however, require exceptionally strong leadership.

For the past two centuries, GDP and carbon emissions have grown hand in hand. The widespread, effective use of fossil-fuel-based energy has been a fundamental driver of economic growth. Only in recent decades have carbon emissions grown at a slower rate than GDP, with the possibility that emissions may have peaked in, for example, Germany, the UK and possibly the USA. In most of these cases, the reversal was more due to energy market developments (chiefly a shift to gas) than deliberate climate policy.

Even if these positive trends are extrapolated into the future, it will not be enough to ensure an acceptable level of climate risk (often interpreted as having a good chance of remaining below 2 degrees Celsius of mean surface warming). Without further action on climate change, a rising trend appears more likely as both China and India, two drivers of future economic growth, have significantly higher carbon emissions per unit of GDP than their Western peers. Even reducing the carbon intensity of the global economy to German levels (one of the lowest for an advanced economy) by 2030 is still above that required for a 2 degrees trajectory, and without continuing improvements post-2030 emissions would begin to rise again (see Figure 1). We are nevertheless optimistic about low-carbon prosperity.

The case for a low-carbon economy

Fossil fuels and emissions-intensive land-use practices are such an integral part of the global economy that it is impossible to reduce greenhouse emissions without incurring an economic cost.

Energy-economy models typically put the cost of stabilising greenhouse gas emissions at a safe level (that is, consistent with 2 degrees Celsius) at around 2-6% of global consumption by 2050.[4] This is a substantial amount in absolute money terms, but perhaps less sizeable compared with expected GDP growth. The cost of climate protection is equivalent to an estimated one or two years of economic growth over four decades.

This seems like an acceptable insurance premium, compared with the risks of unmitigated climate change. Scientists warn about the risks to food security, more severe droughts, storms and floods, and irreversible damage to crucial ecosystem services on which we depend. Under higher concentration levels, there might be regime shifts in fundamental climatic processes, such as ocean circulation patterns.[5] We are creating an unpredictable new climate regime, which humans, as a species, have never experienced.

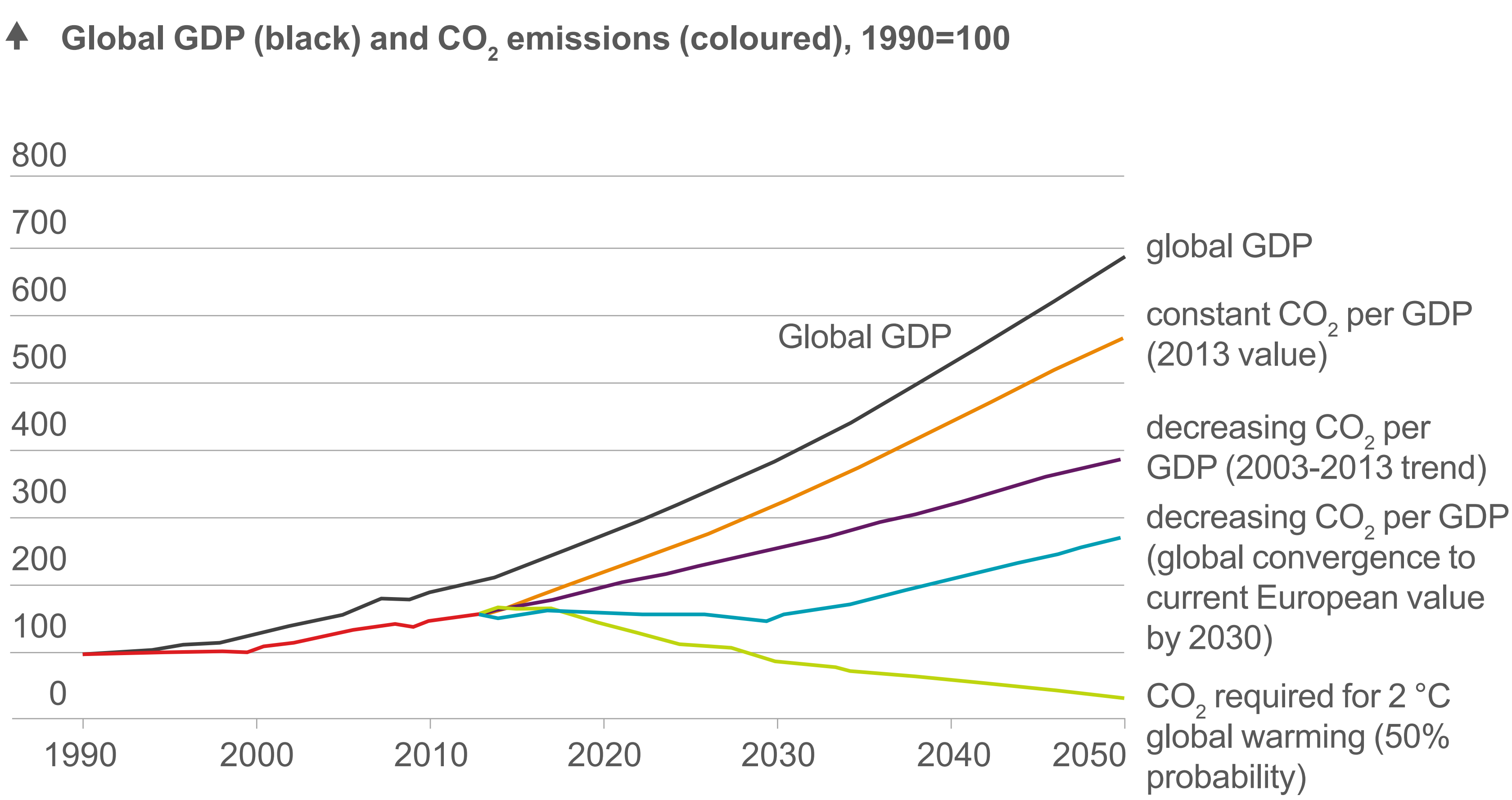

Figure 1: Illustrative GDP and carbon dioxide emissions trajectories.

Of course, the costs of emissions abatement are also uncertain. They could be higher than models predict if political economy constraints prevent an effective response. It is a possibility that is difficult to discard. We must also not underestimate the short-term adjustment costs associated with deep structural change. Analysts have warned about the risk of stranded assets in high-emitting sectors. According to one study, stabilising global temperatures at 2 degrees Celsius could mean that two thirds of current and prospective fossil fuel reserves may eventually have to be written off as unburnable.[6]

Decarbonisation may be much cheaper than models predict

However, decarbonisation may also be much cheaper than models predict.[7] Building a low-carbon economy offers exciting new opportunities. Students of past structural transformations, such as the industrial revolution or the advent of information technology, observe that they often initiate a process of 'creative destruction' where existing market structures are broken up, leading to a virtuous cycle of market entry, innovation and investment.[8]

There is evidence that low-carbon innovation creates higher spill-overs to the rest of the economy than conventional innovation.[9] This gives some weight to the 'creative destruction' hypothesis, although it remains unclear to what extent a policy-driven transformation like the low-carbon transition can have the same dynamic effects as market-driven change.

It is clear that there will be new business opportunities and the chance to develop new areas of comparative advantage as the low-carbon economy develops momentum. Many companies view low-carbon policy primarily through this lens. Breakthroughs in energy storage or low-carbon transport, for example, will be handsomely rewarded in the marketplace. Countries such as China and South Korea play a similarly strategic game and treat climate policy at least in part as industrial policy. They observe that global sales of low-carbon goods and services were already worth

€4.1 trillion ($4.6 trillion) in 2011-12, and that the sector is expected to grow by 4-5% annually over the coming years.[10]

There are other reasons why the costs of decarbonisation might be lower than models predict. One powerful argument is that low-carbon investment offers an opportunity to address other market failures that hold back economic growth. The side benefits of low-carbon energy on local air quality are an obvious case in point. They are one of the reasons why low-carbon energy is attractive to countries such as China, which face severe air pollution problems.

It is also possible that low-carbon energy – in particular decentralised solutions like solar photovoltaics and onshore wind – may increase competition in the energy market and help to reduce the market power of incumbent operators. New market entry is also possible in sectors such as accumulators, primary cells and batteries; electric motors, generators and transformers; and domestic appliances.[11]

For the anaemic economies of Western Europe, low-carbon investment might be one way of locking in economic recovery. The economic crisis of the last six years has been characterised by a weakening in aggregate demand, as households and governments reduced their spending, but also by a drop in investment and productive capacity. Investing in low-carbon infrastructure – clean forms of energy, smart grids and energy efficiency – can boost aggregate demand at a time when it is still weak, and low-carbon investment needs are large.[12,13]

In short, there are reasons to be optimistic about the prospects for low-carbon growth. Decarbonisation is clearly consistent with continued welfare and prosperity. However, the political economics of initiating the low-carbon transition are also formidable.

The political economics of low-carbon growth

The low-carbon transition will require substantial private initiative, investment and innovation. However, at the core of the climate problem are a series of market and policy failures that must be addressed by public policy. The required policy interventions are often grouped into three categories.[14,15]

A first set of policies is needed to address what is arguably the most important market failure: the fact that the social costs of carbon emissions – the future damage to ecosystems, society and the economy – are not reflected in market decisions. Policy makers are increasingly willing to price carbon, explicitly through carbon taxes and emissions trading schemes or implicitly through regulatory measures, the cost of which are reflected in the market price. A survey of OECD countries found prices ranging from less than €12 ($14) per tonne of carbon dioxide in Mexico, New Zealand and the USA to over €105 ($120) per tonne in Germany, Japan, Norway, South Korea and Switzerland.[16]

A second set of policies is required to address market failures related to low-carbon innovation. The societal benefits of innovation are well known and the reason why research and development (R&D) is incentivised through public policy measures such as patents, research grants and tax breaks. These generic forms of technology support are also available for low-carbon innovation, but there is a case for additional intervention. Low-carbon innovation creates higher social benefits than traditional R&D[17] and is hampered by additional barriers that are hard to break.[18] The most common response to these problems so far has been support for the deployment of market-ready technologies (for example, in the form of renewable energy obligations) rather than the promotion of low-carbon R&D.

The third component is measures to overcome barriers to energy efficiency investment. The drive to conserve energy predates concerns about climate change and goes back to at least the oil shocks of the 1970s. Unfortunately, a 40-year track record in energy efficiency policy and a good understanding of the underlying issues[19-21] has not resulted in clear policy recommendations. Energy efficiency policy is still characterised by a fair amount of experimentation to identify workable policies and there are frequent changes to the policy landscape. However, most analysts would agree that the removal of energy subsidies is a crucial first step (and a widespread policy failure[22]).

In addition to low-carbon incentives, other measures will be needed to manage inevitable short-term structural rigidities and to ensure that the transition occurs with the least cost and disruption to the economy. This may include measures to minimise the likelihood of stranded assets by announcing any changes well in advance, and providing adequate time for businesses to adjust and for capital to be replaced. Measures should address issues of competitiveness in situations where some countries move faster than others and the playing field is temporarily misaligned. They should also reduce potential labour market friction and displacement during the transition by re-training and re-skilling labour for the sectors of the future. Policy mechanisms will be needed to manage any remaining negative sector and distributional impacts during the transition period.

Climate action produces clearly identified losers in the short term

The economic case for these policies is well understood and compelling. However, implementing them in practice is complicated by a number of policy and political economy factors.

The transition to a low-carbon economy will produce both winners and losers, and the commitment to climate action is therefore affected by vested interests. This is a common feature of public policy. What makes climate action particularly challenging is that it produces clearly identified and concentrated losers in the short term, while the winners are likely to be diffused and reap the benefits in the longer term.

The costs of taking climate action are likely to fall disproportionately on fossil-fuel-based, energy-intensive and trade-exposed industries such as refining, iron and steel and chemicals, which account for a significant share of industrial energy- and process-related carbon emissions. Sectors supplying low-carbon and environmental goods and services – for example, the renewable energy supply chain or fuel cell manufacturers – that benefit from climate policy are still a smaller and often less vocal part of the economy. More generally, the benefits of taking action are likely to accrue to the wider economy and society as a whole, both now and in the future, in the form of lower climate damage and risks.

Another issue is the long time horizon of climate action. The cost of taking action to reduce emissions is mostly borne in the near term, whereas the benefits accrue over much longer (sometimes inter-generational) timescales. This creates a tendency towards policy myopia and inertia; a tendency which is reinforced by uncertainties – in the science, in the likely impacts of a warming climate, and in the potential costs to the economy and to society of unabated climate change. The short-term policy myopia and inertia, in turn, exacerbates the problem of time inconsistency of climate policy over the longer term: that is, policy makers' preferences are liable to change over time and current policy choices, on which investment decisions are based, could be changed or reversed in the future.

Time inconsistency, and the policy uncertainty that it generates, is a particularly significant problem for climate policy given the substantial and long-term investments required to decarbonise the economy. Decisions to invest in low-carbon assets such as wind farms, or to build a low-carbon supply chain, are made on multi-decadal timescales, which is much longer than the typical political (and hence, policy) cycle. In the absence of credible and long-term policy commitments, short-termism and the tendency to defer policy action on climate change will aggravate existing problems of time inconsistency and policy uncertainty, and dampen incentives for necessary investments (for example, in new infrastructure, technologies and production processes) to make the shift to a low-carbon economy.

A solid legal basis with clear statutory emissions targets and policy signposts is therefore essential. Good examples of strong climate change legislation include the UK's 2008 Climate Change Act and Mexico's General Law on Climate Change of 2012. Both laws provide long, loud and legally binding commitments, which serve to reduce policy uncertainty due to myopia, inertia, and time inconsistency inherent in climate policy. All major emitter countries now have some form of climate change legislation.[23]

Even when binding laws are in place policy uncertainty remains, as UK low-carbon investors will readily confirm. There is a case for supplementing statutory carbon targets, which are essential, with complementary objectives, for example on low-carbon electricity, that affect investor decisions more closely. There is evidence that business responds favourably to clear policy signals by managing carbon risks more actively and stepping up low-carbon innovation.[24, 25]

Energy in the low-carbon economy

Energy plays a fundamental role in enabling and supporting economic activity, whether it is to produce goods and services, maintain a comfortable built environment at work or home, or to transport goods and people. However, consumption of energy is also the single largest source of greenhouse gas emissions – carbon emissions from energy accounted for over 60% of global greenhouse gas emissions in 2011.[26] Moreover, energy-related carbon emissions have been rising faster than overall greenhouse gas emissions – by 38% between 1990 and 2009 compared to a 26% increase in global greenhouse gas emissions over the same period.

The OECD estimates that without additional policy interventions, global greenhouse gas emissions are likely to increase by 50% from current levels by 2050, driven by a 70% increase in energy-related carbon.[27] Shell's New Lens Scenarios find that, without dramatic and non-marginal changes in the next decade, energy use is likely to increase by 60-80% between 2010 and 2050 and cumulative carbon emissions are likely to be significantly higher than is consistent with stabilising global temperatures at 2 degrees Celsius over pre-industrial levels.[28]

Any transition to a low-carbon economy will therefore require fundamental and substantial changes to how energy is produced and consumed, and a reversal in the rising long-term trend in energy-related carbon emissions. This, in turn, requires fundamental changes to the energy system.

Start in the power sectors

Energy transition will start in the power sector, which accounts for approximately 40% of energy sector carbon emissions, primarily due to existing coal-fired generation. Meaningful reductions in carbon emissions from power will require unabated fossil-based generation to be phased out – and a shift to low-carbon sources of energy (for example, renewables and nuclear) or to carbon capture and storage from fossil-based generation.

Decarbonising electric power is essential for the transition to a low-carbon economy. The power sector accounts for the single largest share of energy-related carbon emissions. It has a significantly higher carbon emissions intensity than the economy overall – 3.4 tCO_2e per tonne of oil equivalent in power and heat compared to a 2.9 tCO_2e per tonne of oil equivalent average for the economy.

The power sector also sits in a strategic position within the economy, with a product (electricity) consumed by all other sectors. This, together with the fact that the technologies to decarbonise electricity are broadly known (renewables, nuclear energy and carbon capture and storage), puts power sector decarbonisation at the core of the low-carbon transition. With the use of low-carbon electricity, other sectors such as heat (through heat pumps) and surface transport (through electric vehicles) can subsequently be decarbonised.

Focusing on the ‘upstream’ power sector can also have advantages from the policy perspective. It can help to establish a carbon price across the supply chain. The costs of decarbonising the power sector are likely to be shared across the supply chain, as power generators pass through some or all of the additional costs. This also helps to broaden the range of possible mitigation actions, and unlock cost-effective emissions reductions across the supply chain, reducing emissions across end-use sectors.

Other sectors will follow

The challenge is similarly ambitious in transport, particularly in road transport where gains in fuel efficiency have been more than offset by growth in miles travelled. Transport emissions have increased by more than half since 1990. Emissions reductions consistent with a low-carbon economy require structural changes in the transport sector – a shift to lower emission fuels and vehicles for passenger and freight transport and infrastructure which enables a modal shift away from roads to lower-carbon forms of transportation.

The challenge in reducing carbon emissions from buildings is different but no less ambitious. Barriers such as lack of information, high upfront costs and split incentives between landlords and tenants mean that an upstream price signal from decarbonising the power sector may not be enough to drive building energy efficiency improvements even when they make economic and financial sense. Other complementary measures are required.

The policy challenges are therefore complex and multi-dimensional – delivering significant reductions in emissions while ensuring that energy remains affordable and available to support economic activity.[29] As seen above, pricing in carbon is essential to incentivise the required changes, but pricing alone will not be enough due to the existence of other market failures and barriers preventing an optimal response to the price signal. Parallel interventions will be needed to ensure sufficient investment in low-carbon R&D and the deployment of technologies such as renewable energy, carbon capture and storage, low-carbon vehicles and new industrial processes. Similarly, inertia and barriers that prevent individuals from responding fully to price signals provide the rationale for energy efficiency policies such as product and building standards.

Alongside climate policy, energy market policies and regulations need to evolve, particularly as they relate to the power sector. The existence of natural monopolies in the production and distribution of power mean that these markets face regulation in virtually every country and region of the world. The more liberalised power markets in Europe and the USA are characterised by competition (vertically across integrated utility companies and horizontally across suppliers), independent regulators, and privatisation of state-owned assets. Less liberalised markets such as in China, India and South Africa are characterised by greater price control and state ownership of assets.

The European experience highlights the potentially perverse consequences of not aligning energy market regulations and climate policy ambitions. The design and implementation of climate policies and their interaction with power market structures has called into question Europe’s ability to deliver affordable, secure and sustainable energy.

For example, the European Union's Renewable Energy Directive, which sets mandatory national targets for achieving a 20% share of renewable energy in the final energy consumption by 2020, has had significant unintended consequences for the power market.

It has led to a sharp increase in renewables in the energy mix while simultaneously driving down wholesale energy prices (due to large subsidies which have lowered the marginal cost of renewable energy). This has resulted in a situation where the volatility of the energy mix has increased due to the intermittency of renewables, while the incentive to invest in back-up fossil capacity has declined. Moreover, the squeeze on margins from fossil generation has led to an increase in coal-fired generation (supported by the low relative price of coal and weak carbon price signal) – or the coal-renewables 'energy paradox'.

With renewables likely to remain a significant part of the energy mix, European energy market regulations will need to evolve in order to support and enable (rather than inhibit) the evolution of power market structures in line with climate policy ambitions. This could be accomplished through long-run marginal-cost pricing for generation, locational pricing for access to distribution networks, or fee-based pricing of electricity optimisation and management services. Only then can the energy sector assume its crucial role in the low-carbon economy.

Facing a new economy

Mitigating the risks of climate change requires a fundamental restructuring of the way that modern economies work. This essay has argued that this low-carbon transition is possible without jeopardising long-term prosperity and growth. In fact, tackling climate change is essential for securing robust long-term economic growth and prosperity. However, like all structural change, the low-carbon transition will create both winners and losers. The structural adjustment costs to some sectors, and the distributional consequences, should not be underestimated and need to be managed. But the low-carbon economy will also create new opportunities and may usher in a period of renewal, innovation and 'creative destruction'.

Low-carbon innovation has the potential to be a significant driver of productivity, and hence economic growth, in the future. Policies to support and incentivise low-carbon R&D are likely to produce additional benefits for the economy, by driving down technology costs and reducing the overall costs of making the shift to a low-carbon economy. The market for low-carbon goods and services also provides a potential first mover advantage for individual economies.

The energy sector is fundamental to this process. Energy is essential to enabling the activities and producing the goods and services which support economic growth and prosperity. A prosperous low-carbon economy requires an energy system which balances the objectives of energy affordability, energy security and energy sustainability. This, in turn, highlights the importance of creating the right climate and energy policy framework to enable the smooth transition to low-carbon.

Policy clarity and long-term certainty for low-carbon investors are essential, not just in the energy sector but across the economy. Pricing carbon, encouraging low-carbon innovation and promoting energy efficiency are key. The initial experience has shown that businesses respond to clear and reliable policy incentives. However, investors also respond – less favourably – to policy uncertainty, mixed signals and government risk.

In addition to a strong and stable policy regime, understanding economic displacement and managing transition costs is essential to ensure that the transition occurs at the least cost and disruption to the economy, for example by minimising the risk of stranded assets and facilitating re-training. Similarly, public policy has a role to play in maximising the potential economic benefits from a shift to low-carbon.

As the low-carbon transition gets under way, investors and policy makers should be aware that the required structural changes – and business opportunities – are broader than just carbon. A truly green economy will also have to be alive to other environmental, social and governance issues. With a certain amount of climate change now unavoidable, it will in particular have to be resilient to those climatic changes that are already locked in.

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Samuel Fankhauser is Co-Director at the Grantham Research Institute on Climate Change, and Deputy Director of the Centre for Climate Change Economics and Policy, both at the London School of Economics. He is also a Director of economics consultancy Vivid Economics, and a member of the Committee on Climate Change, an independent public body that advises the UK government on carbon targets. Previously, he has worked at the European Bank for Reconstruction and Development (EBRD), the World Bank and the Global Environment Facility.

Mallika Ishwaran is senior policy and regulatory economist in Shell's global finance and strategy team. She advises on policy and regulatory issues relating to Shell's scenarios development, strategic country engagements, and carbon dioxide and energy market polices more generally. She was Deputy Director in the UK Department for Environment, Food and Rural Affairs. She was a member of the UK Government Economic Service and has worked in the Cabinet Office, the Department for Environment, Food and Rural Affairs, and Her Majesty's Revenue and Customs. She has published a number of UK government position papers. Earlier, Ishwaran worked for several years as an economist in the USA – in academia as well as in the public and private sectors. She received her PhD from Carnegie Mellon University in 1999, after receiving her BA from St. Stephen's College, Delhi University.

References

1. IPCC (2014). *Climate change 2014: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, CUP: Cambridge.
2. T. Everett, M. Ishwaran, G.P. Ansaloni & A. Rubin (2011). *Economic growth and the environment*, Defra Evidence and Analysis Series, Defra, https://www.gov.uk/government/publications/economic-growth-and-the-environment.
3. T. Jackson (2011). *Prosperity without growth: Economics for a finite planet*, Routledge: London.

4. IPCC (2014). *Climate change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* CUP: Cambridge.
5. IPCC (2014). *Climate change 2014: Impacts, adaptation and vulnerability. Vide supra*.
6. Carbon Tracker (2013). *Unburnable carbon 2013: Wasted capital and stranded assets*, Carbon Tracker Initiative and Grantham Research Institute, London School of Economics: London.
7. A. Bowen & S. Fankhauser (2011). The green growth narrative: Paradigm shift or just spin?, *Global Environmental Change, 21*, 1157-1159.
8. C. Perez (2010). Technological revolutions and techno-economic paradigms, *Cambridge Journal of Economics, 34*, 185-202.
9. A. Dechezleprêtre, R. Martin & M. Mohnen (2013). *Knowledge spillovers from clean and dirty technologies: A patent citation analysis*. Grantham Research Institute, London School of Economics: London.
10. BIS (July 2013). *Low carbon environmental goods and services*, Report for 2011/12, UK Department for Business Innovation and Skills, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/224068/bis-13-p143-low-carbon-and-environmental-goods-and-services-report-2011-12.pdf.
11. S. Fankhauser, A. Bowen, R. Calel, A. Dechezleprêtre, D. Grover, J. Rydge & M Sato (2013). Who will win the green race? In search of environmental competitiveness and innovation, *Global Environmental Change, 23*, 902-913.
12. D. Zenghelis (2011). *A macroeconomic plan for a green recovery*, Grantham Research Institute, London School of Economics: London.
13. D. Zenghelis (2012). *A strategy for restoring confidence and economic growth through green investment and innovation*, GRI Policy Brief, April 2012.
14. M. Ishwaran & F. Cimato (2009). *Making the right choices for our future: An economic framework for designing policies to reduce carbon emissions*, Defra Evidence and Analysis Series, Defra, http://archive.defra.gov.uk/evidence/series/documents/economicframework-0309.pdf.
15. S. Fankhauser (2013). A practitioner's guide to a low-carbon economy: Lessons from the UK, *Climate Policy*, *13 (3)*, 345-362.
16. S. Bassi, S. Fankhauser, F. Green & M. Nachmany (2014). *Walking alone? How the UK's carbon targets compare with its competitors*, Policy Paper, Grantham Research Institute, London School of Economics: London.
17. A. Dechezleprêtre et al., *vide supra*.
18. P. Aghion, A. Dechezleprêtre, D. Hemous, R. Martin & J. Van Reenen (2012). *Carbon taxes, path dependency and directed technical change: Evidence from the auto industry*. Working Paper No. 102, Grantham Research Institute, London School of Economics: London.

19. S. De Canio (1998). The efficiency paradox: Bureaucratic and organizational barriers to profitable energy-saving investments, *Energy Policy, 26 (5)*, 441-454.
20. S. De Canio & W. Watkins (1998). Investments in energy efficiency: Do the characteristics of firms matter?, *Review of Economics and Statistics, 80 (1)*, 95-107.
21. A. Sanstad & R. Howarth (1994). Normal markets, market imperfections and energy efficiency, *Energy Policy, 22 (10)*, 811-818.
22. OECD (2013). *Inventory of estimated budgetary support and tax expenditures for fossil fuels 2013*, Organization for Economic Cooperation and Development: Paris.
23. T. Townshend, S. Fankhauser, R. Aybar, M. Collins, T. Landesman, M. Nachmany & C. Pavese (2013). How national legislation can help to solve climate change, Nature Climate Change, 3, May, 430-432.
24. D. Ellerman & B. Buchner (2007). The European Union emissions trading scheme: Origins, allocation, and early results, *Review of Environmental Economics and Policy, 1 (1)*, 66-87.
25. R. Calel & A. Dechezleprêtre (2014). Environmental policy and directed technological change: Evidence from the European carbon market, *Review of Economics and Statistics*, accepted.
26. IEA (2011). *CO_2 emissions from fuel combustion, 2013 edition*, International Energy Agency: Paris, http://www.iea.org/publications/freepublications/publication/CO2EmissionsFromFuelCombustionHighlights2013.pdf.
27. OECD (2012). *Environmental outlook to 2050: The consequences of inaction*, Organization for Economic Cooperation and Development: Paris, http://www.oecd-ilibrary.org/environment/oecd-environmental-outlook-to-2050_9789264122246-en.
28. Shell (2013). *Shell new lens scenarios*. See: www.shell.com/scenarios.
29. M. Ishwaran & F. Cimato, *vide supra*.

Futures past and present

Different perspectives on the future enrich our understanding of the many ways in which the energy transition can play out.

Some thoughts on the year 2000
The future as seen half a century ago

James Lovelock wrote this essay for Shell in 1966. He intended it as an alternative to the forecasts of Herman Kahn, at that time a pre-eminent futurist and well known for his dark scenarios of a total nuclear war. Lovelock believed that as we had avoided anthropocidal war, we could also avoid environmental disasters. Cities would become dense again, made liveable by new electronic media.

> *James Lovelock*

And the word of the Lord came unto me a second time, saying, What seest thou? And I said, I see a seething pot; and the face thereof is toward the north. Then the Lord said unto me, Out of the north an evil shall break forth upon all the inhabitants of the land.
Jeremiah 1:13-14

I have just read a version of the year 2000 according to Esso. It is a pleasant glossy publication enclosing a series of essays by Toynbee, Asa Briggs, Cockcroft, Buchanan and other distinguished persons. Their predictions were all founded upon the assumption that the current 5% compound interest rate of growth of wealth and energy use would proceed unchecked. Each contributor was prepared to consider the possibility of minor set-backs in the field of his own speciality; thus Cockcroft had doubts upon the early development of fusion power sources. But outside each of their own fields these specialists assumed that all would be well and that 'progress' was inevitable. The effect was to make the collection of essays unconvincing; rather like the predictions of the future of a child by his schoolmasters.

Details cannot be seen from 33 years away. Even the real prophets of our times, the science fiction writers, have blundered when attempting such a long sighted view. Thus H.G. Wells in the early 1900s forecast that aviation would never become a significant method of transport or communication. By contrast the general predictions of *Brave New World* and *1984* included much that has stood the test of time. Therefore, in thinking about the year 2000 we should limit ourselves to general trends rather than to considering whether or not we shall go from London to Brighton by foot or by fusion-powered hovercraft.

Even with general trends, this is of all times one of the most difficult for predicting the future. The reason for this can be seen from the trends of human population growth. As with any species, human population tends to constancy, except during major ecological changes. Our species passed through at least two of these and is now in the middle of the third. The first was the development of organised hunting leading to a stable population at a density of 1 to 10 per square mile, such as with the North American Indians; then to an organised agriculture as in Western Europe until about 1700, with 50-100 per square mile; and finally the present techniculture at 1,000 per square mile and still rising.

During a period of ecological equilibrium the factors determining growth and decay are in balance and can be determined. Consequently the prediction of the future can be made with some confidence. For example, it would have been comparatively easy in 1267 to have predicted 1300. In our present state of rapid change the factors determining growth are partially understood but those determining decay can only be guessed for they have yet to exert their effects. In the end, of course, growth is limited by the rate at which raw materials and energy can be supplied. Nevertheless by 2000 even if the present growth rate persists there should still be adequate supplies of energy and raw materials. Whether or not the present 5% compound interest rate of growth can continue for a further 33 years depends upon the chance of a set-back by any one of a number of possible hazards, such as for example those listed in Table 1. Disasters from outside, either galactic or from the solar system are comparatively unlikely, as are internal upheavals of the earth. The most probable curbs come from the biosphere, including especially the human component.

The most probable of all curbs is the threat or even the event of an ecological disaster. Such a disaster could arise from any of a number of possible causes, but most probably through the accumulation of harmful waste products. That merely the threat of such an event is sufficient to slow growth is illustrated by the computation that by the year 2000 the USA alone will have spent $275 billion on the control of pollution. Such expenditure is competitive with that available for growth and indeed may raise new problems. The replacement of the energy obtained from combustion by some perfect and clean source of power would not lessen the risk of ecological disaster, indeed it might hasten the event through speeding the attainment of ecological imbalance.

CURBS ON HUMANITY		
Class	Curb	Probability
Physical external	Supernova near enough for radiation damage to life on the earth	« 0.0000003
	Destructive collision with a large meteorite	< 0.001
	Change in solar output	< 0.0001
Physical internal	Tectonic activity	< 0.0003
	Sea level rise	< 0.001
	Ice age	< 0.001
Biological	Destructive pandemic to man or food plants	< 0.1 to 0.01
Human ecological	Nuclear war	< 0.1
	Accidental or contrived pandemic	< 0.1
	Political or economic disaster	< 0.1
	Socially destructive inventions e.g. cars, a drug-like 'soma'	< 0.1
	Religious revival	< 0.01
	Major ecological or climatic disaster due to human activity	< 0.5

Table 1: The probability that one of the curbs listed might affect the growth of population and of energy consumption during the period from now to the year 2000.

The early growth of the industrial age was made possible by the development of means of preventing or removing pollution from the supplies of fresh water. The energy consumed in maintaining the supply of this commodity rises faster than does the total available supply of energy. Experience with fresh water suggests that the other components of our ecological cycle including the sea and the air will either become so polluted as to prevent further growth or consume so much of our total energy in the prevention of their pollution, as to slow the rate of growth. Already there are signs that air pollution has become a global problem and could develop catastrophically in as little as ten years. In the last few years it has been realised that the sea also is not an infinite sink for waste products, particularly where these are distributed as hydrocarbons at the air water interface where dilution can only take place in two dimensions.

These are the more obvious ecological curbs whose effects we now can foresee. If we combat them successfully and go on to the year 2000 and have available 10 times the power we have now it is almost certain that other ecological problems as yet unrecognised will be with us and exerting their own restraint to growth. It is more important also that a curb does not have to act to absorb energy. Its mere recognition is sufficient. This is as true of the writing of this note as it is of the expenditure on the avoidance of nuclear war.

Considerably before 2000 therefore it seems likely that the current pattern of growth will have changed. Either the total consumption of energy will have levelled off or if it does rise tenfold then the greater part of this increase will be spent in insurance against ecological disaster. I am sufficiently optimistic to believe that, just as we have avoided anthropocidal war, so we shall avoid these other disasters. The cost, however, will be high. On this basis I see the world in the year 2000 as follows.

Cities will become dense again and suburbs will go back to the plough

The personal use of energy in large quantities will be passing. In particular, the present grossly-inefficient domestic heating and cooling methods will no longer be possible, nor will high-powered personal transport. A drastic change in land and sea use may be under way with much less space for cities, roads and airports, etc., somewhat less for agriculture. But the establishment of large ‘park’ areas of undisturbed land in an attempt to restore the ecological status quo.

Cities will become dense again and suburbs go back to the plough. Passive heating and cooling will be used, as will public transport. A great deal of effort will go to making the cities bearable to live in. The entertainment and education industries which use little power will be vastly developed. Full colour three-dimensional TV with excellent programmes will be ubiquitous as will bingo halls or their 2000 equivalent. Non-addicting euphoric drugs may be widely available. Communication by satellite will be so good that conferences by television may render business travel comparatively unnecessary. Conservation will be the great political and religious issue of the day, surplus technical effort will go in this direction instead of to space and war as now. This sort of change of heart is unlikely unless there has been some quite chastening surprise. There is a good chance of an unpleasant surprise, such as a brush with an ice age, during the next decade or so.

Finally, how does this affect Shell? I think that Shell will be doing very well in the year 2000 even though petrol has long since vanished from public use. Although predominance of nuclear power will have greatly reduced the growth of energy supply from combustion it will still probably be greater than now. More important there will be a very large increase in the sales of products as materials and chemicals and even possibly food.

If I am right in my prediction that by 2000 a large proportion of the total energy turnover is going towards the avoidance of ecological disaster, then we can be sure that Shell will be in the business of counter-measures for profit. This might be its major activity. This is not the place for detailed comment, but, to illustrate my thought in this direction, there are the following possibilities:

1. The treatment of desert surfaces with ‘tars’ for climate control. The tar would change the radiation balance both directly and by laying dust;
2. The deliberate modification of the atmospheric composition through either controlled combustion or even the release into the atmosphere of a product specifically chosen to possess ideal ‘greenhouse’ properties.

To summarise. In the next 33 years we enter a phase where human activity becomes a significant portion of the total biological activity of the planet. Hitherto the climate of the earth and the chemical composition of the surface, air and sea have evolved with life to provide optimum conditions for its survival. Furthermore, this optimum was actively maintained by biological cybernetic processes. It is in Shell’s interest to participate in the maintenance of this optimum whatever may be the cause of a departure from it. It should be an interesting challenge and keep us alive.

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> *Herman van der Meyden and Maaike Witteveen*

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> *Tali Trigg*

James Lovelock is a British scientist and environmentalist. He has a been a prominent voice in the climate change debate. In 1957, Lovelock invented the electron capture detector, which allowed for the discovery of the presence of CFCs and their role in stratospheric ozone depletion. He is best known for proposing the Gaia hypothesis, which postulates that the biosphere is a self-regulating entity with the capacity to keep our planet healthy by controlling the chemical and physical environment. His latest book is *A rough ride to the future*, published by Penguin (2014).

Living in overshoot
A forecast and the desire to have it wrong

Back in the 1970s, when Jorgen Randers co-authored *The limits to growth*, it would have been possible for humanity to continue its way of life indefinitely. This is no longer so. Humanity now lives far beyond its means. Humanity's failure to make the right decision has made Randers sceptical about the odds of democratic forces saving the world from the global shocks he foresees from overshooting the planetary limits.

> *Jorgen Randers*

When we wrote *The limits to growth* back in 1972, it was an optimistic time. Human belief in the power of technology was at an all-time high. There seemed to be no challenge that could not be overcome by human ingenuity and growth based on continuing technological advances. In this perspective, the main message of our book was seen by most as unacceptable, as it showed the constraints of development. Man was no longer omnipotent.

Yet the message of *The limits to growth* was actually optimistic. Although it showed that humanity could overshoot planetary limits, it presented a number of scenarios that could steer us away from that fate, before the human ecological footprint grew into unsustainable territory.

Our message was that growth would come to an end, but we didn't mean economic growth. What we really meant was that the human ecological footprint couldn't grow forever. We left the possibility open that economic value would grow indefinitely, as long as its physical impacts remained limited. At the time, we found it almost inconceivable that humanity would allow itself to grow beyond sustainable planetary limits.

Today we know better. Since the publication of *The limits to growth*, the human ecological footprint has doubled, and is now at least a third larger than the sustainable carrying capacity of the globe. The global policies that would have kept society within its planetary boundaries, had they been put in place in the 1970s, do not suffice when implemented now. There are now only two options: 'managed decline' towards a footprint that fits the earth, or 'uncontrolled collapse' induced by nature or by the market.

The message of *The limits to growth* has stood the test of time, although we would word things differently today. Back in 1972 we spoke of 'limits', 'physical growth' and 'equilibrium'; today these concepts have become accepted as 'planetary boundaries', 'change in ecological footprint', and 'sustainability'.

But even if the concepts are better accepted, the human footprint continues to grow, which makes me worry what will happen to my children and grandchildren. Some years ago I decided to try to describe what would actually happen over the next 40 years. Not what I would like to happen, but what the most likely course of events would be. So we could prepare, and hopefully also find out what could be done to improve on that future.

The IPAT formula

The human environmental footprint is a matter of population size, affluence and technology, as was pointed out a few years before *The limits to growth*. This was summarised in the 'IPAT equation': Impact equals Population multiplied by Affluence multiplied by Technology (I = P x A x T).

Back in the 1970s, population ('P' in the equation) was growing exponentially, but the growth rate later slowed down. My best guess is that world population will peak at 8 billion around 2040. The 1970 global average of 4.5 children per woman is already down to 2.5 children, and will decrease further to 1.5 in 2050. This is close to the United Nations' Low Scenario. Many higher estimates have been made, but these often underestimate the effects of growing urbanisation. While a child in a rural setting is an extra pair of hands, in the city it is one more mouth to feed. Parents in the slums of megacities understand extremely well that the costs of having children are high, and that it is more rational to have only one or two children and make sure that those get out of the slum. It is also often assumed that fertility in the West will increase. Yet I don't think many countries will be able to pour the amounts of money necessary into all the kindergartens necessary in order to convince rich-world women to have more children. Most modern women prefer having a job over having more children.

There are other reasons why fertility will decrease further. The education levels of young women will continue to rise. Maternal health has improved dramatically, leading to a decrease in child mortality; the increased likelihood of children surviving means that it is no longer necessary to have many children in the hopes of seeing some live. And contraception is increasingly available.

So population will reach a peak, not because of planetary constraints but because of deliberate human choice.

Productivity

The second factor in the IPAT equation, 'affluence', is in fact GDP per capita. Raising it is the declared aim of economic development.

GDP has grown globally over the last 40 years, actually much closer to exponentially than has the population. Global GDP is now four times higher than when we wrote *The limits to growth*. That makes many economists confident that such growth rates are the future norm.

The output per person will level off around 2050

Yet on closer observation, the growth path of a nation is more like an S-curve. This is seen in the historical statistics of all rich nations, and now also in China. China's growth rate has declined over the last couple of Five-Year Plans, from above 10% per year to perhaps 7.5%. The growth rate will further decrease as China continues to move up the economic ladder, and finally, around the middle of the century, reach the USA's growth rate, which is below 1% (in GDP per person). Tractors and fertiliser pushed people away from their farms and pulled them into factories. Adding machinery and robots liberated labourers and got them into office work. More recently, computers have been moving the workforce into services, entertainment and education. In 30 years, many of us in the rich world will be working in social care. This means that in a mature economy, growth has to occur in offices, research groups, universities or care homes. That is harder than on farms and in factories. That is why individual countries have seen their GDP growth per person declining in the past 40 years.

Globally this is masked by the growth of new countries entering a high-productivity phase. Yet those economies will also mature. That is why I predict that the output per person will continue to increase, but at a declining rate, levelling off around 2050.

Combined with a declining workforce, this results in a GDP which will peak after 2050 at more than double today's value and then start to decline. The world production of goods and services will shrink in the second half of the century. This is a blessing, as it will avoid a full-blown disaster and give mankind a bit more time to learn to live within its means. Yet few economists ever dare to think about this.

Energy

The technology (‘T’) in the IPAT equation is not primarily ingenuity, it is largely energy. Technological advance is largely the substitution of energy for thinking, for muscular power, for transport. Most of the progress in well-being and income has been brought by increased energy use.

Efficiency gains seen over the past 40 years will continue to rise. Cars, houses and industries will use less and less energy per unit of output. Energy use per unit GDP will continue to decrease.

Multiplying this with total GPD gives a peak of global energy consumption around 2030, after which annual use will start to decline.

Yet not every energy source will peak in the same way. Coal use will increase sharply over the next 20 years, largely because of China and other big emerging economies.

‘Peak oil’ will occur, but not as a sharp peak; it is more of a 20-year plateau at a level that has been more or less reached. Today unconventional oils are coming online fast enough to compensate for declining conventional oil production. Technology did come to the rescue – yet in the process, oil prices tripled.

The use of natural gas will increase for decades because it has become so cheap in some countries, such as the USA, where utilities can offer competitive power from cheap shale gas. Politically, it is often an easy choice.

In my forecast, nuclear power will move into a slow decline. By 2050 there will be fewer nuclear plants in the Western industrialised world. Many plants in the USA, the UK, France and Russia will have reached the end of their life-cycle by 2050. New plants currently being built or planned could still be online, but the epicentre of nuclear power will shift to China, India, Pakistan and the big emerging economies.

In the longer run, fossil fuels will be gradually squeezed out by renewables. I foresee a tremendous increase in the installed capacity of wind, solar and biomass energy. Taken together, renewables will be larger than any other energy source in 2050. Still, they will account for only 40% of total energy consumption.

Reaching a 100% renewable economy in 2050 has become virtually impossible. This was different 10 years ago, when the World Wildlife Fund (now World Wide Fund for Nature) wrote its Climate and Energy Plan. Back then it was technically still possible to make the world fully renewable in 2050 without scrapping any already-existing power plant before the end of its economic life. Today that window of opportunity is gone. There is no way to reach 100% renewable without prematurely decommissioning installed fossil capacity. Without such divesting, even in the best case humanity will still rely on fossil fuels in 2050.

At the other end of the spectrum, if nothing were done to push renewables and market forces alone were to decide, the cheapest options would prevail, and wind and solar and biomass would enter much more slowly, perhaps leading to a share of less than 25% renewables in 2050.

But I believe there is still some sanity in the world: we will keep pushing renewables. In reality, the world will therefore end up somewhere in between. Looking at the numbers more closely, I conclude that we will reach a 40% share of renewables.

Climate change

Taken together, my forecasts for demographics, economic growth and energy use give the future impact of human activity, exactly as in the IPAT equation. This gives a sobering prognosis for carbon dioxide emissions. Emissions will not stop growing before 2030, and only then start a decline until they more or less equal today's emissions in 2050. This is bad news for those who hope that carbon dioxide emissions will have started declining in 2015, as is needed to keep global warming below 2 degrees Celsius. My forecast will produce a peak temperature rise of around 3 degrees Celsius. This maximum will be reached around 2080. This is above the threshold deemed safe by the climate scientists.

But it is still below what some fear. It is well below the business-as-usual scenario of IPCC, and the reason is that I forecast a declining workforce and growth rate in productivity. The emissions I foresee are lower than conventional thinking. Yet they remain above what will be needed to solve the climate problem. The world population and economy will grow slower than many expect, but still fast enough to trigger a climate crisis.

By 2050, 105 years after my birth, the ongoing increase in extreme weather events will have reached scary dimensions. Climate scientists are not exactly sure how bad it will be, but the sea levels will rise some 30 centimetres (1 foot), and we will see untypical floods, recurring droughts and landslides in new places. In the latter half of the century, the permafrost may melt at self-reinforcing speed. We could have prevented this back in the 1970s, when humanity was still living within the global limits. By 2050, we will have to spend a lot to reduce the continuing climate damage. One blessing in my forecast is that I don't see any collapse before 2050. There will be intense problems, but no sudden decline in population or standard of living. Things will simply get worse, but we won't hit real limits before 2050. We won't see a sudden and abrupt fall in living standards. Neither do I see acute and unsolvable problems with food, water or other resources.

So although we will reach 2050 without collapse, the future for those living then will look grim. Society will grow poorer because so much money will need to be poured into repair and adaptation. This will come at a time when global GDP shrinks – because of population decline and stagnation in productivity. GDP per person will at best stay constant, but consumption will decline. I can only hope that our grandchildren have better skills in managing their ruined planet than we had.

Some people think that food production will hit a physical limit, having had to increase so sharply over the last decades. But they forget that the planet's physical capacity to produce food is roughly three times what we use today, even when sustainable practices are used. I learned this 40 years ago, when I modelled the food sector for *The limits to growth*.

Making it not happen

My predictions are not what I wish to happen. They are what I think is most likely to happen. Some think that my view is horrible and immoral, claiming that predicting some 60% of energy in 2050 will still be produced by fossil fuels is saying that humanity will not solve the problem and will continue to behave stupidly. I agree this is not a very complimentary view of the human race. But it is the likeliest pathway.

One way to try to improve prospects is to consume less and use less energy. This was in fact the essence of our proposed solution in 1972 in *The limits to growth*. It was again our dream when we wrote the follow-up reports in 1992 and 2004. Voluntary reduction of ecological footprints, either as an individual or as a nation, has been a central element in the environmental movement over recent decades. In my country, Norway, the low-consumption movement was established in the same year we wrote *The limits to growth*.

Build small houses with thick walls instead of big houses with thin walls

Yet in 40 years, very little has been achieved towards this end.

One main reason is the threat of unemployment. If people stop buying, factories will close and unemployment will rise. One way to overcome this is by shifting the demand towards cleaner products – replacing, for example, a regular car with an electric car. Or building small houses with thick walls instead of big houses with thin walls. This would save energy and materials, but wouldn't reduce the number of jobs. But getting people to accept smaller houses and more expensive cars is complicated even in very rich societies. The challenge is to spread the cost of reduced growth in an equitable manner, preventing a rise in unemployment that would increase inequality. One solution would be to reduce everybody's annual work hours, so we have less time at the job to produce more stuff, and more time off to enjoy the intangible aspects of life. This is an old idea. John Maynard Keynes anticipated it in the midst of the Great Depression in his 1930 essay 'Economic possibilities for our grandchildren'. He predicted that technology would free his hypothetical grandchildren from the toils of labour and bring unprecedented leisure, with three hours of labour a day being enough to provide everything they could wish for, thanks to the acceleration technology would bring. His foresight into technological progress was correct and working hours are getting shorter, but not as dramatically as Keynes envisaged, because the majority has wanted more wealth than he could imagine. Also it is much simpler to solve the problems of modern society by growth rather than redistribution. Growth can eliminate poverty without sacrifices; it solves employment and provides adequate pensions. The alternative is not obvious, as redistribution hurts. Yet if society is to slow consumption growth, or at least the growth in the ecological footprint, this is the challenge we face. Forcing people to take more annual holiday would be one way of doing it, which is conceivable with the support of a political majority.

It wouldn't make people any less happy. The New Economics Foundation's Global Happiness Index is helpful in understanding this. It appears that happiness depends on much more than income. People weren't any unhappier in the 1970s, when income was much less than today.

These surveys are very sensitive to cultural context, less so to the perception of actual living conditions. A better way is to ask people to compare their current situation with their situation five years ago and their ideas about the situation in five years' time. Of the 30,000 Chinese we asked these questions in autumn 2012, some 75% saw continued progress. They thought they were better off then than they had been five years earlier and would be better off still five years in the future. In a similar survey in Norway a few months later, only 25% answered better-better, with 25% same-same. This is in spite of the fact that Norwegian real purchasing power has gone up by 15% in the last five years. This supports the fact that income matters less once basic needs are fulfilled. But happiness is also affected by distribution: you are less happy if your neighbour is richer. These simple facts should be the guide for those societies that want to steer towards a happier life for their citizens.

Acting on this requires a long-term vision. You need to trade short-term costs for longer term well-being. Many people are used to looking a few years ahead in their personal life. They are willing to sacrifice income for five years of education, which only pays out much later, and people often save for years to buy a house.

But to solve the energy and climate problems of the planet, a much longer vision is needed. People have to sacrifice today for a possible but uncertain benefit to their children or grandchildren in order to solve the climate problem. But the vast majority of rich-world voters are not willing to incur such costs. The core problem of modern society is that society as a whole has an extremely short-term horizon, institutionalised by high discount rates, four-year election periods, and a focus on quarterly reporting in business. Our society's institutions are short-term, not because they need to be so, but because we want them to be. Sadly, our preferred institutions of democracy and capitalism do not seem capable of solving the problem of shortsightedness. In the last few years I have tried to convince Norwegians to accept a tax increase of €250 per person per year, since this would be enough to solve the climate problem. Yet even in one of the richest countries in the world, it has proved impossible to find broad support for the solution of raising the average income tax from 37 to 38%. Human beings do indeed have a short-term focus. It is indeed impossible to solve the climate and energy problems within the limits of the present, shortsighted form of democracy and capitalism. I believe there is need for added regulation to achieve a better long-term future. Japan, South Korea and China showed the way when they moved from poor to rich nations from the 1950s onwards in a centrally planned manner. In very rough terms one can say that the Ministry of International Trade and Industry built Japan and the Chaebol corporate giants in South Korea shaped that country. China has been successful thus far through the authority of the Communist Party. It is an autocracy, but an inclusive one, with 80 million party members and ample occasion for thought exchange over the Internet and elsewhere. Some other emerging economies may follow this path.

This type of quasi-democracy is not uncommon in the West, especially in times when much is at stake. It was how the Norwegian Labour Party and its Ministry of Finance jointly built the Norwegian welfare state in the first two decades after 1945. Most nations have central banks run by experts who have been given authority to make far-reaching decisions. Even the Italians recently chose a cabinet of experts to run their country in the midst of the financial crisis.

I don't think, however, that we will see a large-scale move towards a quasi-democratic administration in the coming decades; there is too much distrust in strong government. As a consequence, we will see a gradual worsening, to which democratic society will not respond.

Yet it won't be a smooth development. It will be a bumpy ride. The increasingly frequent extreme weather we will see is more than just a little more wind or rain. It starts to get scary when 100-year-old trees start falling down. It will be very unpleasant, and increasingly so.

This will coincide with other potentially explosive imbalances, such as the inequality bubble – the fact that a very small elite, particularly in the USA, has benefited most from recent income growth – and the unemployment bubble, which is most prominent in Europe. There will inevitably be counter-reactions. Spaniards are not going to live with 25% unemployment among the young for 20 years. Debts will not be repaid in full. Pensions will not be paid as agreed. In one way or another we will have to take from the rich and give to the poor. There might be a debt amnesty so that much debt gets scrapped, or a meaningful tax imposed on the rich.

The path to 2050 will be tumultuous and full of conflict, like all other paradigm shifts. The sensible crowd will win in the end, but not fast enough to avoid damage to the planet. They will win only after the destruction caused by climate change, resource depletion, biodiversity loss, and growing inequity can be easily seen and felt.

Please help make my forecast wrong.

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Jorgen Randers is a Norwegian environmental scientist, dynamic systems expert and Professor of Climate Strategy at the BI Norwegian Business School, where he teaches scenario analysis and corporate responsibility. He was formerly President of the BI Norwegian Business School from 1981 to 1989, and Deputy Director-General of WWF International (World Wide Fund for Nature) in Switzerland from 1994 to 1999. He has authored a number of books and scientific papers, including co-authoring *The limits to growth* (1972) and its sequels in 1992 and 2004. He recently wrote *2052 – A global forecast for the next forty years*.

Revisiting the future Reflections on Shell’s 1995 scenarios

Shell long-term energy scenarios describe how technological and social developments play out and determine the evolving supply and demand of energy. Chris Anastasi, who worked in Shell’s scenarios team in the 1990s, looks back on the scenarios he helped to create, its successes and failures, and what we can learn for the future.

> *Chris Anastasi*

Scenarios are a useful tool for imagining the future through the use of creative and analytical thinking. While imminent events cannot be predicted with anything approaching certainty, scenarios explore what is possible, if not probable, and help in the decision-making process. Since the 1970s Shell, a pioneer in scenario analysis, has produced hundreds of scenarios. Most of these are used internally, but it has made public some of the details of its world energy scenarios.

In 1995, Shell's first two long-term energy scenarios covering the first half of the 21st century were developed. These were based on the observation that, over time, competitive forces stimulate productivity improvements in both supply and demand. In the first scenario – Sustained Growth – increasing demand is met by an abundant energy supply at competitive prices, while in the second – Dematerialisation – energy demands are met by more efficient technologies (see Figure 1).

The two scenarios present sharply contrasting views of the future energy landscape in terms of total energy requirements and the spectrum of technologies deployed. The Sustained Growth scenario describes a world in which renewables could play a key role in the world's energy mix with biomass, wind and solar prominent in the transition to a low-carbon future. The most attractive feature of this scenario is the promise of a world where energy consumption is no longer seen to be a bad thing.

The Dematerialisation scenario, on the other hand, describes a world in which a combination of energy efficiency and changes in economic structure result in lower energy consumption. Paradoxically, this world mitigates against the widespread adoption of renewable technologies such as wind and solar because they are unable to compete against the efficient use of the mainstream fossil-fuel technologies.

Although their outcomes are quite different, there are some important similarities in these two scenarios. Both recognise that there is considerable inertia in the energy system with continued fossil-fuel consumption, and the carbon emissions associated with it. Atmospheric carbon dioxide levels were projected to rise steadily until 2060, breaking the 400 ppm threshold early in the 21st century, and then reaching 500 ppm in 2060.

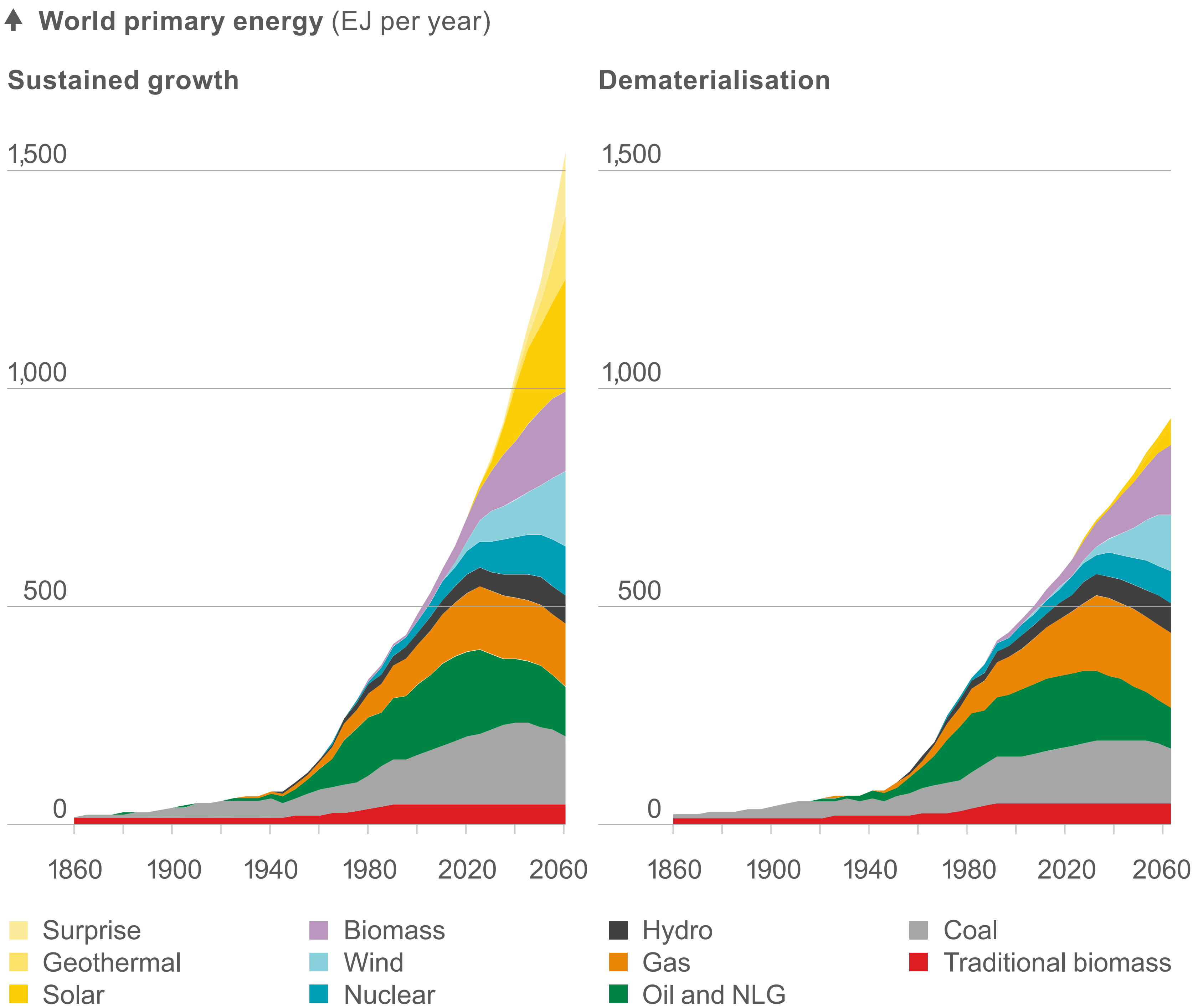

Figure 1: Total primary energy production for the Sustained Growth and Dematerialisation scenarios, showing the energy share projected for each type of production. Note that in Sustained Growth, total energy consumption is greater, and the share from renewables is larger.

Despite considerable political rhetoric on the dangers posed by climate change, the first milestone has already been met – in mid 2013.

Lessons from the scenarios

Looking at these scenarios now, almost 20 years after they were developed, what can be learned? Are the driving forces identified still the same, or have new forces emerged that will better define the future? And what surprising developments have occurred that may signal a fundamental shift in the energy system in the future?

Three distinct insights came from these studies: recognition of the host of scientific discoveries and technological innovations achieved in the generation before the 20th century; an understanding of the fundamental drivers of energy consumption and the practical application of this knowledge; and new concepts that help explain why some emerging activities thrived while others suffered delayed development or failed entirely.

These same three insights are equally valid today with the caveat that the prominent role of technology in determining the make-up of the future energy supply may be surpassed by the influence of human behaviour.

The discoveries that served to shape the world at the beginning of the 20th century were delivered by a global population of 1.7 billion people, an incredible effort in a world where education was limited and opportunities to excel were rare. Between 1871 and 1911, major discoveries and inventions led to the creation of new technology sectors: electricity, telecommunications and transport (see Figure 2).

Some discoveries made during this time were actively pursued, while others fell victim to competing developments. There were also complete 'surprises' such as the detection of natural radioactivity, which would not begin making a contribution to the energy system for another 50 years.

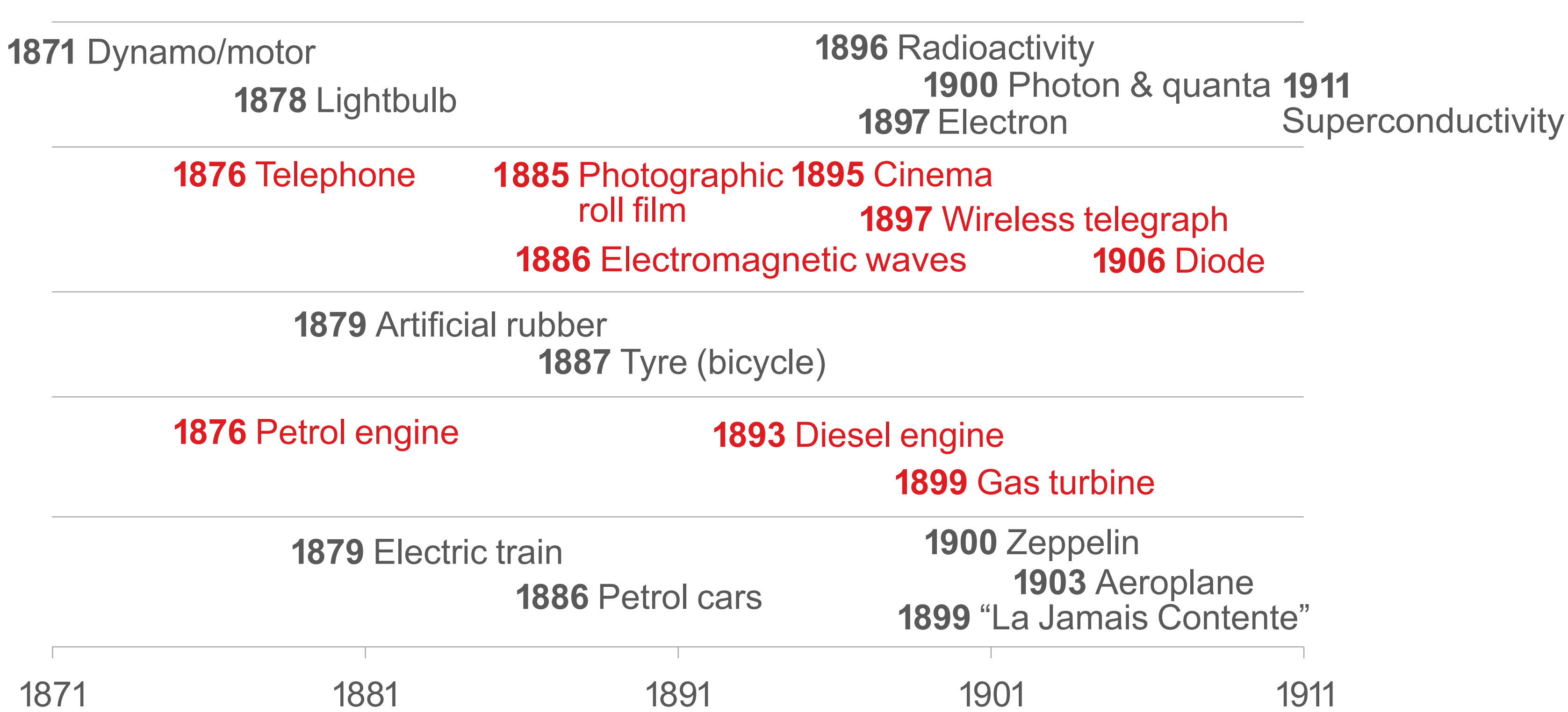

Figure 2: Timeline of significant inventions and technological discoveries for the period 1871–1911 in electrical energy, communication, synthetic materials, fuel and transportation. These breakthroughs have had a significant influence on shaping today's world.

At the outset of the 21st century the global population was 6 billion and it is increasing by about a billion people every 15 years. Education has become a basic right, and there are few boundaries to accessing knowledge. The intellectual capacity of the world today has grown substantially since the beginning of the last century, and history suggests that this will enable the rapid pace of technological innovation to continue throughout this century. The challenge to emerging technologies remains the same: how to advance new innovations, and how to define the roles of the market and the government in that process.

Converging developments

It can be difficult to identify a single driver for the evolution process. Advancements in a number of apparently unrelated fields can suddenly converge and give rise to entirely new developments. Converging development features a coming together of societal needs, technological innovation, resource exploitation and manufacturing improvements. For example, by 1870 coal was emerging as a leading energy source, steel cost was decreasing while its quality improved, and mechanical and civil engineering were the flagships of technology. In parallel, industrialisation had accelerated the urbanisation process, which increased the need to transport goods and people between cities and within suburban areas. These factors led to the development of railways and mass transport systems such as the London Underground, which opened in 1863 and is still one of the largest systems of its kind in the world.

In the history of economic development, there are times when converging needs and resources can result in a radical change in lifestyles. In the 1920s, the capacity for individual mobility was realised with the advent of the mass-produced, affordable car. Its development arose from the convergence of a new fuel with high energy density (oil), new and improved materials, new manufacturing techniques and a social desire for freedom and consumption.

The ‘supercar’ is the outcome of converging social and technological developments in the 1990s. Social issues involved increasing competition among car manufacturers and public concerns about pollution from car exhausts, primarily in urban areas. On the technology side, advances were being made in internal combustion engine control and efficiency, in fuel cell development, and in the formulation of more diverse, higher-quality fuels. There were also advancements in energy storage systems, from improving conventional batteries to exploring the potential of revolutionary high-speed composite flywheels which could deliver extremely high energy output and unmatched power storage density. Today an increasing number of pure electric or hybrid cars are commercially available, and they are putting pressure on manufacturers of conventional vehicles to improve their performance.

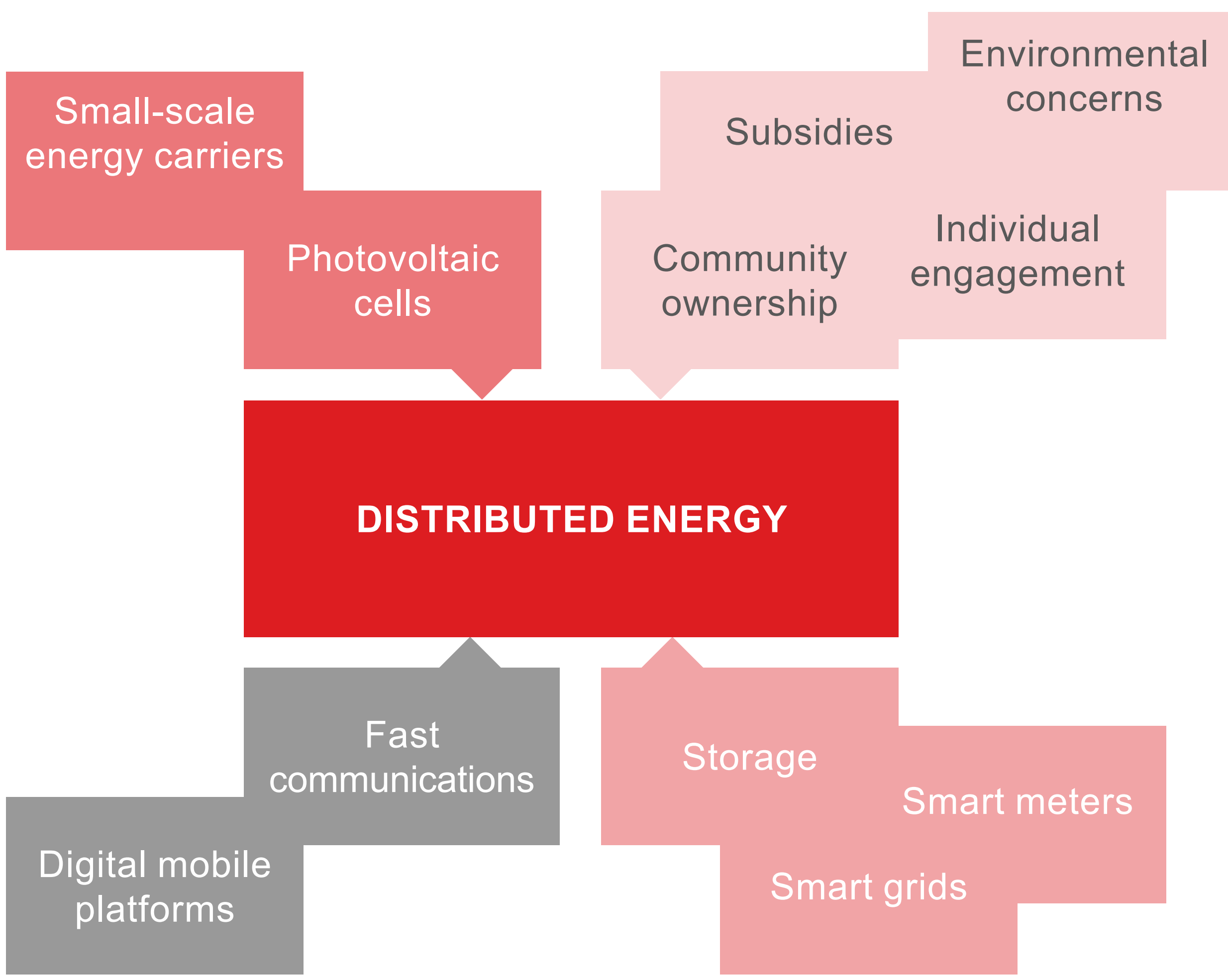

Figure 3: Converging developments today could signal a change in the way electricity is provided to consumers.

Electric car technology is not an entirely new concept, only one that failed to gain a foothold in the past. A battery-driven electric car with a light aluminium body, La Jamais Contente, was usurped by the internal combustion engine despite the fact that it held the land speed record at 105 kilometres per hour in 1898. Today, as the number of electric vehicles increases, it is evident that this technology faded in importance but did not vanish; it only required favourable converging developments to return and become viable.

What can this tell us about potential future developments? Consider Distributed Energy, a local method of delivering electricity to consumers. The societal motivations advancing these systems are environmental concerns (and the provision of subsidies for the technologies that address them), the appeal of community ownership, and the desire of individuals to take greater control of their energy needs (see Figure 3).

These same drivers have worked to promote the deployment of a number of small-scale, mostly renewable technologies. Although biomass and more recently wind power have been the main focus of activity, attention has turned increasingly to photovoltaic cells as a potentially disruptive technology. These systems require smart meters allied with smart grids, and new storage systems that are able to smooth electricity flows. The communications revolution of the last 20 years that has empowered individuals is also a necessary prerequisite for these systems, since it will allow individuals and companies to better respond to changing daily and seasonal needs.

Co-evolution of technology

While converging developments describes the coming together of technological development and societal needs, the concept of co-evolution of technology recognises that development can be complex, requiring a more holistic approach. This concept addresses the need for co-ordinated innovation in different areas to develop new, potentially disruptive technologies, and explains the challenges faced in delivering new products to the market in a timely fashion, from plastic bottles to computers to mobile phones.

In the Sustained Growth scenario, it was recognised that the commercialisation of photovoltaic cells would require developments to bring about cost reduction to make this technology competitive with more established technologies. This technology also required innovations in materials to improve the efficiency of cells, new manufacturing techniques to facilitate volume production, advancements in energy conversion and storage, and the development of decentralised grid management methods to allow interaction between consumers and local distribution systems. Failure or development delays in any of these areas would hamper progress for this technology.

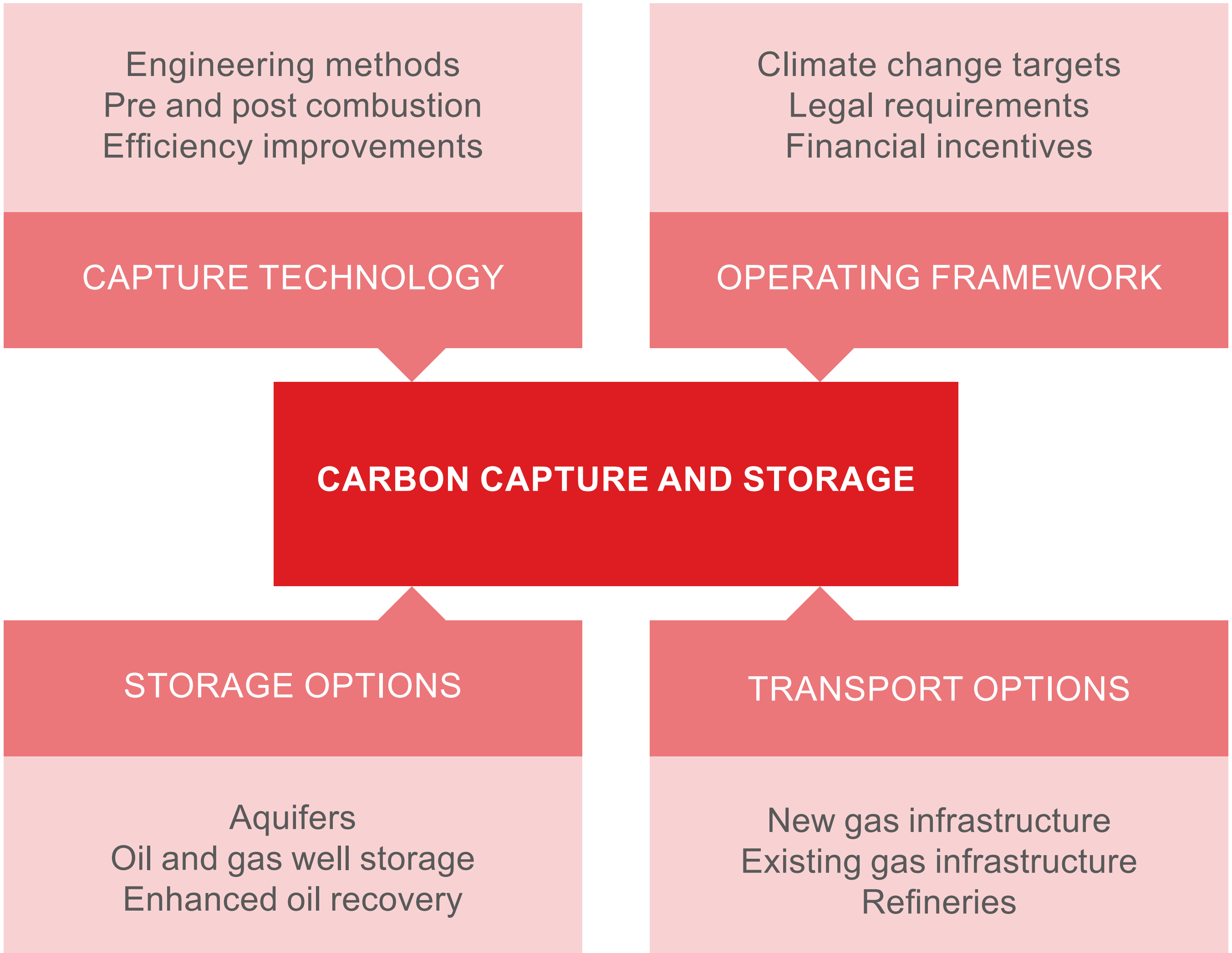

Figure 4: Co-evolution of technology in the development of carbon capture and storage.

Carbon capture and storage is a recent technology that many believe is essential to meet the challenge of decarbonising the electricity and manufacturing sectors because it can make the continued use of fossil fuels benign. Applying the co-evolution concept, technological developments for three distinct capabilities must coalesce to advance this technology: carbon capture, transport and storage (see Figure 4). It is true that some established technology exists in each of these fields, but further innovation is required for its optimum configuration. A climate of co-operation between the disparate companies that will work together to build this new and highly complex process must also be developed.

And finally, deployment of this technology hinges on the creation of a robust framework to regulate storage operations, and on assurances from government that confirm the environmental integrity of the storage medium since it ultimately assumes the carbon liability on behalf of its citizens. The success or failure of this technology could ultimately determine the future of fossil fuels as part of the world energy supply.

Cost decline and the learning curve

Cost decline is critical to the development of technologies. The concept of learning curves (where costs decline as knowledge increases and methods improve) has been clearly demonstrated in the manufacturing sector where a rapid reduction of unit costs resulted from the use of new materials and processes, the development of innovative practices, and an increase in the scale of production. Ultimately, the continuing cost decline of any product is constrained by the technical limitations of the technology used to produce it.

In the 1995 scenarios, the learning curve concept was used to explore potential cost reductions for new energy providers, and especially for the newcomers to the electricity sector: wind, biomass and solar. As development of these renewable energy technologies progressed, they were expected to follow steeper learning curves than mature players, initially capturing niche markets, and then later competing in the core market. In the Sustained Growth scenario this core market competition was projected to begin between 2010 and 2020, depending on locations and markets.

Just as projected, solar photovoltaic cells have experienced a dramatic cost decline brought about by generous subsidies that have encouraged deployment at scale, advanced efficiency gains, and fostered the development of new manufacturing techniques. The resulting collapse in price has led to an exponential increase in deployment and there are more developments on the horizon. When this technology is integrated into new applications its customer base will grow, leading to innovations in a number of new areas that will further reduce costs. Of all the renewable energy technologies, solar photovoltaics has the best chance to become a fabled ‘disruptive’ technology.

What about the learning curve for other renewable technologies highlighted in the Sustained Growth and Dematerialisation scenarios? Onshore wind has become a mature industry with costs gradually converging with other mainstream technologies in the energy market. There has also been significant progress with offshore wind, particularly over the last decade, with the major factor in reducing the cost of this technology being increasing scale. Offshore costs could potentially continue to fall, particularly because it is possible to deploy larger turbines in this environment without protest. Subsidies have helped the development of this technology in the short term, but it is uncertain how long these will continue.

The use of biomass as an alternative fuel, particularly for electricity generation, has proved even more problematic, with concerns about sustainability and competition for resources likely to limit deployment. These issues will probably not be resolved in the short term and further advancements in technology and public acceptance may be required to make biomass a significant contributor in the global energy scene.

The progress of the marine technologies – wave and tidal – has also been disappointing over the last 20 years. Learning has just begun, and they will require more development and extended demonstration to fully assess their potential over the long term.

In short, in spite of impressive advances, there are still major challenges ahead which may limit future deployment of these renewable technologies in the future, the most important of which is the need for flexible generation in the mix and the lack of new scalable storage options. For wind, there is growing resistance to onshore deployment by local communities who obtain relatively little benefit by contributing to national renewable aspirations, while offshore wind costs may remain stubbornly high and the public may ultimately not be willing to continue with subsidies for an extended period. Biomass development has suffered from sustainability issues, and marine technologies have simply not advanced. The 1995 scenarios assumed that the required technical solutions would be forthcoming and did not take into account the societal backlash against the more intrusive renewable technologies.

Could nuclear power present a solution? The 1995 scenarios and the latest long-term scenarios have noted that nuclear power can produce large volumes of low-carbon electricity, and for this reason it seemed poised to make a significant ongoing contribution to the world's energy mix. Unfortunately, the latest accident at Fukushima Daiichi has stalled what may have been a nuclear renaissance. It is unlikely that this technology will be a major contributor to the world's future energy scene, unless a new generation of nuclear technologies can be developed. Nuclear fusion continues to excite with the potential for limitless production of clean energy, but this technology seems perpetually destined to elude successful exploitation, with commercialisation at best many decades away.

And what role might fossil fuels play in the future? There is undoubtedly significant inertia in the energy system that works against the rapid removal of fossil fuels from the energy mix. Both the Sustained Growth and Dematerialisation scenarios projected a continued rise in the use of fossil fuels, with peak consumption at around 2020, followed by a gentle decline over the remaining decades of the 21st century. The latest Shell long-term scenarios, Mountains and Oceans, have the peak pushed back further to about 2050, followed, once again, by a gentle decline over many decades. It appears that peak oil consumption, like nuclear fusion, is an event that lies on a continually retreating horizon.

It is unlikely that nuclear technology will be a major contributor

Part of the reason for the ongoing consumption of fossil fuels is their continued availability at affordable prices. As in the past, with high oil (and gas) prices and technological developments, more resources become economical to exploit. Today, the reserves-to-production (R/P) ratios for oil and gas are higher than 30 years ago – the R/P ratio for oil has risen from 35 years in 1982 to 52 years in 2012, and the R/P ratio for gas has risen from 52 years in 1982 to 56 years in 2012.

A surprising development is that the R/P ratio for coal has fallen markedly, from 228 years in 1992 to 108 years in 2012. The biggest decline is in the coal R/P for the Asia Pacific region, which has dropped from around 180 years to just over 50 years, reflecting the past 20 years of high economic growth and heavy reliance on this fuel. Although the

1995 scenarios recognised the difference between resources and economic reserves, and limited expected coal exploitation accordingly, they did not anticipate such a rapid decline in R/P ratio.

Today, there are concerns that political events in producer countries could lead to a fall in production, but history shows that these declines would be temporary and short-lived because those economies rely heavily on oil and gas revenues. In reality, fossil-fuel suppliers and consumers are clearly dependent on each other, and as indicated in the scenarios, fossil fuels will continue to play a significant role in the energy mix throughout this century.

Events on the horizon

The 1995 scenarios introduced the idea that there are always surprising discoveries and developments on the horizon, and like those seen at the beginning of the last century, breakthroughs will ultimately have a major impact on the energy system. The emergence of carbon capture and storage could be such a disruptive technology, but even with some minor successes in this area, a full demonstration project has yet to be commissioned. It will take at least another decade until this technology becomes mainstream. Or perhaps the long-awaited nuclear fusion reactor will be the surprising development in the second half of the 21st century.

When the scenarios were created, they made note of some of the potential technological developments that were on the horizon at that time. Molecular design was rather new, but had the potential to contribute in many areas; molecules could be made by conventional chemistry, but their atoms could also be manipulated directly, and this new realm was called ‘nanotechnology’. Although not specifically foreseen, graphene, a two-dimensional carbon-based material, was successfully created in the laboratory around the turn of the century using molecular design technology. Experts believe this novel material will revolutionise a number of industries, most notably electronics and manufacturing, but its most important use may be in photovoltaic devices and energy storage systems which could ultimately help these technologies become major contributors to the world’s energy supply.

Technologies that use graphene are still at a very early stage, and it can typically take years, possibly even decades for such innovations to deliver useful and commercial products. Nevertheless, considerable technical and business knowledge exists that can maximise our chances of fully exploiting the potential associated with this material.

It remains very difficult to anticipate the long-term effect on the energy sector of the use of molecular design in both biotechnologies and solid state technologies. Some developments will result in improved energy systems with cheaper and abundant energy supply (for example, improved biomass yields, solar photovoltaics, superconductivity) or they may extend opportunities for using energy (for example, increased mobility, more widespread longevity). Other developments will lead to energy savings from the use of lighter and novel materials (such as bio-polymers) to new methods of food preservation.

Information technology (IT) today has a major positive impact on our work and home environments, but the 1995 studies projected that IT use would go on to revolutionise energy use in other ways, for example, through the application of 'virtual reality' and the evolution of 'intelligent' houses. These expectations have not yet been realised – in some cases, the technologies have not been forthcoming, but their adoption has also been limited by an inability to engage the individual in meaningful ways.

Transforming the energy system

Over the last 20 years, the world's energy system has been shaped in part by societal concerns over climate change and the resulting efforts to slow its progress. Carbon reductions have been sought in many sectors of the economy, and there have been some encouraging new developments in this area that were successfully projected in the 1995 scenarios: hybrid cars, photovoltaic cells and new methods of communication will continue to play an influential role in the future energy system.

These concerns and efforts have not proved sufficient to transform the system completely, although other societal drivers, such as the need for individual mobility, have succeeded in doing so in the past.

There are suggestions that a climate change ‘signal’ would mobilise the necessary action across the world; however, the effects of climate change are slow and gradual, and regardless of repeated attempts by scientists to gather and present the evidence of these effects, there has thus far been relatively little change in human behaviour.

The financial crisis in 2008 shifted priorities with climate change dropping lower on the political agenda, and investment in green technologies becoming more difficult. There has been some concerted action in creating and implementing carbon mitigation policy, most notably in the European Union where firm targets for carbon emission reductions and the deployment of renewable technologies have been adopted; elsewhere in the world, action has been patchy. A global agreement for addressing this problem is needed, but a lack of political will is apparent, and so carbon concentrations in the atmosphere continue to rise.

The need to adapt to climate change will become increasingly important

Another more worrying factor, which was not anticipated in the 1995 scenarios, is the emergence of climate change ‘fatigue’, particularly at the policy level, and this may further reduce the drive to decarbonise the energy system.

Looking ahead, the need to adapt to climate change will become increasingly important, especially because the earth’s capacity to sustain life in a climate-changed world may be limited. Many of the strategies for mitigation are also helpful for adaptation, for example, developments that reduce energy use in the home and workplace can help us to adapt to a world where energy is scarce. Adaptation will certainly require innovations to address, for example, water and agricultural shortages and threats to public health. All of these will have implications for energy use in both the natural and developed environment.

One school of thought is that the enormous innovative capacity of humankind will provide the solutions to transform the energy system, not only to meet the challenge of climate change but to ensure sufficient resources for future generations. An alternative view is that there is insufficient collective will at the political or individual level to affect the changes needed, and that humankind will sleepwalk into a very uncomfortable future world.

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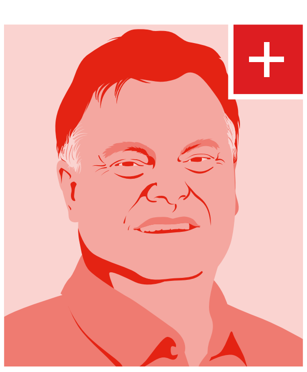
Chris Anastasi worked in Shell's scenarios team in the 1990s and has been a member of a number of Government Committees and Advisory Boards, in the UK and elsewhere.

The author wishes to recognise Georges Dupont-Roc, who made a major contribution to the Shell 1995 long-term scenarios.

Towards net-zero emissions
An outlook for a prosperous world

A world with net-zero carbon emissions, in which 10 billion people prosper, is feasible – but getting there will not be easy. We will need huge and courageous progress in economic restructuring, co-evolution of the emerging and established components of the global energy system, and the large-scale implementation of technologies such as carbon capture and storage. Casting our eye forward towards the end of the century can help us to design the path to follow.



> *Jeremy Bentham*

One of the great challenges of the 21st century is matching on a global scale the prosperity and wellbeing that industrialised economies enjoyed in the 20th. An even greater challenge, however, will be achieving that prosperity and wellbeing without stressing the environment to such an extent that it diminishes the quality of life for everyone, especially the most vulnerable.

The global energy system is key to both challenges. If we as society want to develop infrastructures, utilities, homes, industries, jobs, trade and transport capable of providing a decent quality of life for a global population likely to approach 10 billion, we will need twice as much energy as we have today – even assuming heroic improvements in efficiency. At the same time, we will need to stabilise the accumulation of greenhouse gases in the atmosphere to alleviate pressures on our climates. To do this global society must realise net-zero emissions from energy and other sources.

Given the size of the task, it will take considerable time to change fundamental economic structures and to implement them globally across multiple sectors in multiple countries.

But it is feasible.

Setting the scene

A pivotal change occurred around the turn of the 21st century. Modern renewable energy technologies – biofuels, solar energy and wind energy – were liberated from the confines of laboratories, test centres and demonstration sites and began to be deployed for real. This is powerfully illustrated by the growth in investment in these technologies, which rose from around $10 billion in 2000 to roughly $300 billion in 2014.[1]

Around the same time, a newly prospering China became a powerful force on the global stage, pushing up demand for the full spectrum of resources – including materials and energy. From 2000 to 2014, China's primary energy demand rose from 50 to 120 exajoules per year – 12% and 21% of the world's total demand respectively. What has played out in China over the last decade will almost certainly play out across the developing world in the decades ahead. We cannot and should not think that people in countries like Nigeria and Pakistan can be denied the prosperity that further development of their industries and infrastructures can bring.

Growth in energy demand and the rise of renewables play out against the spectre of climate change induced by anthropogenic greenhouse gas emissions. Since the turn of the century, again, the scientific consensus has gradually moved towards an increasingly constrained picture of the allowable emissions budget necessary if we are to stay within the limit of a two degrees Celsius temperature rise – the yardstick around which the climate debate revolves. To stabilise the atmosphere at any reasonable level, however, implies that net greenhouse emissions will have to be managed down to zero, with the ultimate impact on the world's climate dictated by how quickly this is achieved.

Taken together, these changes form the backdrop to the broader energy transition now unfolding. In the light of this challenge it is helpful to look out towards the later phases of the transition to better understand the direction we need to take today. Many energy outlooks and scenarios halt their analysis at mid-century, which is either part way through the transition, or mechanistically forces an end point in a manner that stretches the bounds of what seems feasible in the real world. Neither of these approaches effectively identify crucial practical lessons.

In this essay I want to explore the later phases of transition, when the world will be approaching net-zero carbon emissions from energy, then work back from that as a means of understanding implications for the near term.

Future energy demand

As a starting point for this exploration, let me quantify the magnitude of future energy demand. We know that as incomes grow, energy consumption typically rises proportionally with GDP up to a level of some $20,000 per capita per year as more energy-intensive infrastructure, heavy industries, and cities become established. Above that, saturation begins to set in as additional GDP increasingly comes from less energy-intensive sectors and technology improvements drive efficiencies.

In North America this saturation level of primary energy use is around 300 gigajoules per capita per year, while in more efficient Europe and Japan the level is around 150 gigajoules per capita per year.

Looking ahead, if developing nations use better, more efficient technologies, it may be possible to achieve a decent quality of life with primary energy use converging around 100 gigajoules per capita (Figure 1). Converging around a figure as low as this actually represents huge strides in the efficient use of energy. As shown in the figure, the energy intensity of economies is continuously lowered as energy consumption levels off or declines despite continuing development. Nevertheless, it is very difficult to lower intensity at double the pace of the past decades, the rate needed to converge around 100 gigajoules per capita per year. For the USA, for example, it would mean reducing energy consumption to a third of today's.

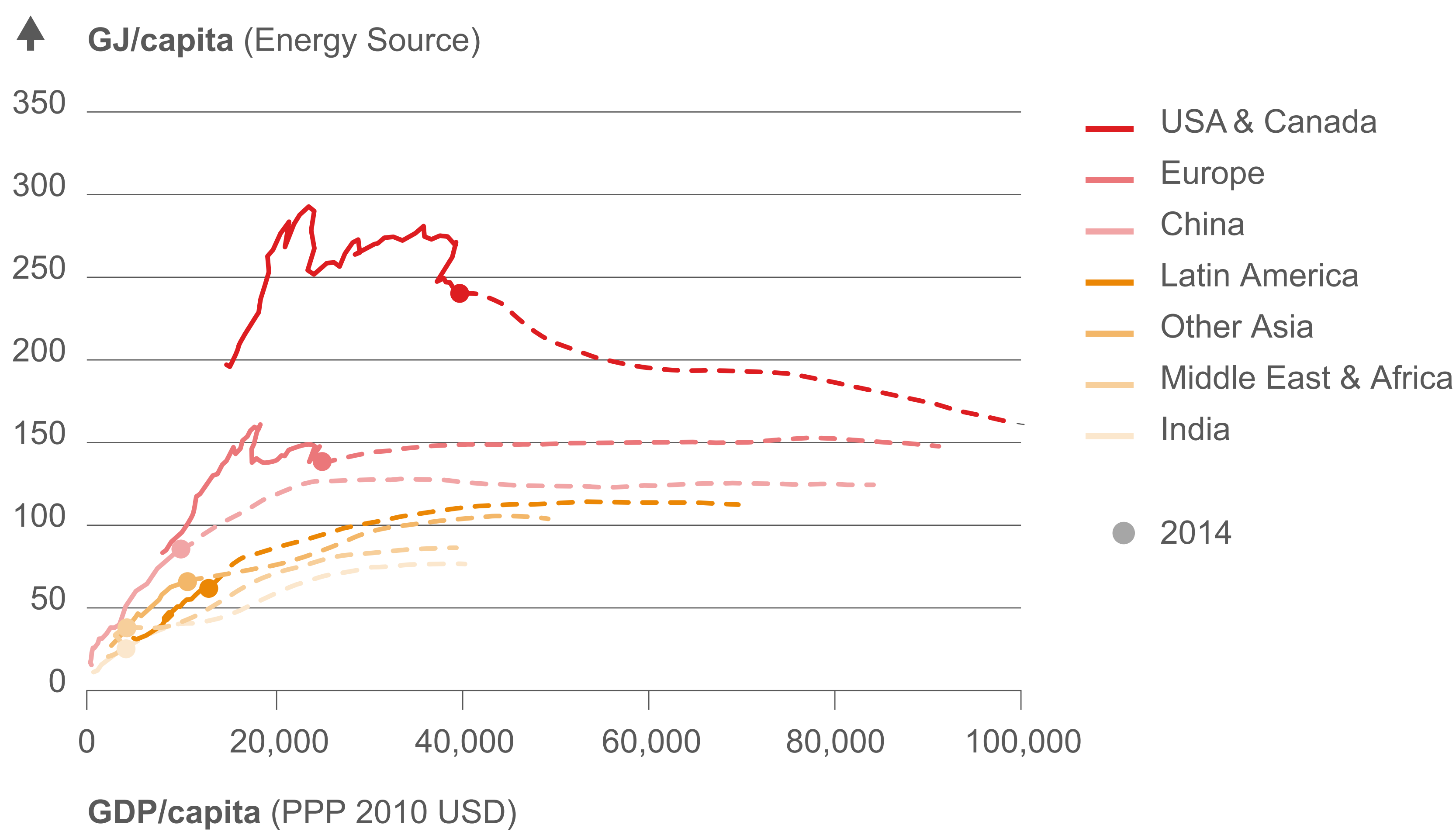


Figure 1: The development of per capita income and energy use from 1960 to today for major regions, with a forward projection to 2100 according to Shell's Oceans scenario,[2] showing the convergence of per capita energy consumption to between 75 and 150 gigajoules per capita – much narrower than today's range which runs from 25 to 300 (filled circles).

As we progress through this century, we should expect 5 to 7 billion additional people to move to levels of energy consumption associated with moderate prosperity. Having a total of some 10 billion people and an average primary energy demand of 100 gigajoules per capita per year pushes overall global demand up to at least 1,000 exajoules (or 10^{21} joules), roughly twice the level of today.

Hydrocarbons alongside renewables

The energy system in this world will be something of a patchwork. Different degrees of decarbonisation and energy efficiency will be achieved at different paces, in different places, and in different sectors of the economy.

Renewable energy technologies have an indispensable role to play in a world which aims at net-zero emissions. But on their own they are not a silver bullet. They contribute at different levels in different sectors. They vary in availability and in intermittency and have a low energy density. Even if we stretch the limits of technology the world cannot live on renewables alone. The production of chemicals and plastics, for example, would continue to rely on hydrocarbons. Where high temperatures are required – such as in various chemical processes – thermal heating involving fuels will still be needed. In addition, some activities naturally produce emissions or require carbon input, such as the production of cement and steel – although if we were to recycle steel more and use electric-arc furnaces, emissions could be moderated. Where particularly dense energy storage is required, such as in air travel, marine freight, and even long-distance road freight, we will almost certainly see the continued use of combustion engines running on hydrocarbon fuels.

There are also likely to be regions that will decarbonise at a slower pace, either for political and economic reasons or because they have a particularly high or low population density. For emerging economies the costs of *not* having a reliable energy supply for industry and infrastructure are very high, so energy reliability and storability are as important as affordability. Energy sources with a high density, such as hydrocarbons, have an advantage in this regard. Coal is widely available at a relatively low variable cost. Natural gas has also become more widely available and more affordable, and its use requires relatively low investments. It can be used to compensate for the intermittency of renewable sources and will be increasingly integrated with renewable energy sources, for example in integrated gas and solar micro-grids. It is also benign in terms of air quality, which becomes more and more important as populations achieve even modest levels of prosperity and urbanisation.

While some hydrocarbons can be obtained from biomass, there is a trade-off between scale and the practical requirements of sustainable land-use management across the globe. Analysis by Ecofys and Shell[3] suggests that biomass is unable to meet the total demand for hydrocarbon fuels, so that a mix of biomass and fossil fuels will be required.

Net-zero emissions

Any realistic scenario for a carbon-neutral future should take account of the fact that not all regions will join equally in the effort, and that not all industries can be made carbon-neutral. It is important to recognise that a net-zero-emissions world is not necessarily a world without any emissions anywhere. It is a world where remaining emissions are offset elsewhere in the system.

Global society must achieve net-zero emissions much earlier than we can reach a completely emissions-free world. This means that we will need 'negative' emissions in some sectors to offset remaining emissions. One way to do this is to combine sustainable biomass gasification with the capture and storage of carbon dioxide (CCS) in power generation. Other ways include agricultural practices that raise the carbon content of the soil, and reforestation. The result is that carbon dioxide is taken from the atmosphere, offsetting unavoidable emissions elsewhere. Deploying CCS will, therefore, be an essential component of any emerging net-zero-emissions world both for mopping up remaining emissions and enabling 'negative' emissions.

Hydrocarbons are likely to still provide about a quarter of primary energy in a world where global energy consumption will double (Figure 2). Almost half of these hydrocarbons will be needed as feedstock to produce materials and chemicals. Non-energy use will account for the equivalent of 100 exajoules per year. While it is technically possible to produce plastics and other materials directly from biomass, as already noted, there will not be enough biomass to do this responsibly on a really large scale. Moreover, the use of fossil feedstocks need not add extra carbon to the atmosphere. This only happens if the materials produced from them are burnt at the end of their life; this would release an extra 6 gigatonnes of carbon dioxide per year. This can and should be avoided. Carbon may be captured at modern waste incinerators, materials should be recycled whenever feasible, or – if no other option is available – waste should be permanently stored.

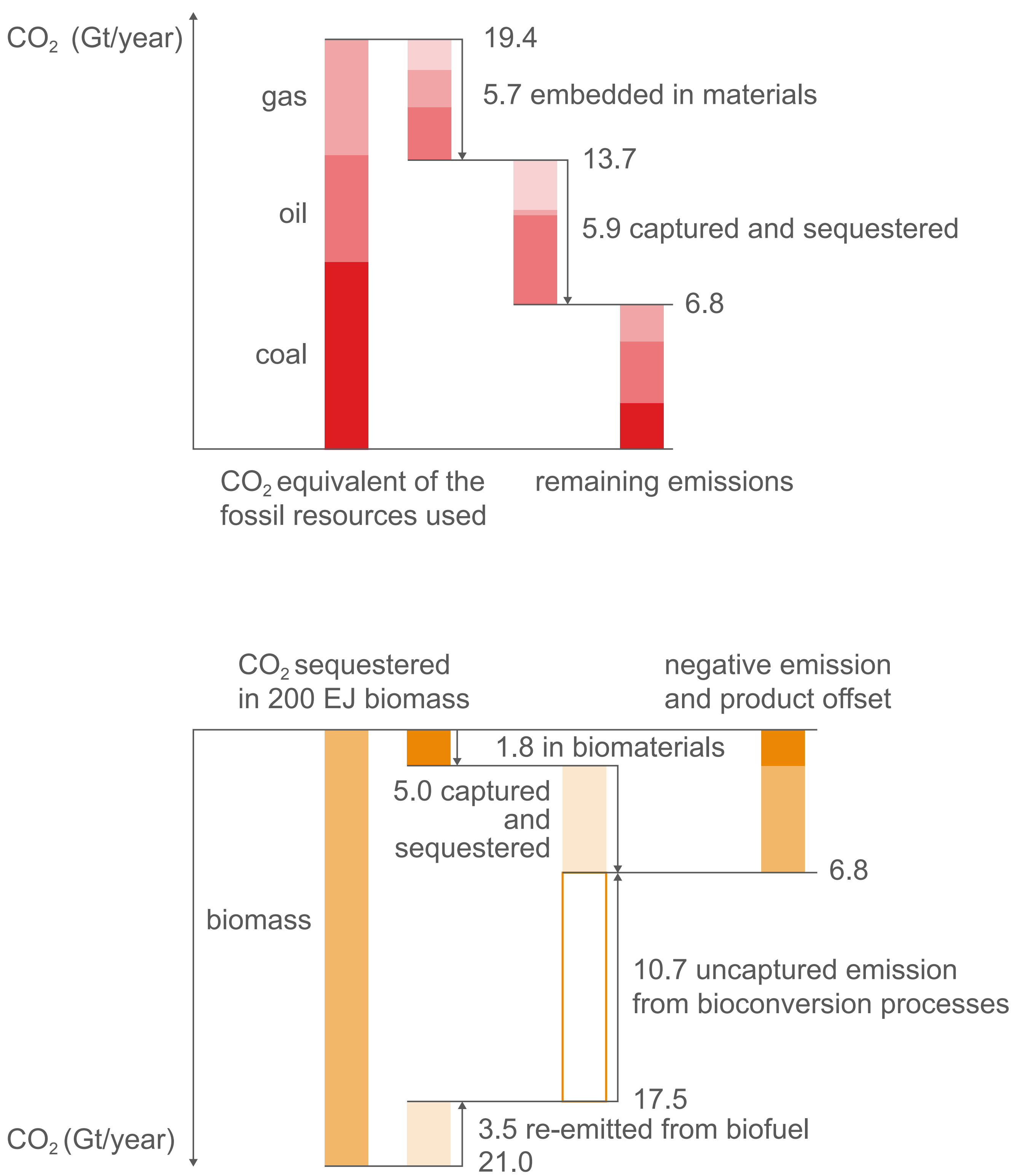


Figure 2: Emissions net out to zero as remaining emissions from fossil fuels are compensated by 'negative' emissions which result from the capture and sequestration of carbon dioxide from bioenergy conversion processes.

The remaining hydrocarbons will be needed for energy use. If unabated, this would release almost 14 gigatonnes of carbon dioxide per year into the atmosphere. As noted, not all of these emissions can be avoided. Most oil products will have dispersed emissions, notably in transport, and carbon capture may not be practical for perhaps a third of remaining coal and gas use. Realistically, about half of the emissions from fossil fuels can be captured and sequestered, leaving the other half unabated – almost 7 gigatonnes of carbon dioxide per year. This needs to be offset by 'negative' emissions from elsewhere (Figure 2). Some 4.5 gigatonnes may come from the use of biomass and waste for energy in combination with CCS. The remaining 2 gigatonnes can be compensated for by carbon embedded in bio-based products, permanently removing it from the carbon cycle.

As a result we will need a widespread deployment of CCS. To bring emissions down to zero, some 11 gigatonnes of carbon dioxide per year need to be captured and stored, equivalent to just over a quarter of today's total emissions. This is a huge endeavour, but it is doable, as Ron Oxburgh explains elsewhere in this book. If the capacity of 11 gigatonnes of carbon dioxide per year is not completely reached, it may be supplemented by reforestation and change in agricultural practices. The capacity of CCS needed would eventually shrink in the approach to, and evolution of, a net-zero-emissions world, as emissions continue to decline in general.

This is about as far as we can go in decarbonisation. It also makes it clear why we need to limit energy use to 1,000 exajoules per year. Without significant measures energy use could easily rise to at least 1,500 exajoules per year, a value which already assumes efficiency improvement well beyond a 'business-as-usual' scenario. Due to land-use constraints, it would not be possible to grow enough biomass and build enough solar and wind power to accommodate 1,500 exajoules or more and still achieve net-zero emissions. Also, the extra CCS capacity needed would be difficult to realise, making 1,000 exajoules per year stand out as the round number that best matches human aspirations with the need to live within planetary boundaries with respect to greenhouse gas emissions.

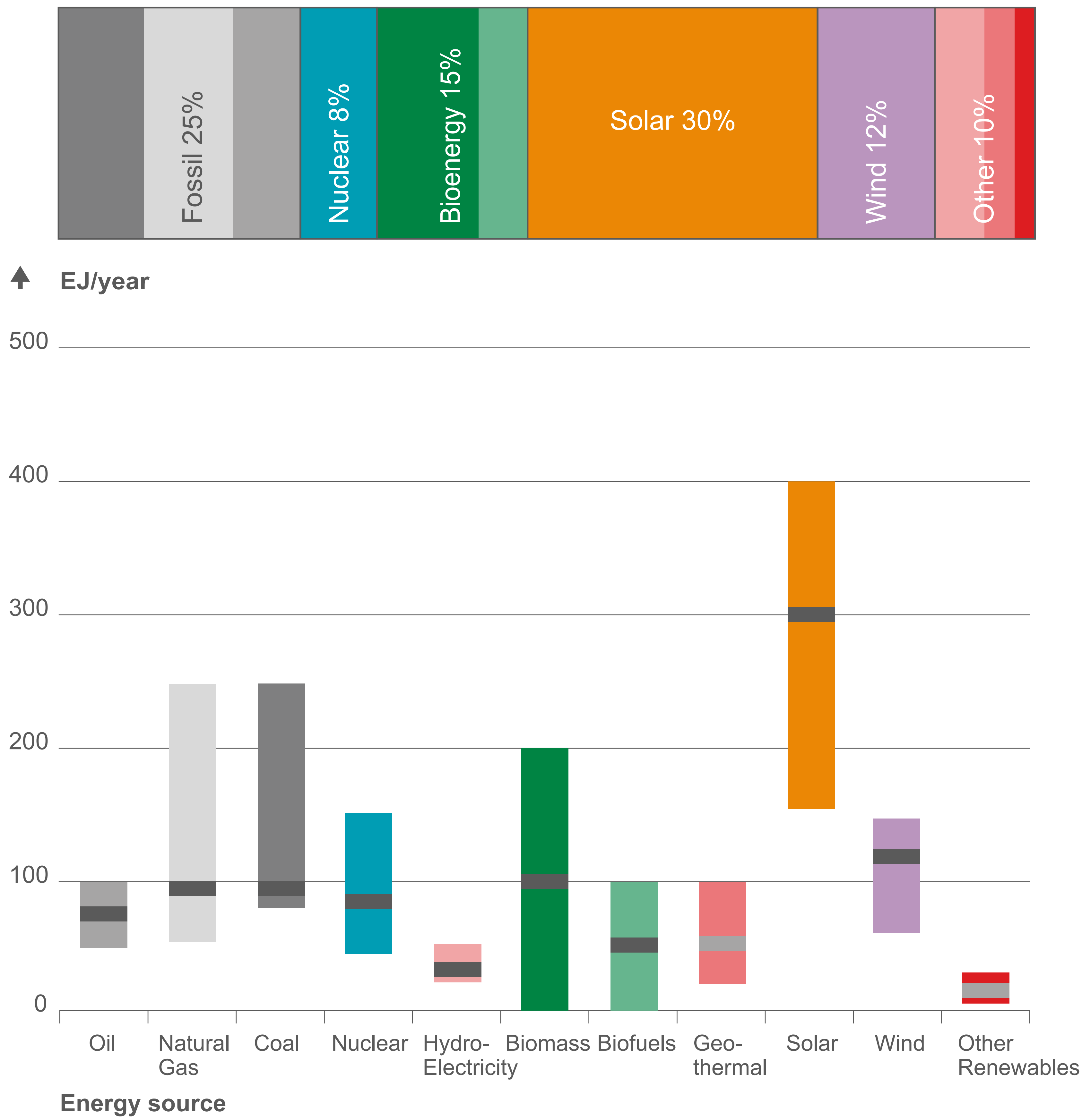


Figure 3: Example ranges for a feasible energy portfolio providing 1,000 exajoules per year primary energy that is commensurate with net-zero emissions.

Carbon-free energy carriers

In order to come close to a net-zero sum, the world will call on an array of carbon-free energy carriers (Figure 3). Electricity will become the most prominent energy carrier because renewable technologies that generate electricity, such as wind and particularly solar, are already becoming established and will be increasingly cost-effective. They will come to dominate power generation in the net-zero-emissions world. Electricity provides only about one fifth of the energy consumed by end users today. This will need to increase to at least a half, extending its penetration into many additional applications. Most of this electricity will come from solar and wind energy – together eventually providing over 40% of global energy.

Electrification will be particularly high in households and service sectors, not only for familiar appliances and light, but also for heating and cooling, with electric heat pumps, for example. Electrification needs to extend into other sectors where practically possible. In industry, this is within reach for mechanisation and processes operating at moderate temperatures, such as in food processing. For transport, electric drives will become common. For commuting and other short journeys that leave plenty of time for recharging, battery-electric vehicles will benefit from improving energy density and charging times for batteries.

Hydrogen is an attractive, additional energy carrier in a net-zero-emissions world. It can be made from surplus electricity and from fossil – particularly natural gas – and biomass with CCS. The net-zero-emissions world is likely to use much more hydrogen than we use now. Today hydrogen is produced largely for chemical use, for example in fertiliser production and oil refining. But it will also become a valuable medium for storing energy. It could provide high-temperature heat in industry. Hydrogen fuel-cell electric vehicles may become the most attractive option for personal transport for longer ranges and faster refuelling, especially if battery development stalls.

Other carbon-free sources such as hydro-electric, geothermal and nuclear will together contribute 20% of global primary energy. With bioenergy adding an additional 15%, the total non-fossil primary energy sources will grow to 70-80% of the world's energy supply in a net-zero-emissions world, in contrast to the more than 80% supplied by hydrocarbons today.[4]

The promise of efficiency

Limiting global energy demand to 100 gigajoules per year for every man and woman on this planet, while allowing for a decent quality of life, would only be possible with heroic efforts on efficiency improvement. Considering that a typical intercontinental flight consumes 40 gigajoules per passenger it is clear that achieving 100 gigajoules per year will require both extraordinary improvements in energy efficiency and changes in lifestyle for some.

We shall need new technology to improve the energy efficiency of individual end-use applications. Making cars lighter will more than double the efficiency of internal combustion engines, and electric drives are intrinsically more efficient. We need to employ heat-pumps, LED lighting and other appliances. We could see more recycling, and improved industrial processes. In some cases, huge improvements in efficiency are possible in individual applications, but the overall impact will depend on the rate of renewal and retrofitting of existing housing, offices and other capital stock.

Infrastructural changes lock in efficient behaviour

Many efficiency measures, however, encourage economic growth and – other things being equal – energy use. The control of this so-called rebound is a serious issue. It is therefore important to focus on infrastructural changes, which lock in efficient behaviour and thereby achieve durable long-term benefits. The huge difference in energy use between the USA and Europe can partly be explained by their city format, which was locked in a century ago. Compact urban development provides great opportunities for improving efficiency. If we avoid urban sprawl and develop reliable and attractive public transport networks, with city layouts that support mixed modes of mobility including cycling and walking, our need for transport will reduce significantly. Depending on the level of development and available finances, we might achieve efficient public transport through rapid bus and metro transit systems. Somewhat less efficiently we could make use of driverless electric vehicles that could be summoned like today's taxis. We can considerably reduce the environmental footprint of a city if we learn how to integrate water and waste management with power generation and district heating.

Compact cities have benefits beyond transport and heating/cooling efficiency. Buildings and other urban infrastructures can accommodate photovoltaic solar panels. By limiting land use for city development, there will be more land available for agriculture, more biomass for energy and other uses, and more land to produce solar and wind energy.

With an ever-increasing share of the population living in cities, urban efficiency is crucial to allow affluent energy demand to saturate at around 100 gigajoules per capita per year, one of the key assumptions in realising a net-zero-emissions world. Still, 100 gigajoules per capita is an average. Some countries with a dispersed population and a cold climate, like Finland, would probably need more. And some individuals – those who need to fly, for example – would also use more. Conversely, there will be regions where energy consumption is lower, for instance well-planned, compactly designed cities.

Some argue that an even lower average per capita energy use may be possible but, in doing so, typically call on humanity to reconsider its basic wants and needs, invoking concepts of sufficiency and finitude, as Jan Boersema and Thomas Princen explain in this book. This has proved to be a hard sell – particularly since even relatively basic infrastructures like waste systems and urban development are energy-intensive. This is why I would put my money on technological progress and the judicious, timely deployment of new technologies which can – and hopefully will – deliver the energy we need.

Policy measures

Achieving net-zero emissions before it is too late will involve both growth and the transformation of basic economic structures. Our progress in this area will determine the quality of our lives and our ability to manage long-term environmental stresses such as global warming. We will need to modify our industrial, agricultural and urban development practices and our consumer behaviour. And we must develop policies which shape, incentivise or mandate these changes. Key to the feasibility of this transition are measures that do not compromise economic development. We would not do humanity a favour by abating emissions but neglecting to provide a decent life for many billions of people.

There is a broad consensus about which measures are relevant to reduce carbon emissions (see the overview of policy measures in the box). Yet if we are to come close to a net-zero-emissions world, ambitions need to be raised particularly around the pace and integration of developments. First, we need to focus financial incentives on carbon in general, avoiding as far as possible targeting particular technologies, especially when they have matured beyond demonstration projects and crossed the threshold to materiality and commerciality. This means a timely removal of energy subsidies where they still exist. Carbon taxes or other fiscal measures are very powerful, as they not only encourage efficiency but also motivate other investments in emissions reduction. They also allow for the market to find the optimal mix, which, as I have argued above, is likely to include renewables, fossil and biomass energy with CCS and nuclear. None of these should be excluded from the financial incentives. Since in the real world the global implementation is likely to be patchy, measures should be taken to prevent cross-border ‘carbon leakage’.

Carbon pricing is a very powerful instrument

To lock in efficient behaviour by smarter urban planning, stricter regulations are needed to densify sprawling neighbourhoods and to promote energy-efficient buildings, public transport and integration of infrastructures.

Finally, we need to rethink land-use and agrarian practices. As humanity lays an ever-larger claim on the earth’s biogenic productivity for food, feed, fibre and fuel, we must ensure that the net result is positive. This requires an approach that is tuned to local conditions, as Lewandowski and Voss make clear in their contribution to this book. That is why we will need many different techniques to convert biomass into usable energy, in the form of fuel, heat or power – where possible with CCS. This also includes policies regarding reforestation and soil regeneration.

To achieve a net-zero-emissions world, society will need all the measures listed in the box. These are all good measures, almost irrespective of the depth of the transition or the level of ambition. This is good news, because they are thereby robust. Yet a condition for realising a net-zero-emissions world is that they establish a spiral of aspiration, where success in one area allows policymakers to raise the bar elsewhere. There are good technical reasons for such knock-on effects – illustrated in this book by Amory Lovins' concepts of radical innovation. A spiralling acceleration takes off only after a threshold is crossed. This is an explanation for the current too-slow pace of progress, but it also offers hope for the future. If we manage to set the spiral in motion, a net-zero-emissions world might be realised even before the end of this century.

Moving forward

It is possible to envisage a prosperous net-zero-emissions world – one which involves both growth and fundamental transformations in basic economic structures. And the pace at which this is achieved will shape quality of life and long-term environmental stresses, including increases in global average temperatures.

Achieving a net-zero-emissions world at pace will require significant developments in technology and technology deployment; industrial, agricultural and urban development practices; consumer behaviour; and policy frameworks which shape, incentivise or mandate these transitions. To move at pace will also entail high levels of collaboration between policymakers, businesses and civil society. No one pretends that achieving all of that at the same time will be easy. But such are the rewards if we succeed – and the dangers if we fail – that it is something we can and must work together to achieve.

Sensible measures for progress towards a net-zero emissions world

- Carbon pricing or equivalent incentives to motivate investments in emissions reduction and energy efficiency. This will also encourage the deployment of renewables, CCS and nuclear, as well as efforts to reduce the use of coal.
- Financial support for R&D, and for the early-stage deployment of promising technologies.
- Measures and incentives to help people move from traditional biomass to commercial energy sources.
- Smarter practices and stricter regulations for compact urban development, integrated infrastructures and efficient buildings.
- Regulations or incentives to invest in low-emissions transport.
- Timely removal of energy subsidies where they still exist and fiscal measures to maintain relatively elevated energy prices for end users – enough to encourage efficiency and investment in technology development, while not stifling economic activity.
- High energy-efficiency standards for a wide range of end-use applications.
- Land-use, reforestation and soil regeneration.
- Measures to prevent cross-border carbon leakage.

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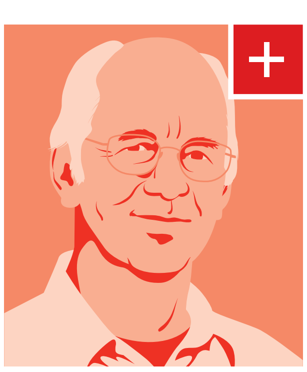
Jeremy Bentham is Vice President Global Business Environment at Shell, head of the Shell Scenarios work, and a member of the corporate strategy leadership team. He has more than 30 years' business experience in Shell and has studied at Oxford University, California Institute of Technology, and Massachusetts Institute of Technology.

References

1 Frankfurt School-UNEP Centre/BNEF (2015). *Global Trends in Renewable Energy Investment 2015*, Frankfurt am Main, www.fs-unep-centre.org. Produced in collaboration with Bloomberg New Energy Finance.
2 See New Lens scenarios at www.shell.com/scenarios.
3 Y. Y. Deng, M. Koper, M. Haigh, V. Dornburg (2015). Country-level assessment of long-term global bioenergy potential, *Biomass and Bioenergy 74*, 253-267, doi:10.1016/j.biombioe.2014.12.003.
4 *Ibidem.*

Start stopping
Towards a fossil fuel ethic for a cultural transition

It is time to resurrect the magic of fossil fuels, the early magic, the magic that made such substances special. This time, the magic would not derive from their scarcity, but from their abundance.



> *Thomas Princen*

High-consuming societies, including those that externalise significant environmental and social costs, will be moving away from fossil fuels and towards renewables. But, due to huge cause-effect time lags, not soon enough. They need to be nudged, maybe shaken up a bit. The transition must be accelerated.

For that nudging and shaking, in this essay I look for values, the non-material elements of transition, elements that cannot be spoken in such materialist circles as energy production, materials flow, climate science, resource economics. Specifically, I look for *sources* of values in extant beliefs and cultural norms that can be appropriated to accelerate the transition.

I look for value sources not to win the debate, not to condemn defenders of business as usual, not to sort out the ‘good guys’ and ‘bad guys’. Rather, it is from an examination of values, asking such easy-to-ignore questions as what is the purpose of energy, of an economy, of growth, that insights might be gleaned into the exit from fossil fuels. So, I claim, it is values or, more precisely, the careful adaptation of extant values to new needs that is the prior step in a positive, accelerated transition out of fossil fuels and into renewables. It is values which determine what should be done with the fossil fuels that are still in the ground, fuels that could be used to boost GDP or save lives, fuels that could further degrade the environment or be used to develop renewables and even obviate certain energy needs. Clearly, criteria are needed for using fossil fuels, for guiding the transition.

The vision I wish to sketch here is one of *cultural transition*, prompted by, but not primarily about, energy transition. Because visions are easy to dismiss as idealistic, I should be clear that this vision is realistic in two senses. First, the material and cultural change will be dramatic and unprecedented, especially for high-consuming societies that will have much to ‘let go of’ – for example, the elixir of growth (material growth tightly coupled to economic growth) for solving so many problems including the problems of growth.

Second, humans at all socio-economic levels are resilient, they have the capacity to adapt and to thrive (an assertion backed up, as I read it, by substantial literatures from biology to history to psychology), both individually and, most importantly, collectively.

I offer three concepts to elicit potential sources of values for that resilience and thriving in an accelerated, cultural transition – principles of social organisation, resource ethics and environmental worldviews.[1]

Social organising principles

Societies organise themselves to find, extract, process, distribute and consume natural resources. For all that organising, they employ, explicitly or not, social organising principles. Principles matter from the playground to the trade floors, from families to global economies. They are the grand 'should' statements. They set the stage and guide behaviour. They enact values. They are successful, moreover, if they fit the needs of the times. In the past, the issue might have been establishing colonies and expanding trade, or spurring industrialisation and consumption, or prohibiting competitive trade practices and rebuilding a war-torn economy. The dominant principles were growth, efficiency, consumer sovereignty. These are arguably the very principles that got us into the current predicament. It defies logic to think that the same principles will get us out – that they will do the very opposite of what they were chosen for.

Now the issue is restoring the planet's life-support systems and transitioning to renewables. We need principles that fit the needs of these times – namely, living on the regenerative capacities of current resources and waste sinks. So here I offer three such principles. These principles are, arguably, 'ecologically consonant', that is, attuned to how ecosystems actually function; and they deal with the human propensity towards excess. The values they express may not be 'modern', that is, resting on 20th-century mechanistic and expansionist assumptions about resources and waste sinks, but they could well be current, that is, 21st-century ecological and self-organising assumptions of living within our biophysical and social means, the cultural core of transition.

The intermittency principle

Buying produce in season, hanging laundry out when the sun shines, fishing when the fish are running are all common behaviours that require that one react to patterns of availability, anticipate future use, forgo immediate service at times, and adjust to the rhythms of others and of natural systems. In these personal examples, such behaviour feels normal. Elsewhere, though, in the ‘real economy’, normal is quite another thing.

Energy experts lament the fact that solar and wind energy are intermittent. They seem to agree that this intermittency is a terrible deficiency. But it is so only if one assumes that energy in our homes and stores and factories should be continuously available, uninterrupted and perfectly controllable, which is to say, like a machine. It is to assume that we, as its users, its end consumers, should never have to wait, never be without, never plan ahead, which is to say, we should be like a cross between a robot and a toddler. What energy experts see is, at best, a juvenile world, one where every impulse must be answered, every craving addressed, every desire satisfied. An economy so structured is an immature economy, one that takes as normal only what machines (if they could think) and immature humans would see as normal. It is a use-it-up-and-buy-some-more economy that is not economical at all. It is a wasteful economy, hugely wasteful, and not just of resources but of people’s ability to self-organise, to connect, to find meaningful work.

Energy experts see a world where every impulse must be answered

A mature economy would indeed be economical, ecologically, socially and psychologically. It would demand of its participants, its producers and consumers, as much as they demand of it. It would be demanding in a way wholly unlike the way it is today: consumers demand comfort, convenience, speed and low prices, and producers comply, no questions asked.

Intermittency is one such demand from nature. When the sun shines, we hang laundry out and solar cells generate electricity. When the wind blows, the laundry dries faster and the windmills pump more. When it’s dark we go to bed, and when it’s light we get up. When it’s summer, we have fresh strawberries and green beans. When it’s winter, we have strawberry jam and canned beans. An intermittency principle thus says that ecological services need not be continuous, let alone ever-abundant and cheap. Instead, they should fluctuate with natural and social rhythms. This kind of demand requires discipline, in the richest sense of the term. It says we can enact an economy of care, of doing well by doing less than the most possible, which takes us to the next principle: sufficiency.

The sufficiency principle

In a fishing community off the coast of Maine in the USA lobster catchers throw back lobsters that are fertile or too small or too big. They impose a six-month season on themselves. And when everyone up and down the coast was increasing the number of traps they set and causing a mutually destructive arms race in traps, they decided to limit their traps to 600 per boat. On top of all this, the state stipulated that only traps could be used, not trawls or submersibles or nets. The curious thing is that this lobster fishery is the healthiest in the North Atlantic, healthy biologically and healthy economically. This is curious, at least, to those who believe the best fishing is the most efficient fishing, the fishing that makes the most use of the resource and expends the least effort possible and generates the greatest return on investment (monetary return on monetary investment, that is).

What we see in this fishing community and many like it around the world is sufficiency in practice. It is doing well now and into the indefinite future by organising to do less than the most possible now. It may not be as profitable as it could be. It may not bring the maximum conceivable return on investment. But, in practice, sufficiency is not second best either. It is first best, given the desire, in this case, to maintain the fishery, the lobster communities and the human communities that depend on them, and given the desire to do so into the indefinite future.

So what is the sufficiency principle? Intuitively, it is that sense of enoughness and too-muchness. It is a sense self-evident at two extremes of scale. At the individual level all of us know when we've had enough sleep or eaten too much; at the planetary level, from the astronaut's view, we see that the earth's thin skin of life, like our own skin, can be perturbed a bit, but certainly not too much.

Organisationally, sufficiency goes beyond the intuitive to pose questions of enoughness and too-muchness in day-to-day operations. Sufficient organisations and, for that matter, a sufficient economy routinely challenge the tendency to grow beyond one's means and at the same time they look for opportunities to take downtime (for example, the six-month off season) and build in a buffer against overuse of a resource (for example, the 600-trap limit).

Sufficiency thus aims at excess. It is not sacrifice in the negative sense of the term, not second best. It is first best when users want to do well now and into the indefinite future.

The source principle

The source principle says that it is prudent to preserve the source. People can mine and manufacture, commodify and discard, but a sustainable society cannot destroy the source – a river's headwaters, a grassland's soil, a reef's coral, a forest's seed trees, a fishery's spawning ground, a grain's genetic stock, an atmosphere's chemical integrity.

The source principle actually plays out routinely in the economic realm, the dominant realm of modern life. In commerce, manufacturers and retailers alike protect their sources, their suppliers, by developing cordial relations or writing intricate legal contracts or vertically integrating ownership. They do this because they know how vulnerable they are if supplies don't arrive. Similarly, in economic development, governments build infrastructure – roads, communications, electric power – as the springboard from which industry and retail can launch. What is upstream, economically speaking, is precious, essential to protect.

If the sources of manufacturing, retailing, and economic development are self-evidently in need of protection, then, in an ecologically sustainable world, so too are natural sources, the water and soil and atmosphere that are the logical and ultimate upstream origin of all that is human-made. But, unlike most economic sources, natural sources are the ultimate material sources. They have no substitutes, they can be irretrievably lost, and so they must be absolutely protected: biophysical ultimates require social absolutes.

Spiritually speaking, ultimate sources are sacred. To sacrifice an ultimate resource is a sacrilege. In contrast, to sacrifice the benefits otherwise derived from using up an ultimate source – to refrain from stripping topsoil, from draining an aquifer, from driving an organism to extinction, from opening the ozone layer, all for commercial gain – to sacrifice these benefits is to elevate human action. It is to reach the highest form of restraint in humans' material relations, to find humans' place in nature. Or, as writer and farmer Wendell Berry puts it, it is to preserve the ends in the means. It is to achieve purpose in life, to connect with the larger world, to gain meaning by protecting the means to the good life, especially the ultimate means which in the material, ecological world are sources.

Another writer, Edward Abbey, was once asked if there is a shortage of water in the desert. He said no, there is no shortage of water in the desert; there is just the right amount. We might go on to say that if there is any shortage, it is in our proclivity to live within our means on this one and only planet. It is there that we must adapt to the fluctuations of nature. It is there that we need to find enough, and not too much. It is there that we have to accept that some things have no place among living things and should be capped or banned. And it is there that ultimate sources cannot be sacrificed, precisely because they are irreplaceable and sacred and should be treated as such.

Intermittency, sufficiency and sourcing may appear unduly demanding, but probably no more so than the demands on those who created a nation or promoted industrialisation or fought for abolition and against totalitarianism. Certainly these principles are at least as sensible as the observation that there is just the right amount of water in the desert. This is because these principles are aimed at fit – at fitting human's material system, its 'economy', to the requisites of the planet's regenerative systems, not the other way around. And while they may apply at any scale – local, regional, national, international – they aim at place, at the very foundations of an economy. What's more, they all embrace a notion of limits, just as the earth and its inhabitants and its cycles of water and nutrients and seasons exhibit limits. They thus imply an encompassing approach to resource use values, namely, an ethic of use.

A fossil fuel ethic

So for the second conceptual source of transition values, I focus here on one crucial question regarding the cultural transition: how to turn away from fossil fuels.[2] Put differently, what value configuration would lean society in that direction? The starting point is to assume that accelerating a society's withdrawal from oil, gas and coal dependence, ahead of a geologic imperative, ahead even of economic and financial imperatives, is ultimately an ethical act.

A moral confrontation with a wildly successful material order

It is a politics (as in the shaping of society's core values and steering a particular path) of temporal extension, of taking seriously humans' past and future, including their geologically and ecologically distant past and future. Temporal extension necessitates ethical extension – from resources to ecosystems, from extraction to regeneration, from human life to non-human life, from us to other, from present generations to past and future generations, from material gain to societal integrity and spiritual uplift, from goods-are-good-and-more-goods-must-be-better to the 'good life'. It is in part conceiving of *an ethic of fossil fuel use that would be compatible with phasing out that use.*

Transitioning away from fossil fuels entails more than hastening the next energy transition, more than arresting climate change, more than shifting to a post-industrial world. It is a moral confrontation with a wildly successful material order, an order that has heretofore been presumed net beneficial, salutary, indeed essential and just. There has long been an ethic of fossil fuels, however implicit, however submerged in the political discourse, however 'natural' its constructors have made it out to be. Now, for the transition, a new ethic of fossil fuel use is needed, which would have two faces: first, the reconstruction of the fossil fuel ethic from net beneficial to net detrimental; and second, from total use to special use. I call the resulting politics 'delegitimisation' and 'making special'.

The current fossil fuel ethic begins with an implicit normative stance that industrial societies have adopted: fossil fuels, like other valued resources, must be used. Like standing timber and fish swimming freely in the sea and fresh water flowing across the land, a resource is of 'no value' until it is extracted, processed, distributed and used. And completely used; anything less is a waste, inefficient.

In this, the dominant construction of resource use, the age-old notion of dominion combines with a theory of use value and a principle of efficiency to create an ethic of total use: *A resource should be used, not left in place; it should be used completely, as much as markets demand and technologies allow. To do otherwise would be to waste a useful substance.*

If an ethic of total use made sense for renewables – timber, fish, water – it certainly did for non-renewables: what good is coal or oil just lying underground? It doesn't grow or propagate; it doesn't improve on its own. It just lies there, worthless. Got to use it, all of it, as much as people want and as much as we can get out, given the geologic facts, the technologies, the economics and the politics.

It has been a powerful ethic. It has created previously unimaginable wealth, including material abundance for all who partake in its fruits, which is to say a very large portion of the earth's population. What is more, it has conferred great power on those who play the game well. It has created a politics where key players write the rules of the game, obtain access, and do very well for themselves and their constituents. It is a politics where conflicts can be swept aside as all boats rise. The dominant resource ethic is, in short, one of growth, of economic growth tightly coupled to material growth, an ethic only now analysts and policymakers are learning is dependent on cheap fossil fuels – cheap economically, cheap energetically, and cheap environmentally.

To move toward a fossil fuel ethic for the transition, it is helpful to pose the ethical dilemma thus: *If it is patently wrong to burn all available fossil fuels in the coming decades (wrong because human life is severely diminished), then how can it be right to burn another barrel of oil, another lump of coal today?*

There is a simple answer to this question: if each unit of fossil fuel is wrong to burn today then we should stop now. Upon a bit of reflection, this answer is ethically unacceptable. To do so would, of course, wreak great havoc, the extent and cruelty of which is impossible to measure, or imagine. In other words, to abruptly and completely stop using fossil fuels now, when fossil fuels comprise some 80% of all energy consumed worldwide, would be to trade one global calamity for another, a primary difference being the timing – now versus the future.

But to stop using fossil fuels now is only a thought experiment. It won't happen, even if incontrovertible evidence arose that said such use is taking us promptly to oblivion. Fossil fuels are the ultimate path-dependent commodity. They are the proverbial 'lifeblood' of industrial society. But because continuation along this path is ultimately destructive of industrial society, indeed of livelihood and life as we know it, humanity *will* stop, or severely diminish fossil fuel use at some point, one way or another, planned or not, equitably or not. The question is not when we will stop, or should stop, but when will we start stopping. That in turn raises the practical question of how to *start stopping.*

This framing – how do we start stopping – goes to the crux of the current ethical dilemma with respect to fossil fuels and their mix of extraordinary benefits (historically speaking, their one-time existence makes them literally extraordinary) and extreme costs (death and destruction experienced by, among others, automobile passengers, asthma sufferers, miners and rig workers, and casualties of war). What's more, start stopping is a notion that has been around at least since Sheikh Yamani, the Saudi Oil Minister, quipped in the 1970s that the Stone Age didn't end for lack of stones and that the oil age will end long before the world runs out of oil. Then, and for several decades since, that end was so far out of sight, so much in the distant future, so uncertain, that no one really had to take seriously the nature of the end of the oil age, let alone consider the cultural dimensions of the transition. Now, however, with one scientific study after another, that future is, with increasing certainty, now. By asking about purpose and values, we gain a degree of control of that future. In the 20th century it may have been control over the environment. But now it is necessarily control over our choices that is at issue. We can choose business as usual or we can choose fundamental change. We can choose incremental adjustment or we can choose to start stopping.

Start stopping

The crucial question is thus not how and how much to reduce fossil fuel use (the current political dilemma), nor even when to stop using fossil fuels (as if the matter can be deferred to the 'right time'), *but how to start stopping now.* Ethically, each barrel of oil and each lump of coal burned is wrong. But each unit is also right because otherwise lives will be diminished and destroyed. So, because of the reality of extreme path dependency in industrial societies for fossil fuels, and because lives will be diminished and destroyed without fossil fuels (just as they are currently being diminished and destroyed with fossil fuels), criteria are needed for using fossil fuels in the transition out of fossil fuels.[3] I posit three criteria, each of which elevates one set of values while depressing another set:

Life saving. This first-order ethical criterion says that another unit of fossil fuel burned is justified at present if lives are protected – if it is the ambulance, hospital, fire station, police station or army base that uses that unit of fossil fuel; or if the desperately poor can subsist another day because they use that unit; or if the victims of an attack can repel the aggressor with that unit.

Transition. This second-order ethical criterion says that if the next unit of fossil fuel to be burned at present is for the purpose of making the transition out of fossil fuels, if it enables substitution of renewables, for instance, or obviates the need for its use (for example, more insulation obviates more heating fuel; a localised food system obviates centralised production and costly transport), then that fossil fuel use is justified. It is justified because it protects *future lives*, lives that would otherwise be diminished or destroyed with continued fossil fuel use.

Livelihood. This third-order criterion aims at ensuring people's capacity to self-provision, to associate, to thrive. Notice that while this criterion may be a top development objective, here, as a fossil fuel transition objective, it is subordinate.

The effect of this strategy would be to delegitimise current fossil fuel practices – that is, extraction and combustion rates beyond anything remotely assimilative by known waste sinks such as the atmosphere and oceans, let alone living bodies.

By delegitimisation I do not mean a vilification of the fossil fuel industry or blaming drivers of gas-guzzling vehicles or ‘all of us’ because we all use fossil fuels. Delegitimisation simply recognises that a substance once deemed net beneficial can become net detrimental. It starts with the observation that there are some things humans cannot handle. Their level of understanding, their susceptibility to convenience or power, their inability to organise globally and for the long term all mitigate against having such things as ozone-depleting substances, drift nets and landmines. For fossil fuels, humans are now demonstrating that it cannot handle these rates of extraction and combustion. So delegitimisation reconceptualises fossil fuels or, to be precise, humans’ *relations* with fossil fuels, how we *use* fossil fuels. It says that now, with today’s accumulated knowledge and with a complexity of threats that jeopardise human existence, it is time to drastically reduce the rates and the practices and impacts that go with them. It is time to fess up to the impossibility of marginal improvement: just as more humane shackles didn’t address slavery as an institution, nor filters on cigarettes the industrial tobacco culture, more efficient cars and high-tech clean-up technology won’t address the system-jeopardising properties – physical and social – of fossil fuels.

But, crucially, the strategy of start stopping implied by these ethical criteria would at the same time legitimise or ‘make special’ modest rates. Such rates we might then call sufficient with, say, intermittent use and protection of critical sources and sinks, from water and soil to the atmosphere and oceans. Making fossil fuels special would be analogous to how we treat certain drugs, useful, even essential up to a point, destructive thereafter. How to think about this is my next topic.

Making fossil fuels special

What is special at this historical juncture is the emerging necessity of living as if, as a species, we have just one planet, living as if, as a society, life is better when we acknowledge limits, indeed embrace them, and live within them. The evidence, scientific and experiential, is overwhelming: a significant number of people are living beyond their means. From a material throughput perspective, excess defines their lives, their economy, their politics. No substances are more implicated in, indeed more symbolic of that *excess* than oil, coal and natural gas. Or, put systemically, no human relation to a portion of its natural surroundings is more material to humans' well-being, now and into the future, than its relations with fossil fuels. Getting that relationship right will most certainly not cure all society's ills – after all, slavery, drug trafficking, torture and war preceded the fossil fuel era – but the hyper-energised, globalised, consumerised, overpopulated world we now inhabit is certainly visiting untold depredations on vast numbers of people and places, with more to come.

Humans' relations with fossil fuels can be special. But as highly distanced, commoditised, placeless global substances, they are routinely treated as anything but special. They are ubiquitous and cheap, available with the flick of a switch or the click of a nozzle. In the current order all uses are legitimate – growing rice in a desert, heating driveways in mountain resorts – as long as the user can pay for it (the consumer sovereignty principle at work). Interruptions are, like interruptions to food supplies, an offence no politician wishes to encounter. Intermittency, let alone a sense of enough and too much, are anathema.

So how would fossil fuels become special? Like fine jewellery or a dangerous weapon, the simplest way is not to use them, or use them only on special occasions for special purposes and to keep them under lock and key at all other times. To lock away fossil fuels is to say that we will use them only when we must, only when no alternative exists – including the alternative of non-use – only when we are sure, or as sure as we can be, that such limited use will not cause cascades of depredations across landscapes and through the body politic as they are now doing. Maybe it is time to resurrect the magic in fossil fuels, the early magic, the magic that made such substances indeed special.[4]

Updated for the 21st century, that magic would necessarily derive from highly limited use. Limits here would not be external constraint –

draconian, top-down, governmental measures, say – but self-imposed, internal restraint, that which ennobles and enlivens as people figure out how to live well on that which truly regenerates – fertile soil, recharging aquifers, crops and wildlife. Fossil fuels would be reserved for functions only they can perform. The magic of fossil fuels would then derive not from their scarcity (physically they are not at all scarce) but from their abundance, an abundance experienced as having plenty because their uses, so highly limited, are so special.

Making fossil fuels special would be a cultural act to complement the materials management acts of conventional policy making. Thus, at the same time a transition to a new era away from fossil fuels begins by *delegitimising* fossil fuel use, the old era ends by *celebrating* fossil fuels too. The delegitimisation is about excess rates, the celebration about the remaining modest rates. The result would, of course, be a profound cultural shift, precisely what is needed in a time of great urgency and policy deadlock.

Making fossil fuels special would be the antithesis of sacrifice or ‘doing without’ or retreating to the past. It would be ‘letting go’, but in the higher sense of doing well now and into the future by deliberately using less fossil fuels, much less, than the most possible now. The energetic basis of the good life, then, would be relying mostly on regenerative sources, keeping within their regenerative capacities, and, when the occasion demands, a bit on fossil fuels. Fossil fuel use via protected sources and intermittent use would make fossil fuels an integral part of a sustainable society, not a diabolic hindrance to such a society.

Worldviews: Constructing adaptive capacities

Imagining a sustainable and just role for fossil fuels is one thing, enacting it another. Since the dominant ethic is total use with its implicit 20th-century principles of growth and efficiency, where would we find the values for such a 21st-century fossil fuel ethic? One source, I suggest, is worldviews. Worldviews frame perception, shape behaviour and emphasise certain values over others, all of which is a means for adapting to new circumstances. All humans have worldviews of the environment.

For some ‘the environment’ is simply all that is outside one’s skin. It may be literally worldwide in scope (say, the astronaut’s view of the blue planet) or just that which one perceives in daily life – one’s home and neighbourhood, place of work and worship, playground and café. For others ‘the environment’ is the natural world, especially the parts that are untrammelled by humans.

Worldviews are indeed views, what we see and what we do not see. Each has an optical range, a perceptual field. In the tropical jungle, we don’t see the office towers where people decide to cut the jungle’s trees. In the urban jungle, we don’t see the tropical forests cut to build our houses and fire our furnaces. So where we stand determines what we see. To this extent, worldviews are *chosen*: where we cast our gaze largely determines what we believe exists and what we do to construct a liveable world.

A worldview is both physical and conceptual. And because it is necessarily selective, it is normative: it incorporates and expresses values. We humans are not limited to one worldview. We acquire different views from early childhood, unknowingly for the most part, but we change them as conditions require. Even if one worldview is dominant (it’s a dog-eat-dog world out there; humans are gregarious and naturally co-operative), we also hold others, and we draw on each as circumstances warrant. So just because the tropical jungle dweller and the urban jungle dweller occupy vastly different worlds, there is no reason to assume their worldviews are incompatible.

So worldviews are chosen, but not all at once; they are not ready-made. What is chosen is constructed, deliberately fashioned to serve a purpose. Worldviews are the binoculars that connect humans and their sense of self to their surroundings, their environment, their world. With the chambers and lenses of a worldview, we ‘see’ a world literally – that is, visually and through our other senses – and we ‘see’ a world in the sense of understanding it, of making sense of it, of distinguishing what is important and what is not. People have multiple worldviews, including conflicting views, and those views can change, separately and in combination.
An individual or a society is well adapted when its shared collection of

worldviews connects to the physical and social environment and when it can shift worldviews as the physical and social environments shift, all to enable people's surviving and thriving.

Four worldviews of the environment

In the current industrial, commercial and expansionist order, four worldviews of the environment can be discerned. I will call them naturist, agrarian, mechanistic and economistic. Each is an 'ideal type', a stylised, polar-case construction meant to highlight particular features. And each has a field of view, a focus of attention, a timescale, and a set of archetypal actors.

In the *naturist* worldview, 'the environment' is all about matter and energy and living things, all out there that is 'natural', all that would exist whether or not humans exist. The field of view ranges from the subatomic to the universal. The focus of attention is on knowing this environment, on modelling and explaining physical laws, chemical bonds, organismal development, speciation. The timescale ranges from the lifespan of a quark to the lifespan of a galaxy. Archetypal actors are physicists, chemists and biologists. Those actors who have cross-cutting focuses – the paleontologists, ecologists and atmospheric chemists, for example – approximate the knowledge essential to ecological practice. Yet in this ideal type worldview, the focus is not on practice but on knowing, on analysing, describing, explaining and predicting the natural world – that is, primarily a non-human world.

In the *mechanistic* worldview, the environment is a system of interlocking pieces of atoms and molecules, land and water, minerals and organisms, tectonic plates and magma, all in place and in motion according to the laws of gravity and thermodynamics and quantum mechanics. As with a machine, the pieces fit together yet can be rearranged. And like a machine, the environment can be rebuilt, made better, and entirely new ones can be built as well. The field of view includes all that can be manipulated, traditionally everything from agricultural plants and animals to rivers and mountains. The focus is on arranging the environment for beneficial human use – that is, intervening and managing. The time frame ranges from hours and days (for example, food) to decades (for example, buildings). Archetypal actors are engineers, planners and architects.

The naturist and mechanistic worldviews of the environment explicitly encompass the natural world (unlike the economistic; see below) and yet are poles apart in their ideals – knowing versus manipulating, understanding pristine nature versus creating a new nature.

The *agrarian* worldview of the environment is, like the mechanistic, interventionist and managerial, yet its knowledge is acquired through practice and for the purpose of enhancing practice – agrarians' own practice and that of their community. Direct interaction with the land – farming, fishing or logging, for instance – and direct social relations within their residential community are the bases of that knowledge and practice. What's more, that knowledge and practice accrue and evolve over a lifetime and across generations. Like the naturist view, the agrarian view is inherently cross-cutting, even holistic, and long-term. Unlike the naturist, however, and more like the mechanistic, the agrarian view has the goal of resource use, of material provisioning, all for human sustenance.

For the agrarian, consequently, nature is 'in here' – in a crop's yield, in a stock animal's birthing, in a fish's attraction to bait. And it operates on a limited scale: its field of view is that of the practice itself, not watersheds or bioregions, let alone the planet, but the farm or the fishery or the timberland. While the naturist worldview aims to be all-encompassing (systemic, universal, sometimes holistic), the 'nature' of relevance to the agrarian is only that which can be manipulated and that affects one's harvest – the soil, seed, livestock, sunlight, moisture, ocean bottom. Its focus, therefore, is yield. Archetypal actors are farmers, fishers and loggers.

The *economistic* worldview of the environment is also one of the material world, but not the entire material universe, only that of human exchange, of producing and consuming. It is products and services that are of interest, not atoms, molecules and energy, let alone living systems. And it is all about transaction, about buying and selling, investing, pricing, retailing and purchasing. It is, above all, about the clearing of markets and the efficient allocation of resources, physical and human. Its field of view stretches from one side of the input-output model, where raw material enters production, to the other, where wastes exit – that is, from sources to sinks. If either sources or sinks become scarce, rising prices via the market stimulate new sources, new sinks and substitutes. Its focus, therefore, is price. Its temporal scale is short-term, even instantaneous; it systematically discounts the future (through the 'discount rate') and ignores the past. Archetypal actors are economists, planners, policy analysts and investors.

The economistic worldview of the environment has no natural or ecological component; everything of concern is reducible to money or hypothetical 'utiles', and all is substitutable. But its dominance in modern life (along with the mechanistic) warrants inclusion in a framework of worldviews aiming at an ecological order.

The adaptiveness of worldviews

These four worldviews of the environment – naturist, mechanistic, agrarian and economistic – are starting points for action. They are among the overarching systems of perception, belief and value from which an individual's and a society's resource behaviours stem. They are not determinative, but they frame perception and shape behaviour. They set what is expected – what is normal and what is deviant. And they provide the raw material to build the institutions and the language for major goals such as transitioning out of fossil fuels and into renewables. Significantly, they can adapt to new circumstances and new knowledge if two conditions are met. First is a major perturbation – a life-threatening event, for instance, or a dramatic shift in income. The second is external support, a family or a social institution that reinforces the requisite new perceptions, beliefs and values.

To illustrate, imagine that an engineer worked all his professional life on the levees surrounding New Orleans in the USA. He measured and calculated constantly, supervising new construction and maintenance. He long advocated Category 3, even Category 4 hurricane protection. He firmly believed that whatever the weather event, a levee system could be built to withstand the forces of nature. And he knew that his work was an important contribution to such a system. Then along comes Hurricane Katrina. After the shock of all the destruction and after new calculations he comes to the conclusion that no levee system can be as foolproof as he once thought. In fact, after talking to numerous ecologists and hydrologists and joining the Society of Ecological Engineers, he now firmly believes that the only way to protect New Orleans is to reconsider the channelling of the Mississippi River upriver and the draining of the delta downriver; in other words, he now sees that protection is an issue of the entire watershed and, with climate change, eventually the entire planet. He still works on the levees, measuring and calculating: it's what he does; it is his work. But he now views his world differently. He has shifted from a predominantly mechanistic worldview of the environment to one that includes a naturist worldview.

So what shifts are most useful for the transition? As much as some sustainability proponents would like to see a wholesale societal conversion to a completely new worldview grounded in, say, the naturist worldview (especially its cross-cutting ecological variant) or to the agrarian (especially the food-growing variant that challenges industrial agriculture), a premise here is that the economistic and mechanistic are too deeply embedded in modern industrial societies. Moreover, although the economistic and mechanistic may appear completely antithetical to the goal of ecological sustainability, each has elements compatible with the naturist and agrarian. The key analytic task is not to pick the winning view but to specify the criteria by which the elements of existing views are selected for decision making and institutional design. Because the fundamental concern is living within our ecological means, the selection criteria must be rooted in the biophysical, the ecological, and these, it turns out, are best represented by the naturist and the agrarian.

How, then, would the economistic worldview contribute to a sustainability worldview? Consider finance, a subset of economic activity where there are time-honoured maxims to counter the human tendencies to overspend, to put all one's eggs in the same basket, to draw down one's account, to spend now, pay later. These tendencies and the problems they generate for the individual and society are analogous to drawing down a natural resource, harvesting as if there was no tomorrow, killing the brood stock, eating the seed corn. The following financial maxims are thus analogous to ecological imperatives:

- Spend within one's means.
- Diversify the portfolio.
- Draw on the interest, not the principal.
- Balance the budget.

To illustrate, investors know well the wisdom of having a diversified stock portfolio. So do community and national planners: single-product economies are inherently unstable, prone to collapse when consumer preferences shift, capital moves elsewhere, the economy takes a dive, or new technologies replace the product. Imagine the dependency of a company town that produces one thing, such as timber, by one company or a country that exports one commodity, such as oil or bananas. But just as economic diversity protects investments and jobs, ecological diversity protects the natural resource base. Applying a diversification principle to agriculture, for example, would raise serious questions about the wisdom of monoculture farms that cover vast acreages or plantation timbering with ever shorter rotations. Applying a spend-the-interest-only principle to groundwater would challenge the tendencies to increase pumping rates regardless of recharge and to search for 'new sources' of water. I am obviously only selecting a portion of the financial world, what might be better termed 'classical finance', that which has ancient roots – insuring, saving, investing, diversifying.

Other worldviews can be similarly refocused and combined. The crucial first step is to identify segments of the worldview that appear to have ecological and social content, that is, that correspond to identifiable processes and constraints and thus point in the direction of a stable, long-term ecological order. The next step is to combine two or more such segments and derive principles and metaphors for sustainability. For example, the naturist view has an inherent notion of limits, whether of energy (the laws of thermodynamics) or of ecosystems (a range of operation beyond which the system 'flips') or of individuals (a range of temperature and water tolerances). The agrarian has a notion of husbandry (caring for natural elements so as to supply human necessities) and cycling (crops need rotating, animals need rest). These two notions lead to principles of sufficiency and intermittency (see above).

In short, this non-exclusive, pluralist and dynamic approach to worldviews is one way of saying that individuals and societies are, or can be, resilient by being adaptive, that what worked in one era (localised husbandry in the agricultural period; expansion in the age of exploration; mechanistic reasoning in industrialisation; economistic reasoning in the commercial, consumerist period) can shift in another era, in one driven, for instance, by biophysical constraint. Moreover, it suggests that many worldviews of the environment, not just the naturist or agrarian, say, are potential sources of values for positive transition. It is the shift in worldviews, supported by institutions and language, by social organising principles and ethics, that leans behaviour away from mining and toward sustaining.

The adaptability that inheres in a pluralist approach to worldviews may be the crucial feature of a positive cultural transition. It is that ability to cope and create, individually and collectively, and at all levels of society, rich to poor, intellectual to manual, that is arguably needed. It is not enough for elites to define the problem, offer solutions, and 'get people to behave right'. Rather, a social organising principle, a resource ethic, and a worldview can be chosen, deliberately constructed and embraced, as previous principles, ethics and worldviews have been. There is nothing about the current set that makes it superior or permanent or that represents a culmination of cultural development. The current set may have been well adapted to '20th-century' conditions – that is, cheap and expanding supplies of concentrated energy, near costless waste deposition, and an inability of 'downstream' populations to effectively resist. But those conditions no longer pertain, not for the transition anyway. The 21st century is a time of learning to live within our means, biophysical and social, and for that values sensitive to ecological relations, biophysical limits and humans' propensity toward excess are necessary and possible. This is a realistic yet demanding possibility.

In the end, then, transition, at once energetic and cultural, will occur; a path will be chosen. That path will be positive to the extent it draws on what is known about human behaviour, individual and collective, that makes for healthy individuals and communities, namely, that humans are at their best when they are faced with a genuine challenge, are creative and productive, find meaning in their own problem solving and in acts larger than themselves, help themselves and help others, self-organise and self-govern and feel they are getting a fair shot at the benefits of their work. And that path will be adaptive to the extent it draws on values in extant worldviews to develop principles and ethics that are ecologically consonant and sensitive to excess.

For all the contestation now, with more to come, for all the wrenching change likely as high-consuming countries downshift, the transition itself may be a welcome challenge, a chance for some to express values long suppressed in a growth-obsessed, consumerist, high-speed, unequal world. The transition may be an opportunity to reconnect with others, with natural systems, and with higher values, including the ethical and spiritual. The transition may be just what the world needs – fossil fuels that are special, renewables that are indeed renewing, and people who are resilient because they know the abundance of enoughness.

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Thomas Princen explores issues of ecological and economic sustainability at the University of Michigan, USA. He is the author of *Treading softly: Paths to ecological order* (2010/2013) and *The logic of sufficiency* (2005), and lead editor of *Ending the fossil fuel era* (2015) and *Confronting consumption* (2002), all published by MIT Press.

Notes and references

1. For elaboration of many of the arguments of this essay see T. Princen (2005), *The logic of sufficiency* (MIT Press: Cambridge, MA); Princen (2010), *Treading softly* (MIT Press: Cambridge, MA); Princen (2014), *'The politics of urgent transition: Fossil fuel exit and the localization of attention'*, in Y. Wolinsky (Ed.), *US climate change policy and civic society* (CQ Press: Washington, DC); T. Princen, M. Maniates & K. Conca (2002), *Confronting consumption* (MIT Press: Cambridge, MA); and T. Princen, J.P. Manno, P.L. Martin, Eds. (2015), *Ending the fossil fuel era* (MIT Press: Cambridge, MA). For helpful comments on earlier versions of portions of these arguments I thank Tim Kasser, Raymond De Young, Gert Jan Kramer, Jack Manno, Pamela Martin and Adele Santana.
2. By posing the question as 'turning away' from fossil fuels, I am assuming that *promoting* renewables is not enough. For elaboration of this assumption and its implications for 'going to the source' and eschewing 'end-of-pipe' solutions, see 'The problem', Chapter 1 in Princen, Manno & Martin, *Ending the fossil fuel era, vide supra.*
3. Notice that the posed ethic is an ethic of *fossil fuel use*, not of conservation or climate stabilisation or carbon distribution. Nor is it an ethic of the rights of nature or intergenerational equity. It is simply about using fossil fuels with the premise that indeed we will continue using them at some level, like it or not, safely or not, and we will be transitioning out of them at some rate. The question here is under what conditions is their use justified, given that continued use, at current or near current levels, will be catastrophic.
4. See Princen, 'The culture of fossil fuels', in Princen, Manno & Martin, *Ending the fossil fuel era* (ref. 1 *supra*) for elaboration of the magic and mystery of fossil fuels and the politics thereof.

Redefining progress
What our ancient roots teach us about humanity's dominion over nature

Humanity has pushed back the wild and subdued the Earth, with mixed results. We built civilisations, but nature paid a price. We need to rethink human rule over nature and the religious traditions in which it is rooted.

> *Jan J. Boersema*

The mastery of energy has fuelled progress. An ever-increasing use of energy in ever-denser forms powered our ancestors and enabled them to advance. Energy and progress have been intimately connected. This means that reflections on the energy transition will eventually touch on our perception of progress. This requires an examination of both environmental and religious traditions of thought.

A central notion in both traditions is the dominion of humanity over nature. Our religious texts call us to exercise power over the Earth and tame the wild. “Thou hast given [man] dominion over the works of thy hands; thou hast put all things under his feet, all sheep and oxen, and also the beasts of the field, the birds of the air, and the fish of the sea, whatever passes along the paths of the sea.” This psalm tells us how man is master of creation. “Thou hast made him little less than God.”[1]

The US historian Lynn White famously held that this belief opened the way for people to exploit nature for their own ends. In a seminal article in *Science* he argued that the ecological crisis was rooted in Judaeo-Christian thinking. The solution for this crisis, White stated, will not be found in the application of more science and more technology: “Since the roots of our trouble are so largely religious, the remedy must also be essentially religious, whether we call it that or not.”[2]

The dominion of man over nature has now indeed taken devastating forms. We have burned the treasures of the earth, the air is pregnant with hazardous substances, and the seas are increasingly devoid of fish. Are these the inevitable consequences of humanity’s dominion over creation? And do we need a religiously inspired cure for the ecological crisis? It is time to reread ancient texts and rethink the religious roots of our societies.

The battle against nature

The biblical command to “subdue the Earth”, given in the first creation account in Genesis 1, *does* indicate a special position of the human being. Humanity had to secure its own place on an Earth full of difficult and hazardous natural conditions. The command to rule the Earth in Genesis is joined together with the task to “be fruitful and multiply”. That has to be understood in a context where it was hardly possible to increase the population of the Earth. Until remarkably recently, parents who had seven children often managed to keep only one or two alive. There was actually not much growth for thousands of years, until about 1750. The biblical command to multiply and subjugate the Earth came with a promise that the Earth would be made habitable and humanity would take and hold its place in the world.

My fellow countrymen can attest to the struggle that this involves. It requires a constant battle to keep the water out and protect harvests and lives. It’s sink or swim. Or, as the Dutch expression goes: pump or drown. The early Dutch knew very well that their low-lying moors needed a common effort using mills and pumps to keep the environment habitable. Anyone who wants to live in the Netherlands takes part in action against nature. Humanity needs to control nature and is entitled to do so. With land ‘reclamation’ something is claimed back that somehow did belong to us.

That battle against nature is not exclusively Dutch, of course. Similar stories could be told for the United Kingdom, Italy and other European countries. The German engineer Johann Gottfried Tulla (1770-1828) describes the Rhine as a snake, a dangerous beast that winds through the German countryside. Those who know the role of the serpent in the loss of paradise will understand the sentiment that snakes must be conquered. So the Rhine was channelled – partly by Tulla – between Basel and Bingen. The Rhine was shortened by 75 kilometres in the first half of the 19th century at the expense of one of the largest river ecosystems of Europe. Afterwards, however, the river was barely safer for residents or more navigable. It had to be constantly dredged. Tulla felt that intervening in nature necessitates a continued involvement.

The intervention in nature was accelerated by the use of different energy sources. That not only helped with pushing back water, as the many windmills and pumping stations in my country attest. Places become habitable by taming fire and heating and cooling houses. The ability to make the Earth more habitable with the application of energy is exemplified by the development of Houston. It used to be a sleepy little town, but the advent of air conditioning made it a bustling industrial city. The availability of cheap and abundant energy has boosted food production, helped increase the world's population and empowered humankind to invade the wild.

There is nothing intrinsically wrong with dominion over nature. Most of us wouldn't accept people being eaten by a tiger, freezing in the snow, or falling victim to a storm surge. We need to accept some control over the wild to secure our own lives. Somehow the wilderness needs to be fenced up. Our relationship with nature always includes a requisite form of dominion.

All animals are included in the salvation

Dominion over nature has brought great benefits. We have surrounded ourselves with, for example, fruit, cattle, vineyards and fig trees. Nature has acquired a people-friendly, domesticated side, which we find enjoyable. That is the kind of nature that falls under our care. It needs continuous management to keep it domesticated.

Not accepting any form of dominion would do away with what it means to be human. It would also mean that humanity has no responsibility whatsoever for life on Earth, no more than the ant. This extreme eco-centrist position, in its purest form, is simply untenable.

Our Greek roots

The biblical command to have dominion over the Earth, as contained in the first chapter of the Old Testament, was never intended to justify exploitation. Just a few lines later in the same story, man is portrayed as a vegetarian. The rule over nature is not intended as a slaughter. This limitation of humanity's power appears most clearly in the story of the flood. The theme of a big, devastating flood is taken from Mesopotamia, but the authors of the Bible gave their own twist to it. Contrary to the narrative that they drew on, all animals were included in the salvation. Not just humans had to be rescued; instead, the whole of creation came aboard the ark. The flood story is one of horrific destruction, but it is also one of re-creation. The flood creates a new order, not a return to the primordial paradise, however. When Noah came ashore, the animals still needed to fear being eaten by humans and vice versa. Yet seven times, a covenant is announced and made with all living things, in many different ways. God has given living nature a prominent place on Earth and protects it against humanity. It is as if the authors of the Bible felt we should not eat everything, because we would touch too much of God's creation. The animals join in the weekly rhythm of the Sabbath. A draft animal has its right to pause and graze ("You shall not muzzle an ox when it treads out the grain", as it is written). All living creatures have an intrinsic value that can only be infringed upon out of real necessity. Humans shouldn't kill them recklessly, a notion that was later refined in the Jewish dietary laws. The 'man-made' extinction of a species thus poses a real problem.

Man doesn't get a licence to exploit nature for his proper ends, as Lynn White and many others have held. The instrumentalisation of nature rather has its roots in the Greek worldview, most notably in Aristotle's writings, that classifies nature in a hierarchy of utility. Greek philosophers are at the top as most valued. Other people rank below them; the lowest are those who do not speak Greek, the barbarians. Then follows living nature. What is lower has value because it is useful for the higher placed. A tree with edible fruit is valued higher than a tree with fruits that are not suitable for human consumption. Which is again higher than a poisonous shrub. Dead nature, with its minerals and stones, is at the very bottom. The awareness that something could be valuable without being useful is absent in this worldview.

So the utilitarian view of nature has Greek roots because we have read the biblical texts through a Greek lens. Yet even the Greek worldview doesn't imply that humans have a licence to use every last drop of oil, eat every last tiger, or slaughter the barbarians. That's why the philosophers are on top, as gentle, wise kings.

It is our faith in progress that has caused a derailment in our thinking about humans and nature. What started as securing our own place continued as a gradual process of expanding the territory of man. We have pushed the wilderness back ever further, to secure food, housing and an ever increasing array of material goods. In the Netherlands we have reclaimed land from lakes to grow grain. With each new piece of farmland, the yield increased, so that we could eventually export the crops and earn money. This expansion of territory was real progress, but soon such growth became addictive. By increasing our material wellbeing we have, little by little, also steadily increased the amount of territory we have taken from the natural world.

We now know how this led to the overuse and depletion of nature. Yet that doesn't mean that progress itself is bad. Humanity's work has also been very beneficial. The Anglo-Dutch economist Angus Maddison has precisely documented the benefits of progress over many centuries.[3] To name a few: in the developed world, infant mortality and child labour have been dramatically reduced; we do not have to work 14 hours a day for a living; we have reduced illnesses; we live twice as long as two centuries ago. Many take it for granted, but the progress we have made has been spectacular.

Yet, where chasing progress has led to environmental destruction, we have pursued it too narrow-mindedly.

Rethinking progress

The idea of progress is deeply interwoven with a view of history, as an unfolding process with a past, present and future. Time – and history – are viewed as proceeding like an arrow. Humanity develops into ever new experiences. Part of the inheritance that the old narratives from Israel gave to our Western culture is this linear notion of time. The world had a beginning, after which God leads Israel into the future. In some stories this is literally the case, as with the fiery cloud which leads the journey through the desert. It is this linear notion of time that provides hope for improvement and makes working on advancement a sensible undertaking. It also constituted fertile ground for eschatological expectations and utopias.

The linear notion of time was also promoted by those who shaped the Christian church, including Augustine (354-430). The history of the universe is "not a repetition of the same world, but different worlds succeeding one another in a regulated connection".[4] In the Early Middle Ages this idea was lost for a while, when there was a strong orientation on the past, but at the end of the Middle Ages and the early Renaissance, the whole idea of linearity surfaced again. Newton famously said that he stood on the shoulders of giants. The ideas of cumulative development of knowledge also shaped the Enlightenment.

This linear thinking has acquired moral traits. Carroll Quigley, a college professor famously quoted by Bill Clinton, said that “the future can be better than the past, and each individual has a personal, moral obligation to make it so”. The linear conception of time calls for change. If the future can be better, we must make it better. We need to shape the future, developing our culture and the possibilities around us for future generations. This thinking has given our Western culture unprecedented dynamics. The imperative of progress is still omnipresent and alive. Everything can and must be improved and it is our moral duty to work on it every day.

In biblical texts the concept of time is not unambiguous. Also circular notions of time come to the fore. The familiar statement repeated throughout Ecclesiastes, for instance, that “there is nothing new under the sun” is a clear example of circular thinking. There are many more passages in the Old Testament indicating rhythm and repetition. The Sabbath rhythm is a repetition, but also denotes a new beginning, especially in the notions of sabbatical year and jubilee year. Early thought combined linear and circular thinking. This is even reflected in the Hebrew language. The word קדם (*qedem*) means ‘front’, ‘in the past’. And אחרית (*’aharít*) denotes both ‘back’ and ‘future’. This dual usage can only be understood if the future is linked with the past, like the sunrise with the sunset.

The image that emerges is that of a spiral. There are things that come back to life, but the general course of history is still growing, still expanding. This spiralling notion of time has been largely forgotten. Western culture has become so strongly focused on linear progress that it is almost impossible to bid farewell to it, but blending it with a more circular notion of time can help us to get a more beneficial concept of progress. It would acknowledge that going back and restoring the old order may actually help progress. This means that we needn’t see changes to our way of life in favour of nature as restrictions or as decline. Instead, it is a restoration of old relationships, as the Sabbath also symbolises. It is not a reduction, but continuity, and a good preparation for the future.

That is progress redefined. Not an increase in the enjoyment of luxury or the amount of goods that are piled up, but an advance in the well-being of human society. It is similar to giving up smoking. In the beginning it's refraining from something. But at some point you come to see it as a step forward.

This redefined progress goes against the general thrust of our Western culture. There is no deadlier remark in our society than "that's taking us back to the 1950s". Or even worse, "taking us back to the Middle Ages". And indeed, we shouldn't go back. Restoration of older forms shouldn't be a repetition of the past. We can draw inspiration of the community spirit of the 1950s, for example, while finding a shape for it that fits the 21st century.

In this broader idea of progress, we may find an alternative for reducing the wild and using up the resources of the Earth ever further. This new image of progress is already visible in the shift from an industrial society, built on the use of natural resources, to a society driven by services and where closing material circles is important. Crucially, redefining progress means accepting that human dominion is limited. It is the notion that all life has intrinsic value and that we can't continue to expand our domain at the expense of life on Earth.

Sustainability

Progress redefined is still progress. It is radically different from the circular notions that entered environmental thinking. Thinking 'from cradle to cradle' is far too optimistic, as closing the circulations requires energy, which at present doesn't all come from durable sources. This violates the second law of thermodynamics, and it denies the value of cascading material use. It is a false romantic, against a runaway economy. But more importantly, such circular thinking is based on an extremely static image of the world.

We frequently undertake activities which are irreversible. We build cathedrals and cities, we lay a high-speed rail track or build a tunnel under the English Channel. Do the Dutch have to undo the hydro-engineering works that turned the Zuiderzee into the IJsselmeer in order to return to the cradle of their country? Can we ever leave an Earth behind in a state that can be reversed? A circular image of sustainability is not only miles away from reality but is also undesirable – and only possible if every cultural and natural development is undone.

My broader concept of progress is closer to the idea of sustainable development, defined by Gro Brundtland as meeting “the needs of the present without compromising the ability of future generations to meet their own needs”. Yet this concept also has its problems. In order to take future generations into account we would need to know their wishes, notions, standards and values. Certain activities may now be seen as useful and positive, and therefore not limiting future generations. Yet that judgment is time dependent. Our forebears had no problem with digging up peat. Today’s world would be outraged if absolute rulers exploited thousands of workers to build mega engineering projects such as the pyramids the way they did in many ancient empires. So how would future generations judge the restrictions to the sea by hydro-engineering works?

Thinking about the future becomes thinking about ourselves

We can only guess what the needs of future generations will be – apart from some very basic needs, such as clean drinking water, sufficient food and housing, which give little direction to our actions. History tells us that major changes in the perception of needs are common. If future generations have needs that are very different from ours, it is hard to know how to take that into account. The philosopher Derek Parfit speaks in this context of a “non-identity problem”.[5] If you do not know what the needs and concerns of future societies are, it is also difficult to really take them into account. It then quickly becomes little more than ventriloquism.

The only reasonable assumption we can make is that future generations have roughly the same needs as we do. In that case, thinking about the future actually becomes thinking about ourselves and about past generations. Here again, the spiralling notion of time and a more circular thinking about progress is useful. We can think carefully about what went wrong in the past, which wrong tracks were taken, what we have overlooked and what the undercurrents are in our culture. Could we reconsider ideas that have been contested in the past? That is the best route to the future. “Respect for the dead is a foundation of social responsibility and a motive to care for the future”, as the conservative philosopher Roger Scruton wrote.[6] The best we can do is to use our present notions, and those of past generations, to spiral forward in a sensible way.

Cathedrals symbolise this perfectly. Why would we want to keep these beautiful but often large and difficult-to-maintain buildings? Out of respect for the past, not because of their utility or because we know that future generations will also think they are beautiful. Building cathedrals in the first place is not only an act of faith or a gift to future generations. They were built because the builders felt that it was necessary for themselves, knowing that they wouldn’t see the project completed. That’s part of what Aristotle called the concept of the good life. The idea that you contribute to meaningful values and virtues, and that you live in accordance with them.

Improving the environment is a key part of living the good life. It is just as essential as the differences between rich and poor and caring for one another. It is part of the type of society we want to shape. It is not an expense, but rather the innovative impetus for a different type of economy and a different way of dealing with the Earth and the people around us.

Changing our energy use wouldn’t require us to adopt a new religious thinking. Although almost all religions have their stories about fire, energy is less loaded with religious values than many other aspects of our life. Reshaping energy use doesn’t break taboos in a way that changing halal or kosher diets would. The neutrality of energy makes a consensus possible across religions, ideologies and lifestyles. In a way this is already happening. Those who live an organic back-to-nature life can agree with high-tech devotees on sustainable energy. When oil or chemicals are spilled in the sea, protests arise from both greens and conservatives. This doesn’t mean that energy is completely ideologically neutral. Nuclear energy, for example, is fought over from ideological positions. Yet this is only a sideline in the discussion.

The push to accelerate an energy transition could come from a broad coalition. Many different people may understand it as real progress. Such a clear choice may trigger many dynamics. If society really bets on the deployment of solar power, for example, new directions will be tried and targets will be achieved faster. Governments can agree with energy companies on the use of fossil fuels, with a reasonable transition period and compensation. If we had done that in 1970, we would have been a long way towards it already. Perhaps there will be setbacks in learning how to use solar technology or finding rare metals. But slowly, we can get closer to it.

Just as with the builders of cathedrals, we won't know how the end results will look, nor will we see them with our own eyes. Social changes go slower than many people think. In most European countries, women have had suffrage for a century. But women's rights to buy a house and other civil rights were equalised in the course of the twentieth century. Important social changes can take several generations. That is the kind of long-term thinking we need to have.

And we need the master builders to sketch future perspectives. The essay by Jorgen Randers in this book, uncomfortable as it may be, contains the hopeful prospect of a stabilisation of the world's population after 2050 at a lower level than many people think. It makes a huge difference if we have to feed half a billion fewer people. He also says that the world does not have to collapse, but that there may be a gradual decline. In short, there is a perspective to work for, and we can make it even better than he foresees, as his last sentence suggests.

Harmony and decline

Looking back, there are very few historic examples of collapsing societies. Even Easter Island, often cited as an example of environmental collapse, gradually adapted to a changing environment. The details as we now know them make it very probable that the islanders readjusted their lifestyle and created a new order in the face of disappearing forests.[7] The population may have shrunk and culture was no longer marked by eminent sculptures. Yet they had taken their fate in their own hands. Such ideological factors are easily overlooked if only the archaeological records are studied. Human society is more than what materialises. When the first Europeans – explorers from the Netherlands – visited the island, they reported healthy and happy inhabitants.

Humanity can stamp its mark on the course of history. That is also a leading thought expressed several times by prophets in the Old Testament, who imagined the end times as a return to paradise, a return to a harmonious relationship between humans and animals. The prophets desired that lion and lamb lie together. These texts offer the prospect of a reality that is more harmonious. We should not resign ourselves to reality as it is. Nature as we see it is not the norm for our actions. Jewish thinkers take us that far. They say that the creation is not finished and we are co-creators. We must complete the creation.

This restoration of harmony is also reflected in the life of Francis of Assisi (ca. 1182-1226). His preaching for the birds is often held as a sign of brotherhood of creatures and an indirect way to speak to the people of his time. Yet it was also a way to restore the harmony of paradise, before the Fall, revering the intrinsic value of all living things. In a famous story, Francis spoke to a wolf, which was devouring a village, with authority. As it also needed to get its food, the villagers would feed it from then on. That's dominion, but in a way that takes responsibility and restores harmony.

We are not saints, but inspiring examples can show us the right direction. If someone is living the good life, then it acts as an example. We can use our history, explore the human mind and shape our society. If we prevail, it is because we are aware of our responsibilities and live a little more in harmony with the world.

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Jan J. Boersema is a professor of Principles of Environmental Sciences at the Institute of Environmental Sciences (CML) of Leiden University. He was also professor at the Institute for Environmental Studies (IVM) of VU University in Amsterdam and assistant professor at the Universities of Groningen and Leiden. Boersema studied biology with a major in ethology and has a doctorate in theology. He has published in environmental, theological, historical, philosophical and criminological scientific journals and was the editor of several academic books. He is editor-in-chief of the *Journal of Integrated Environmental Sciences* (Taylor & Francis) and the textbook *Principles of Environmental Sciences* (Springer, Berlin, 2009). Occasionally he preaches in the 700-year-old, now Protestant, 'Hooglandse Kerk' in Leiden.

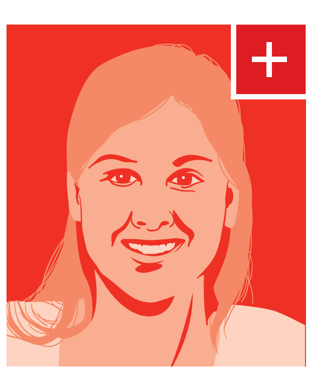
References

1 Psalm 8:6-8 and 5 in the Revised Standard Version.
2 L. White, Jr (1967). The historical roots of our ecologic crisis. *Science 155*, 1203-1207.
3 A. Maddison (2007). *Contours of the world economy 1-2030 AD.* Oxford University Press: Oxford.
4 Augustine, *Civ. Dei*, xii, 19.
5 D. Parfit (1984). *Reasons and persons.* Oxford University Press: Oxford/ New York.
6 R. Scruton (2012). *Green philosophy: How to think seriously about the planet.* Atlantic Books: London.
7 J.J. Boersema (2015). *The survival of Easter Island: Dwindling resources and cultural resilience*. Cambridge University Press: Cambridge/New York.

Parents behaving like teenagers

An intergenerational perspective on the energy challenge

The energy challenge is one of the defining challenges for today's young generation. 'Millennials' have their own ideas of how lifestyles can be changed to address it. Yet today's leaders cannot sit back and simply wait for that next generation.



> *Herman van der Meyden and Maaike Witteveen*

The parable of the teenager and the fridge

The fridge is a seemingly inexhaustible supply of calories to support the growing teenager. It is never empty, since his mother will keep it well stocked at all times. However, when the parents leave for a trip and the teenager remains at home to care for himself, the fridge will start to empty, as the young one indulges in his favourite snacks. But once the burgers are finished, the perception of endless supply is not: exploring deeper realms of the shelves, he will discover food in stuff thus far ignored. He does not feel the urgency of a dwindling supply, because his definition of what constitutes a meal expands at the same time. Until, after a final meal of wilted spinach with mouldy cheese, the fridge is empty. Truly empty.

Wim Wieldraaijer[1]

When we think about our generation's perspective on energy challenges, the first thing that comes to our minds is how narrow our own individual perspectives actually are. We are two Dutch 'Millennials', born in the early eighties. Maaike is a young woman aged 28, with a university degree, a well-paying job and caring parents, and she had a relatively trouble-free childhood. Herman's background is almost identical: a young man aged 32, with a university degree, a well-paid job, caring parents and a different, but equally trouble-free childhood. We both can afford to go on holidays and wear the clothes we like, and we buy our friends presents without much thought about the cost.

Both of us have had the great opportunity of working on the team that develops Shell's Energy Scenarios. This involved an in-depth study of the global energy challenge, which has transformed our thinking and to a degree even our behaviour. We have both reduced our meat consumption. We have switched to smaller cars and use public transport more. Herman has written a book on energy savings,[2] and Maaike has joined the Dutch National ThinkTank[3] project on behavioural change in relation to energy.

Our perspective, therefore, has shifted to one based on sustainability. Yet we are aware that this is a rich-world perspective. One worries less about the disappearance of coral in some remote sea when it is impossible to read about it at night because there is no electric light in the village. And you need to have access to energy before you can save it. Even though developing countries will probably be the hardest hit by environmental degradation and climate change, when basic human needs aren't fulfilled, those tend to be the primary concern.

That doesn't make the issue of sustainability any less pressing for us 'rich kids'. It will hopefully take only one or two generations until the whole world is prosperous enough to be able to afford to worry. By that time, the course that is set will affect everyone, for good or ill.

Today's business leaders and politicians will long since have been in elderly care when the issues described in this book hit home. Our generation, however, is very likely to see the endgame of the energy transition. Our pension dates are set for 2050, the end point of Shell's current energy scenarios, and the time when the lofty 'minus 80%' emission targets will have to be reached.[4] The two of us will still be around to deal with whatever the future of energy throws at us.

Hard truths of the energy challenge

The idea of a seemingly inexhaustible, fully stocked fridge has shaped our economy. Cheap and abundant energy has allowed humanity to make massive progress in the last century. It was material progress, quite literally. Abundant energy has allowed us to mine, forge and shape the material wealth that has been all around us since we were growing up. Our ability to consume, travel and work is literally fuelled by oil, gas and coal. However, this era is coming to an end, marked by the emergence of the energy challenge. The wealth acquired in the age of cheap fossil fuel can now be employed to transform the energy system and give future generations the chance to prosper. The other option is to stubbornly hold on to the status quo and hope for a miracle. The latter option might put too much faith in the 'innovative power of the next generation' to deal with this enormous challenge. It may sound sensible in the abstract, but it is scary for those who *are* that next generation.

The energy challenge has various faces, but the dilemmas at its core are well summarised in the 'three hard truths of energy' that were formulated in the Shell scenarios of 2008. The first is that energy demand is growing fast – driven not only by an increase in global population, but also by a rise in standards of living. Second, that supply of energy across the board, both fossil and renewable, will struggle to keep up with that demand. The third hard truth is that a host of environmental stresses are increasing, with climate change standing out.

What needs to be done is well known

The existing energy system therefore faces a dual challenge: the limits of easy-to-find fossil fuel resources on the one hand and global warming related to carbon emissions from those fossil fuels on the other. If we ignore costs of extraction for a moment, fossil fuels are still abundant. We will, however, run into the limited capacity of our atmosphere to absorb carbon dioxide long before we will run out of fossil fuels. To stay within the global warming limits that scientists say would be safe, annual carbon emissions should peak within 5-10 years and come down by at least 80% by mid-century. So on global warming, our generation certainly cannot continue to pass the buck.

The mischievous demon

Our millennial generation is not the first to ponder these issues. Observations similar to the three hard truths were put forward in the Club of Rome report in 1972, by the Earth Summit Conference of the Parties in Rio in 1992, and on many other occasions. Though it is clear that the importance of the three hard truths increases every year, whatever actions have been taken so far have not been able to reverse the trend.

This is despite the fact that it is well known what needs to be done. The solution is a radical step-up in energy efficiency (Amory Lovins' famous 'factor four'), accompanied by a radical increase in the share of renewable energy. David MacKay,[5] Jorgen Randers,[6] the European

Climate Foundation,[7] the World Wildlife Fund[8] and others have come to the same conclusion, and have calculated that this should be possible with existing technology. In the short term, we can expand the use of natural gas, which is a cleaner-burning fuel and emits half the carbon dioxide compared to coal. Beyond that, the knowledge of how to build wind turbines, solar panels and carbon capture and storage installations is there, we 'just' need to build them. Making our energy system sustainable would not only protect future generations from the impact of global warming, it would also reduce the Western dependence on politically unstable countries and avoid the need to go after hard-to-reach fossil fuel reservoirs. By solving the carbon side of the energy challenge, the twin problem of finite resources can be solved as well.

Unfortunately, there are strong reasons why the existing technologies do not get deployed. The cost of deployment, the economics, is one part. In addition, climate change is a global manifestation of Garrett Hardin's Tragedy of the Commons. It is a complex social and political challenge: who should incur the short-term costs for the collective long-term benefits?

Chris Rapley, a professor of Climate Science at University College London, ably summarised this huge, multifaceted task: "If there would be a mischievous demon out there who would want to design a difficult challenge for humanity, that challenge would resemble the energy challenge." Yet we think it can be done. Looking forward, there is even more to gain from this challenge than safeguarding a sustainable energy supply for future generations. If the global community is able to develop the decision-making processes for an energy transition, then other notoriously difficult issues, such as deforestation or other forms of environmental pollution, could be solved in its wake.

Don't discount our future away

We have stated above how the energy challenge requires huge investments now, for benefits that will really only become visible in future decades. But how much money should we spend today to solve it? The economist's way to answer that question involves discounting.

Discounting assumes that money earned next year is more valuable than the same amount in a more distant future. Most companies work with discount rates of 6-8% per year, implying that they rate income 10 years from now at half today's value. It makes everything we value today count half as much as 10 years out, and essentially nil 50 years out, when we will be old. This implies that even the natural resources and ecosystems we depend on are more valuable today than tomorrow. In a sense discounting decreases the urgency to invest in problems facing the next generations. It discounts our future away.

Although governments don't explicitly use the calculus of discounting, they use the same logic. Governments typically assume growth of 2-3% per year. In doing so, they tacitly assume that society will be much better off a few decades from now and, for example, that pension funds will continue to grow.

Discounting has its use, but only in a steadily growing economy. Over the past decades companies' balance sheets, national GDPs and many people's bank accounts have indeed been continuously growing. As the wealth increased, every next generation was better prepared to deal with its challenges than the previous. The last shelves of the fridge were never in sight. Why would the teenager abstain from eating, when there is a seemingly inexhaustible stock available?

At least, that's how it appeared. In reality, the economic growth was fuelled by abundant fossil fuel. This means that food has already been scraped from ever more remote corners of the fridge. When cheap oil in Europe and the United States ran out, the Middle East took over. When OPEC countries restricted access, oil companies went offshore. When shallow waters had been thoroughly explored, they moved to the deep sea. Eventually oil companies started drilling through massive salt layers underneath 2.5 kilometres (1.5 miles) of water in Brazil. The options for continued expansion rapidly run out. Every corner of the planet has been mapped. Continents are forged together by internet, phone and trade. The Arctic is the last unexplored corner of the earth. Our generation is amidst a shift from an endless world to a small world.

Nonetheless, historical discount rates continue to be used.
We collectively maintain a premise of expansion on an earth that we

know does not grow. In our parable, when the fridge is finally empty, mother comes home from holiday, gets angry, goes to the shop, fills it up, and everyone lives happily ever after. When our global fridge is empty, there is nowhere to shop, unless perhaps Elon Musk is successful with his plan to build a human base on Mars.

Nicholas Stern suggested a lowering of discounting rates in his influential *Stern Review on Climate Change*, commissioned by the British government in 2006.[9] We believe doing so would lead to more generation-inclusive economic choices. A lower discount rate will not only help growth and expansion limits to be taken into account, it will make the impact of future problems more visible in present-day economics.

It might further be helpful to make planetary boundaries visible in national accounting. Isn't it strange that a country with rich fossil fuel reserves, like the Netherlands, reports its extraction as GDP growth? Gas reserves are treated as a source, not as a stock. As ecological economist Herman Daly put it as far back as 1996, "… [GDP] does not reveal whether we are living off income or capital, off interest or principal. Depletion of fossil fuels, minerals, forests, and soils is capital consumption, yet such unsustainable consumption is treated no differently from sustainable yield production …"[10]

Generational differences as a silver bullet

In short, in terms of technology and economic thinking there is no reason to leave the energy challenge to the next generation. Yet it could be that the next generation is better positioned to deal with it by their lifestyles and social structures, and that the energy challenge is not as universal as generally thought. Maybe there is a generational silver bullet, an emerging force that doesn't appear in scenarios and strategies. If this were true, if children found a way to behave more responsibly than their parents, it might constitute our best hope to steer humanity safely through this century.

But are generations different? We need to separate superficial lifestyle issues from the fundamentals of the human condition. There is a constant stream of writings on the specific traits of Millennials, Gen-Xers and Post-90ers and how they are different from the Babyboomers and the Greatest

Generation.[11] On the other hand, evolution is slow and human beings of all generations are equipped with the same type of brain. Reading Seneca's essay "On the Shortness of Life" reveals how little mankind has changed, full as it is of anecdotes about Roman senators struggling with the pressure of ambition and full agendas. To avoid a philosophical discussion on nature versus nurture, let us assume that a person of a certain generation is not fundamentally dissimilar from a person in another generation, but that there are nuances caused by experience.

Our generation, the Millennials, has grown up in a vastly different world from that of our parents. We have experienced the rise of digital lifestyles and the increased awareness of the negative aspects of economic growth. At first glance it seems these developments could prompt us to digitally optimise our lifestyles to fit within the planetary boundaries. Is it a silver bullet in the making?

There are various examples that point in this direction. For instance, IT systems can help us optimise and tune energy use to the availability of renewable power in the home. The widespread use of smartphones is a success factor for city bike- and car-sharing systems. We use online apps to find the nearest bus, shared car or bike. We can calculate an optimal transport mode in seconds, allowing us to lower overall energy use.

Digitalisation of this latter sort challenges the very concept of ownership. Items as diverse as cars, power drills, ladders or disco lights can easily be lent and borrowed through online sharing systems – sometimes even free of charge. A friendly neighbour who is willing to lend you the item is often found within 30 minutes, according to the Dutch Peerby platform. Not only small goods are shared this way: there are also apps and web platforms for sharing office space and even apartments. This so-called collaborative consumption can reduce energy use by decreasing the number of products that need to be produced.

Social structures are affected by the digital lifestyles of the next generation. Sharing systems build communities and create trust between total strangers. Coupled with social media, such as Facebook and LinkedIn, it has never been easier to maintain an (inter)national social network. Could this enable the next generation to form global coalitions to solve global problems? The two of us encounter like-minded young people through global networks such as Perspectivity, Young Club of Rome and Global Shapers and connect with them via social media. If managed well, such networks are great platforms to inspire members and to accelerate initiatives.

The next generation will not have a magic wand

However, this interpretation might over-romanticise the situation. Spending less on ownership will not help much if the money saved is spent on energy-intensive experiences, such as air travel. The effect of more information and apps might also be overestimated as more information does not necessarily equal a change in behaviour. It has become hard to differentiate between an expert's opinion and laymen's comment as all voices are heard with equal strength in the digital world. Semi-informed action groups are formed overnight and could paralyse the debate about global topics as easily as they could help it advance.

At first sight, the financial crisis of 2008 has challenged the neo-liberal paradigm of unlimited growth. Millennials were confronted with the fragility of the economic system and high youth unemployment. At the same time, sustainability has become a positive buzzword that is being embraced by companies and consumers alike. Apple and IKEA are using their sustainable energy ambitions as a marketing message. Sustainable products and lifestyles – even part-time veganism – are getting more attention.

All this could fundamentally change the debate about growth and consumption. However, it could also merely be a trend that fades when the masses lose interest. Constant attention could even lead to issue fatigue. And to be fair, the attention paid to these topics so far has not led to a significant reduction in energy use.

On top of that, our hyperconnected lifestyle may hit our ability to focus. We know 13-year-old girls who get 15,000 WhatsApp messages a month, not to mention Facebook status updates, Twitter messages and pictures shared through Instagram or Snapchat. It remains to be seen if our continuously distracted minds can still concentrate on complex problems, such as the energy challenge – let alone solve them.

There are other things that can be listed as important influences on the lives of Millennials, such as 9/11, the growth of China and open-source technology. Yet none of the developments we discussed will magically solve the energy challenge. Communication technologies and awareness of limits to growth might advance the debate about environmental problems. We urge everyone to use these new possibilities. However, they are certainly neither silver bullet nor magic wand. Every generation is shaped by a complex web of individual choices, and it remains to be seen whether they turn out in favour of a solution to the energy challenge or only make it more difficult to solve.

The legacy to leave behind

A century from now, our great-grandchildren will be able to look back over the centuries of fossil energy use. The first half of the story we know: from the start of the industrial revolution to today, cheap power provided by coal, oil and gas led to an unprecedented increase in global welfare and productivity. This brought stability and international co-operation that enabled research on new energy technologies. The second half of the story – our future, their recent history – we do not know. But two very different stories come to mind. In the first, the cheap power of the 19th and 20th centuries equipped society with the means to invest in renewable energy sources that could not have been achieved with manpower and firewood alone. The fossil fuel era was used to build a renewable energy infrastructure. Our great-grandchildren will see the leaders of the fossil fuel age as great custodians of this natural endowment.

Yet, there is also a fair chance that our great-grandchildren will tell a completely different story. Around 2000, it became clear that the fossil-fuel-based energy system was not sustainable, but mankind ‘forgot’ to use the cheap power of fossil fuels to build renewable alternatives. Society was so focused on the short term that it looked only for further fossil reserves to exploit, at ever greater cost and difficulty. It started spending more and more social capital to get the stuff out of the ground. The strain of this extra work led to more conflict and scrambling for the most easily extracted fossil resources, which complicated international co-operation on new technologies. By blowing carbon dioxide into the atmosphere, society left a more volatile climate and an increased need for adaptation. In 2100, our great-grandchildren will probably think that a lot of the unique energy resource that was once stored in the ground was wasted on short-sighted investments – leaving them not only on their own to build up a sustainable energy infrastructure, but with a greatly diminished ability to do so. Their parents and grandparents behaved like teenagers, raiding the fridge without thinking about the day after tomorrow.

You may wonder why we work for a ‘fossil fuels’ company if we feel this way. Actually, we don’t. We work for an energy company. We believe Shell has the ingenuity and clout to be a powerful locomotive for the energy transition. For the long-term of this ‘next generation’ essay, we are excited by the opportunity to help steer the Shell locomotive towards a future beyond fossil fuels. Meanwhile, oil and especially gas remain a crucial short-term part of the energy challenge jigsaw. We are proud to work for the company that we see as the world leader in delivering these fuels responsibly and safely to their markets.

Let’s go back to our two histories of energy above. The timing of the inflection point is the million-dollar question. We don’t know the answer. Starting early requires short-term economic sacrifice. But good leaders can push this effort forward and take the foot off the pedal before social unrest occurs. No one will complain if a renewable energy infrastructure arrives a few years early. Starting too late, however, might risk a collapse of societal structures as a consequence of climate change and the inevitable resource scramble. Then, there would no longer be a pedal to push.

We, the ‘next generation’, will not be magically equipped to deal with these issues better than generations before us. We find it a solid ethical stance that each generation should leave, at least, as much total societal capital (tangible, natural, human and technological) as it inherited. Today’s leaders in developed countries should err on the side of caution and step up the energy transition effort. In 15-odd years, when the Millennials take charge, we can build on that and continue to work on this huge challenge.

Related essay

Living in overshoot
A forecast and the desire to have it wrong
> *Jorgen Randers*

Herman van der Meyden is a Commercial Advisor in Shell's Integrated Gas division. In his previous assignment, he was part of the Prelude Floating LNG engineering team, after contributing in 2008 to the Shell Strategic Energy Scenarios, Scramble and Blueprints. Outside his job, Van der Meyden is co-founder of the Perspectivity Network, which explores new models of collaboration for an increasingly complex world. He studied Offshore Engineering at Delft University of Technology, the Netherlands, and International Relations & Diplomacy at Leiden University, the Netherlands.

Maaike Witteveen is Assurance Project Engineer at Shell Global Solutions. She is co-founder of a network of Shell employees interested in the energy transition. She was at the time of writing a researcher of Energy Futures at Shell, where she worked on scenarios describing climate change mitigation and adaptation. Before that, Witteveen was a consultant for McKinsey & Company from 2011 to 2013. She is a co-founding member of the alumni board of De Nationale DenkTank, a non-governmental organisation which addresses social issues in the Netherlands. She studied Applied Physics at Delft University of Technology, the Netherlands.

Notes and references

1. Wim Wieldraaijer worked at Shell Technology Centre Amsterdam from 1966 until his retirement in 2009. During the last decade of his career his focus was on alternative energy and sustainability. This parable of the teenager and the fridge was developed around 2007 for a departmental lecture and based on observations of his own, then teenage, children.
2. K. van Alphen & H. van der Meyden (2009). *Het ideale energiegewicht*, Kosmos Uitgevers: Utrecht.
3. www.nationale-denktank.nl.
4. For the European target see: European Commission (2011). *Roadmap for moving to a low-carbon economy in 2050*. Many other regions and nations have adopted similar targets.

5. D. MacKay (2008). *Sustainable energy – without the hot air*, UIT: Cambridge.
6. Jorgen Randers (2012). *2052: A global forecast for the next forty years*, Chelsea Green: White River Junction, VT.
7. www.roadmap2050.eu.
8. World Wildlife Fund (2011). *The energy report: 100% renewable energy by 2050,* WWF International: Gland.
9. N. Stern (2006). *Stern review on the economics of climate change.* Report to the British government.
10. H.E. Daly (1996). *Beyond growth: The economics of sustainable development*, Beacon Press: Boston, p. 40.
11. Different definitions exist, but Millennials are generally defined as those born between 1980 and 2000, Gen-Xers between 1960 and 1980 and Post-90ers after the year 2000. Babyboomers were born in the birth wave after World War II (1943-1960). The Greatest Generation, born between 1901 and 1924, fought in World War II and led the reconstruction period in its aftermath.

Oil, gas, carbon and rock

The world will continue to rely on fossil fuels for many decades to come. However, the 'incumbents' will meet new challenges. And we need to get serious about carbon capture and storage.

The energy shift
The decline of easy oil and the restructuring of geopolitics

Neither petroleum nor other fossil resources are reaching peak production. It is conventional, easy oil that is limited and that has probably reached peak production already. Unconventional resources are restructuring the geopolitical landscape and pose an environmental challenge best met by giving carbon a price.

> *Oliver Inderwildi*

Oil is the most globalised commodity on the planet and, arguably, the most critical commodity for the functioning of the world economy. It supplies most of the energy for transport,[1] a significant proportion of heat and electricity, and it is the basis for the provision of chemicals, textiles and pharmaceuticals. It is also critical for food security.

As a result, energy security, and especially oil supply security, has been widely discussed. In recent years, the discussion has focused on whether the remaining oil resources are enough to meet demand over the coming decades. The International Energy Agency (IEA), the energy watchdog of the OECD, warns of potential shortages and even has an emergency response mechanism in place to mitigate short-term disruptions. In spite of those warnings, many argue that the market will respond to deal with the demand. The key argument is that the price of the commodity will rise with increased demand, which will open up previously uneconomic resources and increase supply. For them, supply and demand are simply regulated via the price – “It’s economics, stupid!” This is accurate as far as it goes, but it is not the complete story.

Peak conventional oil

When talking about oil, most people think of the thick black liquid that is sold in barrels. While it is true that most of the oil produced at the moment is indeed a black liquid which is *priced* by the barrel, hardly any of it will ever see the inside of a barrel. This black liquid, which we refer to as conventional oil, is the oil that is, for a large fraction, the most accessible and least technically challenging to bring into production. It is a relatively low-density, low-viscosity liquid that can be pumped out of the ground without the help of large amounts of energy.[2] It can, for instance, be recovered using water, as it floats on water.

Are sufficient new conventional oil reserves being discovered to meet rising demand over the coming decades? It surely is a limited resource. Its production is currently peaking, at about 64 million barrels per day (mbd).[3] To explore this we analysed the conventional oil reserves found worldwide since 1900 and compared this to oil consumption each year[4] (see Figure 1). The largest amounts of conventional oil were reserves found in the early part of the 20th century and these are the resources that have fuelled the modern global economy. Since 1980, however, in each year discoveries of conventional oil have been less than consumption with the exception of 2009, when the financial crisis caused a slump in oil demand. We are consuming more conventional oil than we are finding year after year.

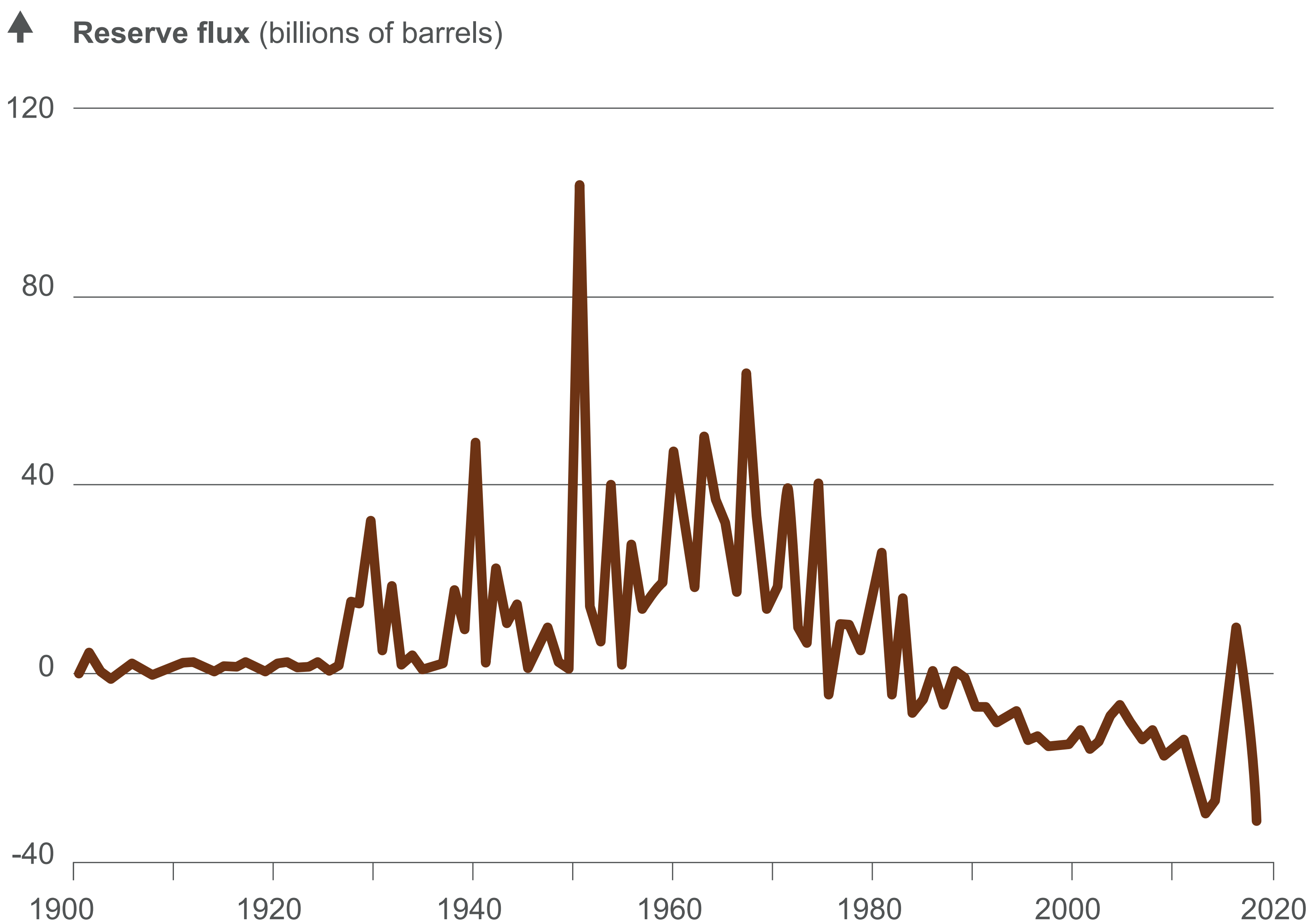


Figure 1: Flux in and out of the world oil inventory (1900-2013). The graph shows the difference between the amount found and the amount consumed in each year. Positive values are given for years in which more oil was found than consumed.

Murray and King stated the same in a different way by examining the conventional oil price as a function of production volume (see Figure 2).[5] Around 2005, this curve became strikingly steeper, analogous to a physical phase change. In the first phase, between 1998 and 2005, production rose from 64 to 74 mbd and the price from $15 to $40 per barrel. This can be attributed to normal elastic supply and demand factors. In the second phase, after 2005, crude oil production ceased to increase, but the price rose and fluctuated between $40 and $140 per barrel. Crude oil plateaued, with the rapid price rise clearly attributable to demand exceeding conventional supply capacity.

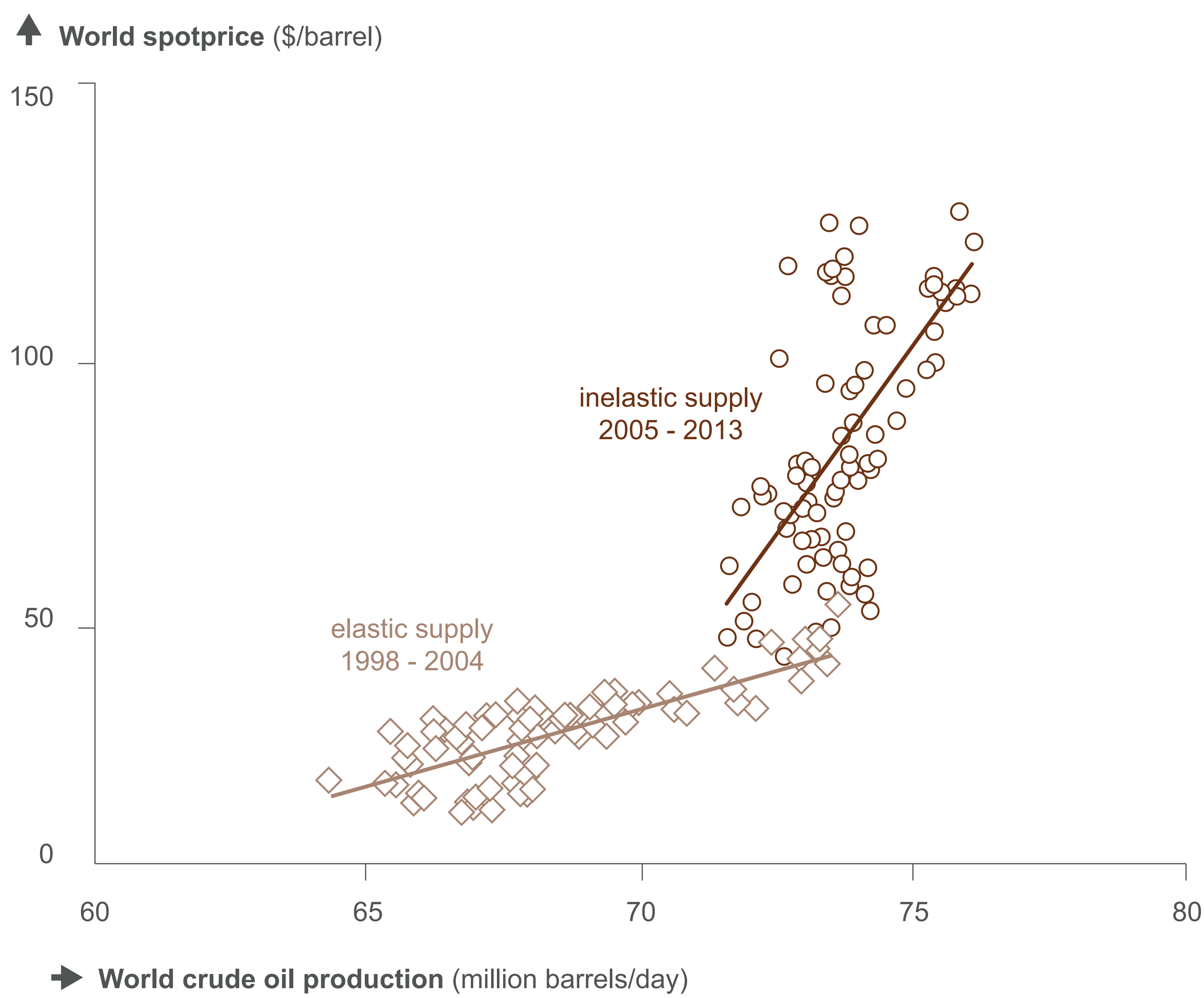


Figure 2: Crude oil production as a function of Brent crude oil price, 1998-2011.[6]

Yet it is a common misperception that we have reached peak oil, as we analysed in 2010.[7] Neither petroleum nor fossil resources are getting scarce; it is conventional crude oil that is a limited resource. Unconventional resources[5] are filling the gap, now at 93 mbd. Unconventional resources are harder to recover. They either cease to flow at surface temperatures and pressures or are submerged in sand or sediment, fairly described as oil sands or tight oil. Recovering these resources is capital intensive and requires significant amounts of supplementary energy. There is indeed an ample potential supply of fossil fuels; however, conventional oil, which is relatively cheap to recover, can no longer meet demand. Yet high oil prices can make previously uneconomic resources marketable. The catch is that the extraction of unconventional types of oil can have many environmental, financial and geopolitical implications not present with conventional oil. This has wide-ranging implications.

Importers versus exporters

Conventional oil reserves are unevenly spread around the world. This means that since 2005 most nations have been importing oil at very high prices (up to $160 per barrel), which has sent trade balances into deficit in many countries, including countries of the European Union, the USA and India. This has created large fiscal deficits and consequently significant foreign debt. This debt has been a key factor in the slow recovery of most advanced economies since the crisis of 2007-08. Emerging markets dependent on oil imports, most notably India, have also suffered from high oil prices. However, the second half of 2014 was a game-changing year for oil prices and thus for both oil importers and exporters.

Oil prices in the second half of 2014 went against almost all forecasts. They dropped, and they dropped significantly. Between June 2014 and December 2014 the price for London-traded Brent crude oil fell by more than 50% (Figure 3). This has had significant geopolitical and geo-economic ramifications. In short, it has turned the tide. Although prices have not fallen to pre-2005 levels (Figure 2), it is taking pressure off the oil importers, both developed and emerging markets, which rely on steady, secure and affordable oil imports. It could act in a similar way to a cut in taxes in all oil-importing countries and might trigger the long-awaited economic recovery.

Yet oil exporters are seeing their incomes shrink, which is a significant issue for economies that are so heavily reliant on this one export commodity to balance government budgets. For example, in the Russian

Federation, energy accounts for 25% of GDP, 70% of exports, and 50% of federal revenues. Oil-exporting countries are now closely examining the so-called fiscal break-even price of their oil exports, the price at which they are able to balance their fiscal budget. Most of the countries will have to go through fiscal tightening in order to avoid significant foreign debt.[8] For some countries, as with Russia, currency depreciations are counteracting the fall in oil prices, which brings at least some relief, though imports are becoming more expensive.

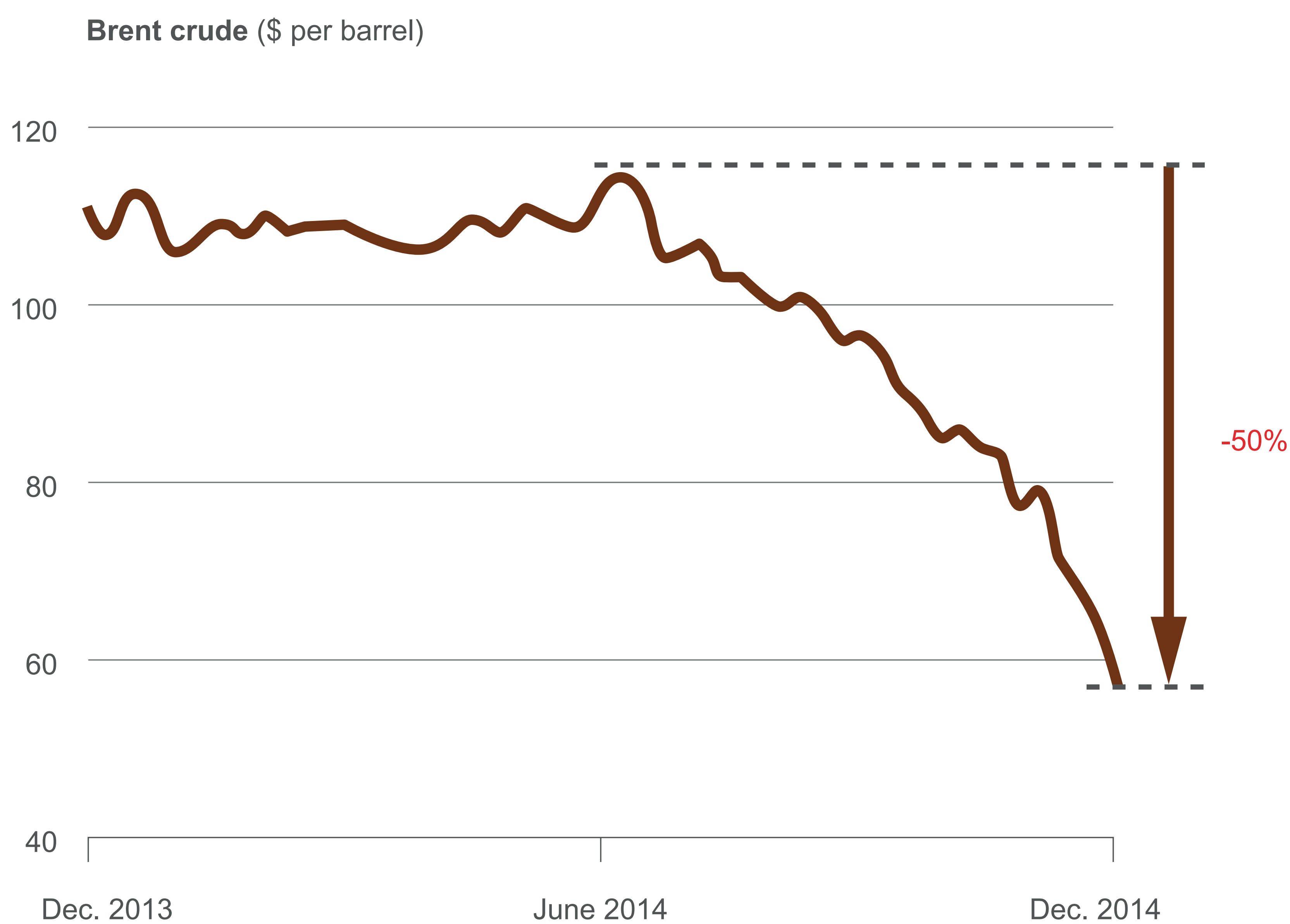


Figure 3: The fall in Brent crude oil prices over the year 2014.

Why did the high oil price, sustained above $100 per barrel since 2008, collapse in a matter of a few months? A slight slowing of global economic growth and the consequent reduced demand for oil have contributed 20-30% to the price drop, according to a recent IMF study.[9] However, metal prices, which typically react to global macroeconomic activity even more than oil prices, have decreased by substantially less. This observation suggests that supply factors have played an important part here. According to this IMF study, the evidence points to such factors as the unexpectedly fast recovery of Libyan oil production in September 2014 and Iraqi production remaining stable in spite of domestic unrest. The major factor, however, was the publicly announced intention of Saudi Arabia – the dominating force within OPEC – not to counter the steadily increasing supply of oil. This was affirmed by the November 2014 decision by OPEC to maintain a collective production ceiling of 30 mbd. This move is likely to be strategic. Excess supply will keep oil prices low and since production costs in OPEC states are lower than production costs for unconventional resources in North America, some of the unconventional fields could go out of business.

The decision of OPEC to maintain a high collective production ceiling, in spite of the perceived excess in oil supply, has induced a bear market. This market has brought the price of oil closer to what may be a new 'market equilibrium', estimated to be between $50 and $70 per barrel.[10] However, this notion is difficult to justify. Production costs, even for conventional oil, are highly variable, and strongly dependent on political factors, which include $500 billion per year oil subsidies in many oil-producing countries, and the operations of the OPEC cartel.

The increased production of unconventional oil and gas in the USA has also contributed to the observed fall in oil prices. Production of US unconventional oil in 2014 catered for 4% of global oil demand, or roughly a quarter of US oil demand. In total 75% of US oil consumption was provided by domestic production in 2014. As they have been producing so much of their own oil, this effect on the global market had to be expected.

Will prices stay at current levels for the time being? If the OPEC strategy does indeed drive some unconventionals out of business, the oil price could rebound, shifting power back to the OPEC states. Alternatively, the OPEC strategy may be to retain prices at a level low enough to keep unconventional supplies out of business for a longer period. Looking further ahead, the evidence is not much clearer. According to the IEA, oil inventories have reached their highest levels in two years and therefore price increases are likely. But how much will prices increase? The futures market suggests that by 2019 the barrel should recover to roughly $73, but past predictions of the futures market don't provide much confidence.

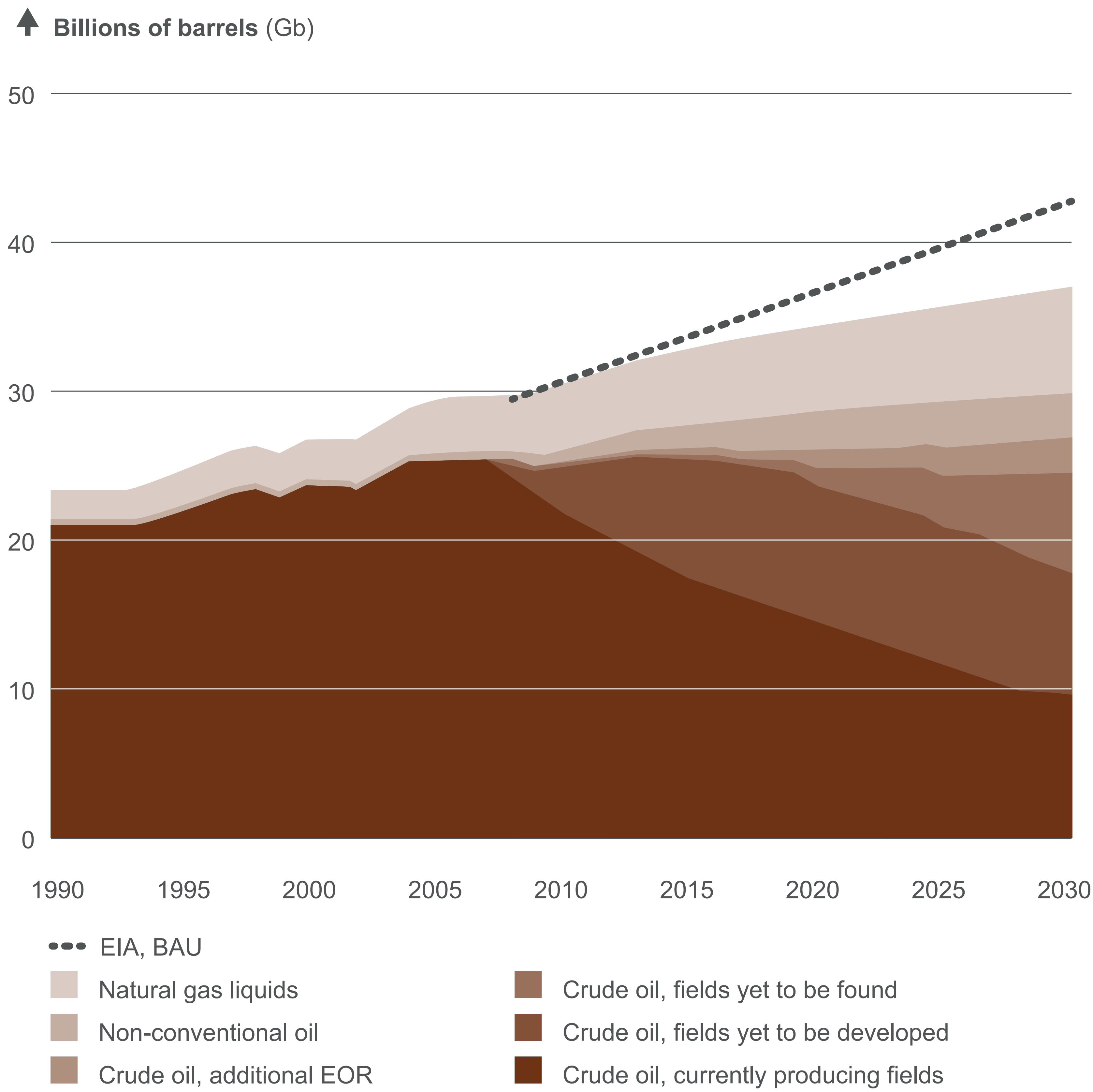


Figure 4: Projected world liquid fuels demand and supply.[11] While conventional oil production is already at a plateau (dark and light blue), unconventional resource production (green) will have to close the gap between supply and demand.

Production efficiency may improve with technological advancements, which may lower production costs for unconventional oil. This will compensate production cost increases as ‘easy’ fracking resources diminish. It is therefore likely that unconventional resources will remain a part of the resource mix over the coming three decades, while in the short term it is likely that prices will stay well below the $100 mark.

The longer-term future will depend on global demand, set to rise with increased consumption predicted for the Asia Pacific region, and with the ability of conventional oil production to keep pace with demand. This is in line with my own predictions in 2010.[12] The reprinted and updated graph (Figure 4) shows that unconventional resources will have to close the gap between supply and demand.

Unconventional resources will close the gap between supply and demand

Political tensions and the environment

The continued dependence on unconventional resources is a major problem, as the energy used in the mining and refinement of these resources is significantly higher than that of conventional resources. Consequently, the greenhouse gas emissions generated by combustion of these fuels is higher. Globally there is an agreement to manage these emissions to limit the temperature rise due to global warming to 2 °C above pre-industrial values.[13] Each step in oil production costs energy. Oil has to be pumped out of the ground or removed from shale. The crude product has to be transported to the refinery where it is converted to gasoline, diesel, kerosene and chemicals. These then have to be transported to the point of demand. The amount of energy needed depends on the quality of the reserve. To gauge the benefits for society, the net energy gain, or energy balance, can be assessed as ‘energy returned on investment’ (EROI).[14] The EROI is the energy contained in the final product, divided by the energy invested to obtain it. Light oil produced in the USA early last century and the oil produced in Saudi Arabia today can have an EROI as high as 100, which means that it provides 100 times the energy invested. However, for unconventional resources the EROI is significantly lower. Shale oil and oil sands, for instance, can have an EROI of as little as 5.[15,16] This compares to 10 for oil imported to the USA from the Middle East or Venezuela[17] and is roughly a factor of 20 lower than early conventional oil. Consequently, the energy benefits from these resources are significantly lower than from conventional oil and those benefits are diminishing.

Consequently, the greenhouse gas emissions generated by these fuels is higher, unless the energy used in extraction is itself sustainably produced. Figure 5 illustrates the total emission of liquid fuels derived from different feedstocks – the emissions increase as the quality of the resources decreases.

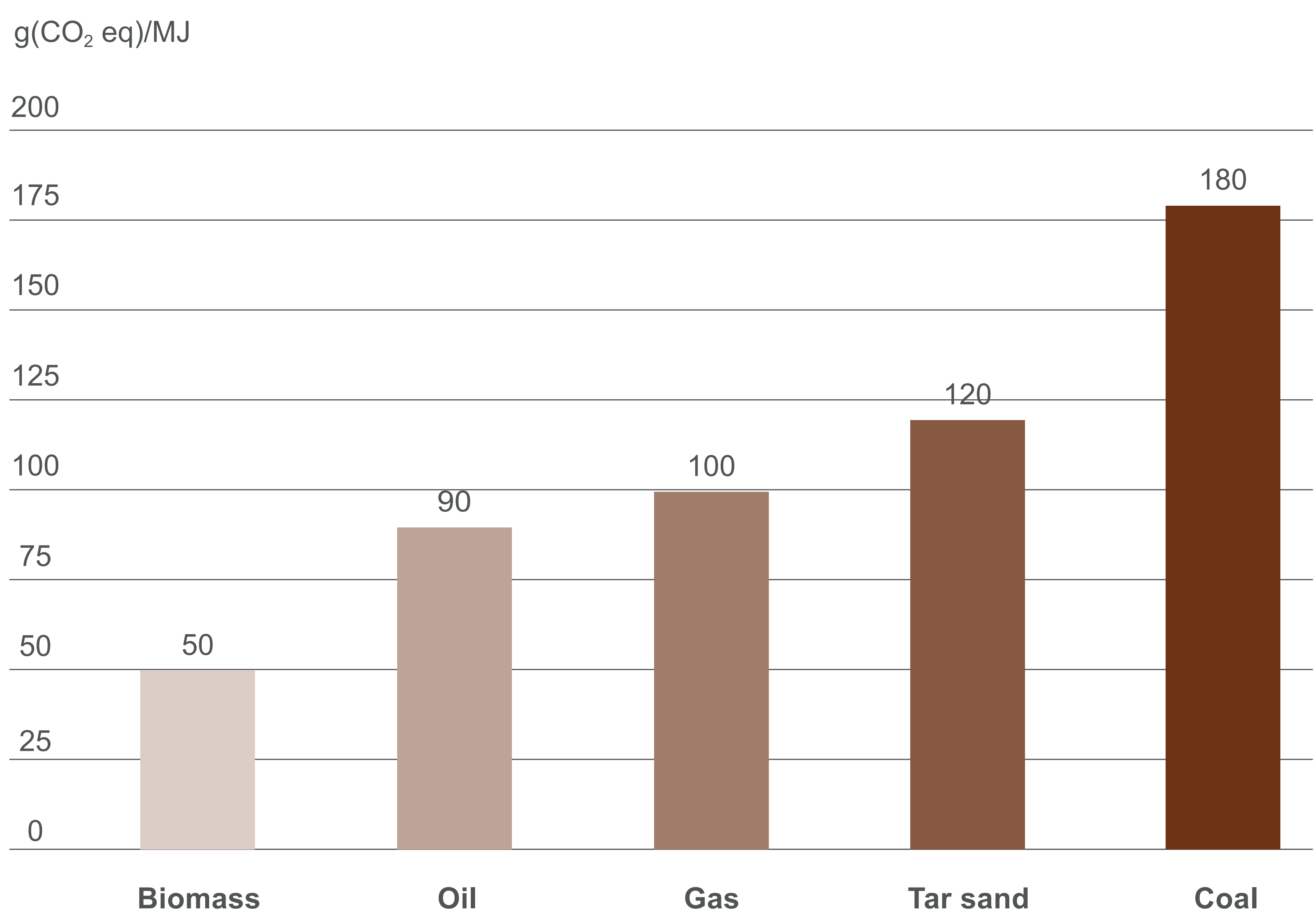


Figure 5: Emission intensity of diesel fuel derived from different feedstocks, in g(CO_2eq)/MJ.

Using gas, coal, oil sands or tight/shale oil for fuels will increase global greenhouse gas emissions more than expected, as a shift to these feedstocks is not included in most predictions. It counteracts decarbonisation endeavours. In doing so, an 'environmental credit card' is being used to meet an entrenched but unsustainable mode of energy for transport which is not suited to the 21st century.

Yet unconventional resources are not always bad for the environment. US shale gas, for example, is crowding out coal, an even worse polluter, and is therefore reducing US emissions.[18] China is at present looking for advanced fracking technology for its more challenging shale gas reserves. This may be environmentally beneficial, since China is also heavily reliant on coal for electricity production. Moreover, this is likely to improve public health, given China's smog problem.

Even Europe is now pushing for fracking technology. The European Union is committed to reducing carbon emissions by at least 40% by 2030 and by at least 80% by 2050. This has increased its dependence on gas, as it provides a good back-up for intermittent renewables such as wind or solar. In order to ensure steady supply, gas-fired power plants serve as back-up due to the current absence of economic power storage facilities. This, in combination with the Nordstream pipeline that delivers Russian gas through the Baltic Sea, has made the European Union – particularly Germany – reliant on Russian supplies. In the light of the recent tensions between the West and Russia, the European Union is seeking to diversify its gas supply, which is a further motivation for tapping into domestic shale reserves. Moreover, additional LNG terminals are available to take up the surplus production created by the US shale gas boom. This should make Russia nervous.

It is not just Russia that may be affected, however. US unconventional oil and gas output has offset shortages created by sanctions against Iran, which may have been responsible for bringing the Iranians back into negotiations on their nuclear programme and weakening their negotiating status.

The USA could counter OPEC's chess move of a high collective production ceiling by keeping their fracking fields in production through import or pricing controls. Domestic production is a strategic imperative for the US as it eases balance of payment issues and keeps the budget off the fiscal cliff. The geopolitical impact of the surge in US oil production due to fracking of tight oil is already in play. The tide has not just turned economically, but also politically. Strategically it is imperative to respond to the new energy politics by integrating economics, politics *and* the environment.

Long-term sustainability

We should make sure that we do not trade off long-term environmental and energy security for perceived short-term economic gain. Unconventional resources of gas do buy time to complete decarbonisation endeavours without running into resource shortages. But in this approach, the extra resources are only of use for a limited time during the transition and must be incentivised as such. To this end, we need to internalise the environmental externality of greenhouse gas emissions. This can be done via regulation, obligation, a carbon tax or a carbon price, for all of which government intervention is needed. The Environment Protection Agency in the USA is setting a maximum amount of CO_2 that can be emitted per kilowatt-hour produced by a power station. This could incentivise either carbon capture and storage (CCS) installation for coal-fired power stations or substitution with renewables or gas. Renewable costs have been dramatically reduced over the past decade, largely driven by the market created by feed-in tariffs in the European Union. Smart grids and energy storage facilities will need to be incentivised through publicly funded research to enable these transformational technologies to competitively enter the market.

In 2012, I published a compendium that outlines how both the energy and the transport sectors can be restructured to conserve remaining easy oil supplies as a precious future resource.[19] This restructuring ranges from alternative fuels to modal substitutions, novel drive-trains and advanced transport management. Since that volume was published, the first commercial second-generation bio-refinery has come into operation: the Granbio refinery in North-east Brazil. This plant creates 22 million litres of liquid fuel per annum for transport from cellulosic, leafy material[20] which is a by-product of nearby sugar cane plantations. Biogas produced as a by-product in the process is used to provide all the energy needed to run the refinery, the baling and transport of the stalks and leafy material after the harvesting of the cane itself for sugar production, with surplus biogas put into the market. The overall production and use of the fuel is negative in CO_2 emissions, since the CO_2 used in plant growth offsets the CO_2 produced in combustion. The product is also commercially competitive even at current oil prices. The roll-out of second-generation bio-refineries in conjunction with food farms can be anticipated over the coming decades.[21] A combination of all this could lead to a sustainable economic system that reduces demand for oil, therefore preserving oil supplies for essential uses, and eventually removing oil as a major source of political instability.

Novel unconventional oil reserves are more costly to produce and cause more carbon emissions

Political will

We are not running out of oil, but we have reached a plateau in easy, inexpensive conventional oil production, which will be followed by a fall in production. Cheap conventional oil has over the past century been the mainstay, globally, of primary energy for transport and for the chemical and pharmaceutical industries. Novel unconventional oil reserves are abundant, but are more costly to produce, provide less net energy and cause more carbon emissions. If the gap between rising demand for oil and the supply of conventional oil is met with these high-emission resources, this runs counter to the accepted global agreement to reduce emissions. We need to internalise the externality of greenhouse gas emissions, so that highly polluting resources such as coal are replaced by renewables, energy-efficiency measures and advanced biofuels. Pricing and regulation will be critical to balance short-term responses to energy security and pricing with long-term climate and environmental security.

At the moment, very strong political and economic forces support the utilisation of unconventional oil recovery. In fact, these resources helped to turn the tide so that key historical oil exporters are now politically significantly weakened due to increased energy self-sufficiency of oil importers. This restructuring of the geopolitical balance towards indigenous primary energy supplies – solar, wind, hydropower, geothermal, tidal, wave, etc. – coupled with energy storage facility and smart grid development is likely to reduce the fiscal burden of current energy import prices for most developed, emerging and least developed economies and also aid the resolution of conflict in key parts of the world.

Unconventional gas resources can be used as an interim measure to buy time to restructure our energy and transport systems, hopefully reducing demand for oil so that that the remaining crude oil reserves can be used as an essential resource for future generations. Achieving this will require policy interventions and significant political will.

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Oliver Inderwildi is Senior Community Manager and Global Leadership Fellow at the World Economic Forum. He is also Senior Policy Fellow at the Smith School of Enterprise and the Environment, University of Oxford.

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Notes and references

1. O.R. Inderwildi & D.A. King (2012). *Energy, transport and the environment: Addressing the sustainable mobility paradigm.* Springer: Heidelberg, London & New York.
2. Conventional oil is unambiguously defined as oil that is less dense than water (ref. 4 *infra*) (the density of water at ambient temperatures is roughly 10 API, expressed in the units of the American Petroleum Institute). This definition of conventional oil includes heavy oil (10-20 API), medium oil (20-30 API), light oil (above 30 API), and condensates. Data from reporting agencies does not distinguish between oil grades according to density and commonly includes a range of 'conventional liquids' including extra heavy oil (0-10 API), oil sands, tight as well as shale oils and natural gas liquids (NGLs). We refer to these reserves as unconventional oil resources and exclude them from the world conventional oil inventory.
3. N.A. Owen, O.R. Inderwildi & D.A. King (2010). The status of conventional world oil reserves – hype or cause for concern? *Energy Policy.*
4. J. Murray & D.A. King (2012). Climate policy: Oil's tipping point has passed. *Nature*, 481, 433-435.
5. *Ibidem.*
6. Ref. 4 *supra*.
7. Ref. 3 *supra*.
8. R. Arezki & O. Blanchard (2014). Seven questions about the recent oil price slump. IMFdirect, http://blog-imfdirect.imf.org/2014/12/22/seven-questions-about-the-recent-oil-price-slump/
9. *Ibidem*.
10. Ref. 4 *supra*.
11. Ref. 3 *supra*.
12. Ref. 3 *supra*.
13. Ref. 1 and Ref. 3 *supra*.
14. C.A.S. Hall & K. Klitgaard (2012). *Energy and the wealth of nations: Understanding the biophysical economy.* Springer: Heidelberg, London & New York.
15. D.J. Murphy & C.A.S. Hall (2012). Year in review: EROI or energy return on (energy) invested, *Ann. N.Y. Acad. Sci. 1185*, 102-118.
16. J. Bergerson & D. Keith (2006). Life cycle assessment of oil sands technologies. Alberta Energy Futures Project. Institute for Sustainable Energy, Environment, and Economy (ISEE), University of Calgary.
17. http://energy-reality.org/wp-content/uploads/2013/05/09_Energy-Return-on-Investment_R1_012913.pdf

18. O.R. Inderwildi, F. Siegrist, R. Dickson & A.J. Hagan (2014). The feedstock curve: novel fuel resources, environmental conservation, the force of economics and the renewed east–west power struggle. *Appl. Petrochem. Res. 4* (1), 157.
19. Ref. 1 *supra*.
20. O.R. Inderwildi & D.A. King (2009). Quo vadis biofuels? *Energy Environ. Sci., 2*, 343-346.
21. O.R. Inderwildi, S.J. Jenkins & D.A. King (2008). *Mechanistic Studies of Hydrocarbon Combustion and Synthesis on Noble Metals 47* (28), 5253-5255.

Dealing with fossil fuels
Carbon capture and storage in a global context

The world will continue to use fossil fuels, making carbon capture and storage a necessity. We need to develop its technology further, to make it globally affordable.

> Ron Oxburgh

We risk changing the way the atmosphere regulates the earth's temperature if we change its composition by openly venting unabated combustion gases from fossil fuels. Effective intervention requires the capture of greenhouse gases from both coal and gas at the point of use (such as power stations) and then their immobilisation. This is the aim of carbon capture and storage (CCS), which, while technically feasible with present technology, remains expensive. Developed countries can afford to adopt it, but CCS is not affordable[1] in the developing world where much of the growth in global emissions will occur.

Second-generation CCS technologies are emerging that will build on current technology and appear to offer the prospect of affordable global adoption. It is very much in the interests of developed countries to promote and, if necessary, subsidise the wide implementation of CCS. As both the largest emitter in the world and a country that is aware of its vulnerability to climate change, China will play a central role in determining whether efforts to control global emissions are successful. Time is of the essence.

Two inescapable truths

There are two truths that seem to me to be equally inescapable. The first is that for a number of decades to come, most of the world will continue to depend on fossil fuels as a major energy source. However much we may wish it were otherwise, there is simply no other energy source in sight that has the flexibility and wide availability of fossil fuels.

The second is that, regardless of what we think of the fine details of the climate modelling, it looks almost certain that increasing the concentration of greenhouse gases in the atmosphere by burning fossil fuels will cause substantial changes in the earth's climate and in the acidity of the oceans. These changes will affect all life on earth but will prove particularly challenging for the majority of human beings, whose life is closely adapted to the limited range of climatic conditions that have been experienced over the last few hundred years.

If we accept these truths and continue to burn fossil fuels, it is urgent that we act to protect our environment. In the future we may look forward to a time when we derive our energy from low-carbon sources but in the meantime we have to find some way of preventing the greenhouse gases from fossil fuels entering the atmosphere. The series of processes known as carbon capture and storage allow those gases to be trapped at source and immobilised.

It is also important to remember that in addition to the emissions from energy production, industrial sources contribute around 20% of greenhouse gas emissions. CCS should be applied to these sources, too, particularly as capture may be less difficult in these cases.

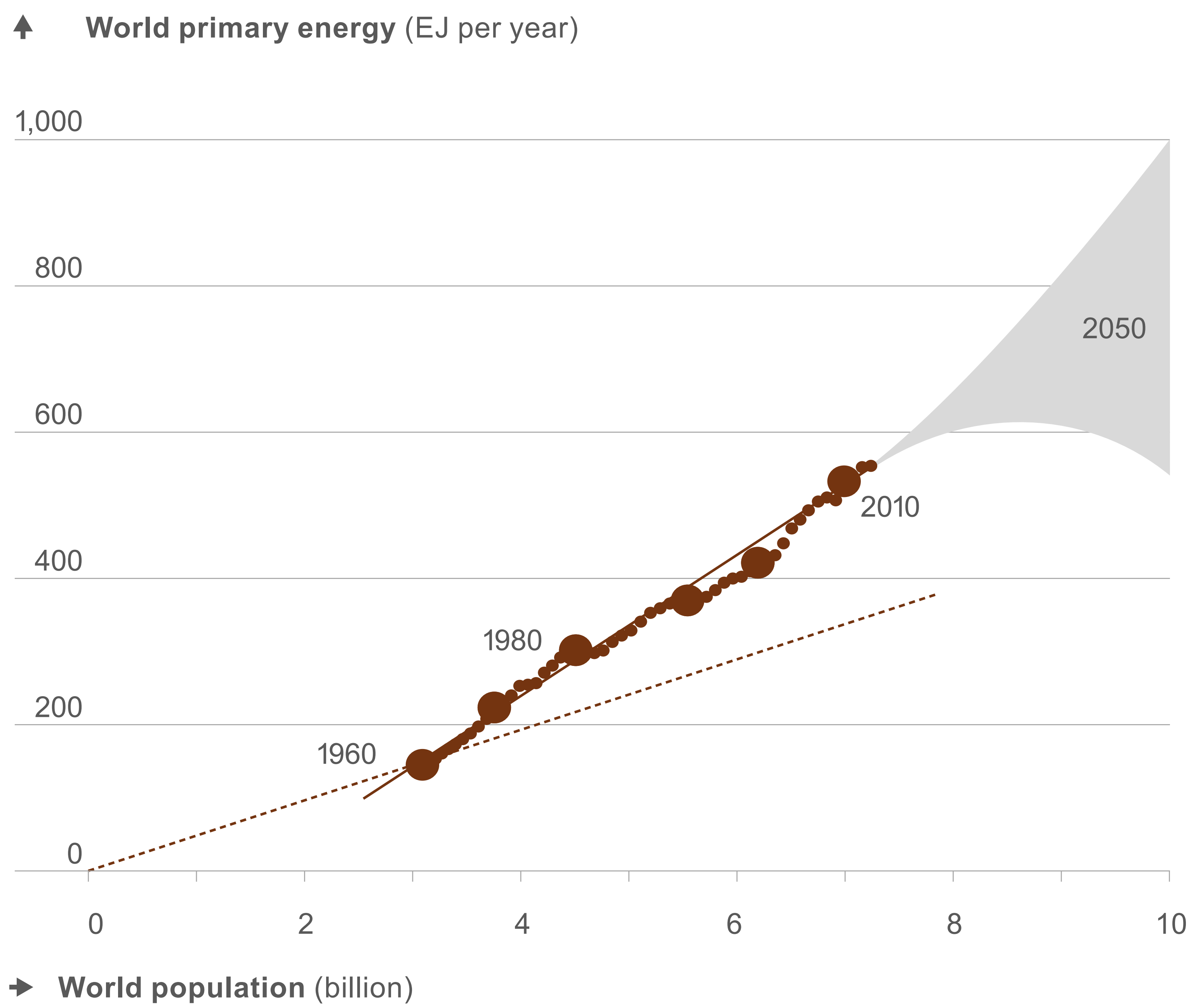

Figure 1: The figure shows global energy use over 50 years as a function of the increase in global population (solid line). The curve shows increases or decreases in global economic activity as short-term changes in slope. The dotted line shows how energy use would have risen had it simply increased in proportion to population, revealing that since 1960 the world economy has become ever more energy intense. The extrapolation to 2050 is indicative of the range of scenario outcomes in circulation.

The global energy challenge

The magnitude of the challenge is illustrated by Figure 1. The world's population continues to rise, and for at least the last 50 years global energy consumption has increased roughly one and a half times as fast as the population. This means that not only is the world population increasing but the average per capita use of energy is increasing as well.

Because over 80% of the world's energy is still derived from fossil fuels, this increase in global energy consumption translates into an increase in global emissions of greenhouse gases. This is in spite of the increasing contribution of renewable and other low-emission methods of generating energy. Their share of the global energy budget has not changed because their growth has simply matched, not outpaced, the overall increase in global demand. Renewable energy from wind, sun, wave, tides, geothermal and hydro will be of increasing importance. However, all these sources have limitations such as intermittency (being dependent on the weather) or geographic considerations (not being practicable everywhere). This does not mean that they are unimportant but simply that without the technology for large-scale energy storage or the development of a robust system of continent-wide electrical interconnection, they offer only a partial solution. In the meantime, rapid backup for intermittency will generally have to be supplied by gas or, where it is available, hydro.

Some countries may be able to derive an increasing proportion of their electricity from renewable sources, with the additional benefit of largely decoupling their economies from potential rises in the cost of fossil fuels. However, they cannot be completely free from dependence on fossil fuels; the wind does not blow all the time and some dispatchable generation will in most cases be needed to provide backup.

Globally, the world demand for more energy seems set to grow along with the population and the question may be asked as to how this can be achieved without increasing emissions of greenhouse gases. Ideally, emissions growth would be constrained by improving efficiency and avoiding waste. To some extent this may be driven by prices, but not everywhere, and not for all fossil fuels. Fossil fuel prices in 2015 are lower than many would have predicted only a few years ago. The only places where price is likely to be the main driver for efficiency are those where fossil fuels or their emissions are heavily taxed. In contrast it should also be noted that in some countries fossil fuel prices continue to be subsidised by government.

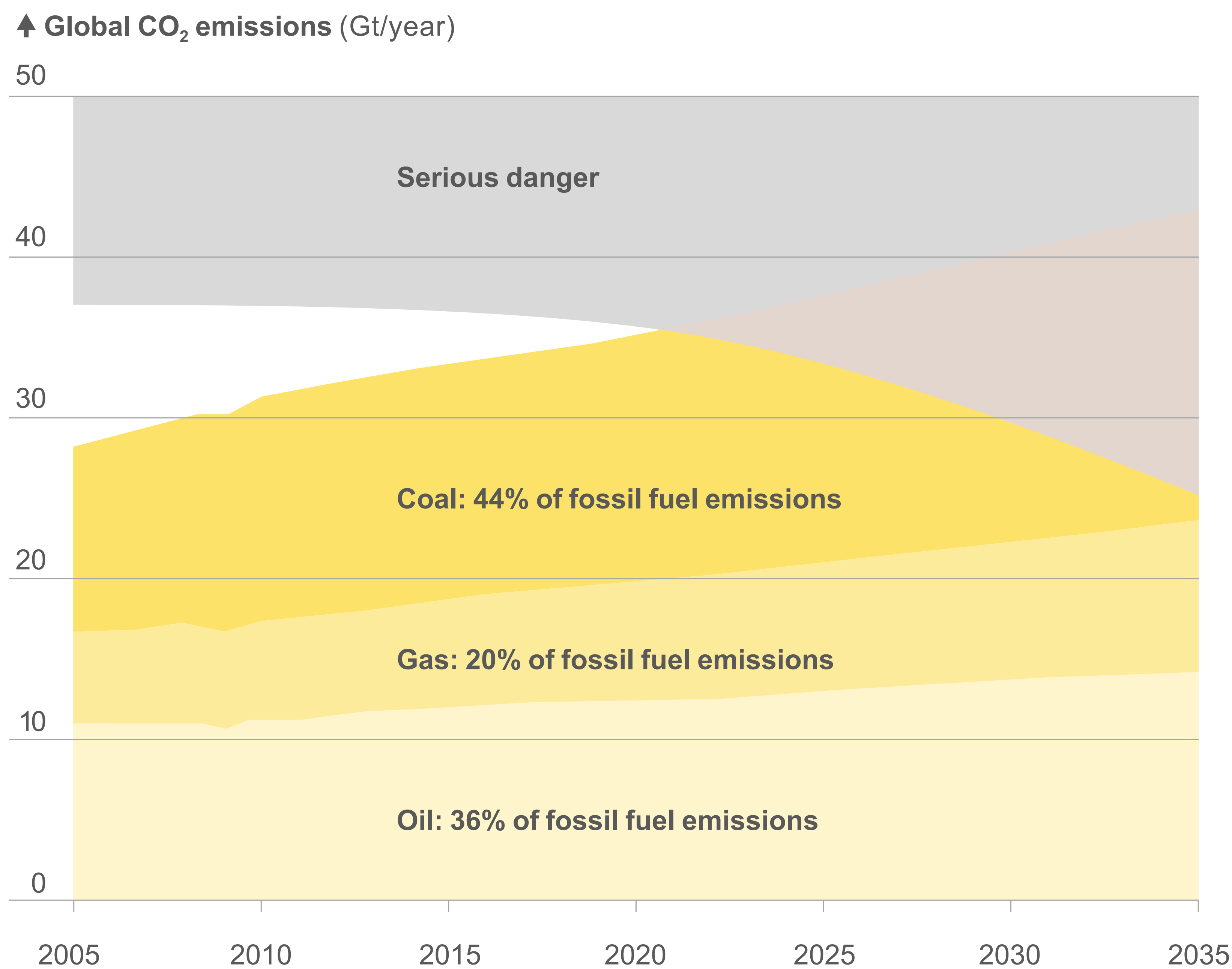

Figure 2: The IEA projection (reference case) of the rate of annual emissions by fuel to 2035. To mitigate the most extreme consequences of anthropogenic climate change and avoid 'serious danger', annual emissions should peak and start to decline as early as possible.

A third strategy for emissions reduction is actively to promote the substitution of gas for coal. The relevant information is included in Figure 2. The carbon footprint of energy produced by the combustion of natural gas is about half that of coal. In some countries such a shift is being promoted by taxation of emissions but, if the fall in world coal prices is sufficiently large, coal-fired power stations may still be cheaper to operate than gas. This is the case in the UK in 2014. In some places, however, such as the United States, where a boom in shale gas production and other factors have lowered domestic gas prices, a shift from coal to gas is taking place through market pressure alone.

Although gas substitution for coal can contribute to a short-term emissions reduction strategy, the overall savings may be somewhat less than suggested above and depend on how the gas is produced and transported. For example, producing gas from shale requires more energy than from conventional sources. Furthermore, gas transported as liquid natural gas also carries an energy (and thus emissions) penalty from the considerable energy required for its liquefaction. Gas leakages can also be a problem. Because natural gas (methane) is a greenhouse gas around 20 times as potent as carbon dioxide, any leakage to the atmosphere during production is serious. This certainly happened in the early days of shale gas production; there can also be leaks from pipelines if they are not well maintained. However, as industrial practice matures, fugitive emissions of methane should become minimal, and probably less than the unseen methane emissions associated with the opencast mining of coal. Replacing coal with gas can therefore be a valuable part of a short-term emissions reduction strategy, although the size of the reduction achieved depends on how the gas is produced and transported. It can be implemented relatively quickly and requires no new technology.

Nuclear energy is likely to play a greater role

Nuclear generation of electricity is likely to play a greater role in meeting base-load demand in spite of the reluctance of certain countries, notably Germany and Japan, to use this technology. Concerns about anthropogenic climate change have generated new interest in nuclear.

Public attitudes to nuclear vary from country to country but it remains the only low-carbon energy source that can be implemented more or less anywhere and for which the technology is relatively mature. However, rightly or wrongly, public interest has been damped by recent events at Fukushima. The three main constraints on nuclear energy are cost (slow to build), relative inflexibility of generation (limited ability to follow fluctuations in demand) and public concerns about safety. At present it is difficult to say whether electricity generation by nuclear, intermittent renewables or fossil fuel generation with CCS (see below) is the most expensive.

A future with CCS

The shift to natural gas, renewable energy and possibly nuclear energy will not reduce the need for further measures to counter carbon dioxide emissions. The carbon footprint of gas is lower than that of coal, but it remains significant. It is notable that the statutory UK Climate Change Committee has written to the government[2] to point out that large-scale deployment of gas-fired power generation is incompatible with the UK emissions reduction targets. The long-term objective, therefore, must be to apply CCS technology to all fixed sources of greenhouse emissions from whatever fuel or process that produced them.

Figure 2 illustrates both the size of the problem and the potentially important role that has to be played by CCS. CCS can in principle be applied to most of the uses of coal and gas. As remarked above, the emissions per unit energy generated by gas are around half those from coal.

The figure allows a ready qualitative assessment of the reductions in emissions that can be achieved by various means. Taking 2035 as a reference date, replacing half the world's coal combustion by gas would clearly be helpful but would not lower global emissions even to today's level (2014). Fitting the remaining coal generation with CCS would improve the situation and might bring down emissions approximately to today's levels. It is clear that to achieve a significant change CCS would need to be applied to both coal and gas. If half of current coal generation was replaced by gas and CCS was applied to half of all fossil fuel generation, the global rate of emission release would begin to decline. These hypothetical examples are intended simply to give some idea of the scale of the CCS challenge.

CCS has only recently been demonstrated at full scale,[3] but its technical feasibility has not been seriously in doubt – although some, who for policy or other reasons continue to oppose CCS, choose to question it. Globally there are around 20 major demonstration projects in various stages of development. The important policy concerns about CCS arise largely from cost. There are three components to the costs – capture cost, transport cost and storage cost. Although local situations may vary, capture is generally regarded as the most expensive, at around 70% of the total cost of CCS. Capture can take place either before or after combustion. It is most efficient when it is built into the separation process at the time of plant design and construction, allowing for pre-combustion separation. However, if an existing plant is to be retrofitted for CCS, post-combustion separation is generally more practicable.[4]

The cost of capture has two main components. The first is the additional capital expenditure at the power plant. The amount involved depends on the capture process chosen. In the case of post-combustion capture current technology involves the construction of large absorption towers in which carbon dioxide can be selectively dissolved from the exhaust gases. The solvent then has to be heated to release the carbon dioxide for disposal elsewhere.

The second component is the cost of the energy needed to operate the separation process (in the case of post-combustion capture, to de-gas the solvent). This is an energy-intensive process and may require around 25% of the output of the power station, although the precise proportion varies with different technologies. This should allow the capture of 80% or even 90% of the greenhouse gases. However, although there may be an 80% capture of greenhouse gases per unit fuel burned, the saving *per unit power output* is around 70% because more fuel has to be burned to maintain a particular level of output.

The transport of gases destined for disposal is the best understood and costed part of the CCS process. The costs of pipeline construction are well known and depend on the detailed specification, length and route etc. In some cases existing pipelines may be used. It is anticipated that gases will be carried at high pressure and there are significant energy costs for gas compression.

Having been transported to their storage site by pipeline (or possibly by ship) the gases need further compression for injection into a suitable geological formation at depth. The challenge is to find sufficient storage capacity as near to the source as possible. The site may be onshore or offshore, but in the UK it appears easier to win public acceptance for the latter. There must be a high degree of confidence that the storage site will be able to retain the injected gas for tens of thousands of years. The injected carbon dioxide is in liquid state and its physico-chemical interaction with the host rock and the fluids it displaces are complex and not yet totally understood. This requires careful geological and geophysical evaluation of storage sites. These costs will vary from site to site but are generally thought to be significantly less than the capital costs of gas separation.

Until at least several full-scale CCS projects have been in operation for some time, overall estimates of both capital and operational costs will remain uncertain in detail. However, the general view today is that electricity would be between 30% and 50% more expensive than without CCS.

Upscaling CCS

The question arises of how feasible the deployment of CCS at a truly large scale might be. Figure 3 is intended to help answer this question. This figure shows the same information as Figure 2 but analyses it by region of origin rather than by fuel. It is evident that today the emissions of non-OECD countries are about 50% greater than those of the OECD. However, looking forward over two decades to 2035, virtually all the emissions growth is in the non-OECD countries.

This is where costs appear to me to be central to the argument. The most recent and comprehensive analysis of the costs of CCS is provided by the Final Report of the CCS Cost Reduction Task Force (2013).[5] It is realistic to assume that while the application of CCS technology today would increase electricity generation costs significantly, there would be a realistic prospect of this declining to no more than a 25% increase in the future.

While OECD countries would not welcome such an increase in their electricity costs, this level could probably be tolerated. That is not true of the non-OECD countries, for most of whom such an increase would be neither politically nor economically feasible. That said, the future costs of inaction would be considerably higher.

The global adoption of CCS will require new and disruptive technologies

The conclusion of the CCS Cost Reduction Task Force's report mentioned above is that feasible cost reductions could reduce the cost of generating electricity with CCS to levels comparable with offshore wind and some other renewable technologies. While this is welcome, it is not a standard of comparison that is relevant for most developing countries. The conclusion is inevitable that if CCS is to be a globally significant technology that is to be deployed widely in both the developed and developing world, CCS costs have to be dramatically reduced.

Implementation of CCS on anything like the scale contemplated above would result in a global CCS industry not dissimilar in scale to the present-day global fossil fuel industry.

Although incremental reductions in the costs of transport and storage are likely, achieving the scale of cost reduction necessary for global adoption of CCS will require new and disruptive technologies. Whether such innovative technologies are feasible remains to be seen. There are certainly novel and potentially less expensive approaches to separation that have been explored in the laboratory. Some of these have involved physical rather than chemical separation methods or the use of novel catalysts.[6] However, they will certainly not be developed unless there is an urgent and determined commitment to achieve cost reductions. This commitment could come from governments or from groups of governments or from global corporations with strong balance sheets. The same political commitment and level of expenditure is needed as was demonstrated in the space race to the Moon in the sixties.

After capture, there remains the question of what should be done with the separated gases. In an ideal world they would not be pumped underground but would be incorporated at source into solids that could be used in construction. This would be the Holy Grail of carbon storage – after all, significant amounts of carbon dioxide are incorporated in the calcium carbonate of deep ocean sediments or in limestone within the earth's crust. Technologies to achieve this and other ways of trapping carbon dioxide in solids have been studied for some time. They are all difficult, but it would be much easier to garner public support for the prospect of using carbon dioxide to produce useful material rather than simply burying it.

China's role

Another factor – and probably the single most important one in determining not only the future of CCS but also of attempts to manage global concentrations of greenhouse gas – is the future energy policy of China. Figure 3 indicates the Chinese contribution to world emissions. Although Chinese emissions are not high on a per capita basis, at 1.3 billion the population is so large that the country as a whole is easily the world's largest emitter. Furthermore, China has one of the most technologically aware governments in the world and one that appears to understand the science of climate change. To judge from the 12th Five-Year National Plan, which was published in 2012, the government recognises that China will be seriously affected and will be one of the biggest losers if climate change progresses as implied by the theoretical models. Around a third of the objectives in this five-year plan relate to renewable energy, energy efficiency, avoiding waste and reducing the carbon intensity of the economy.

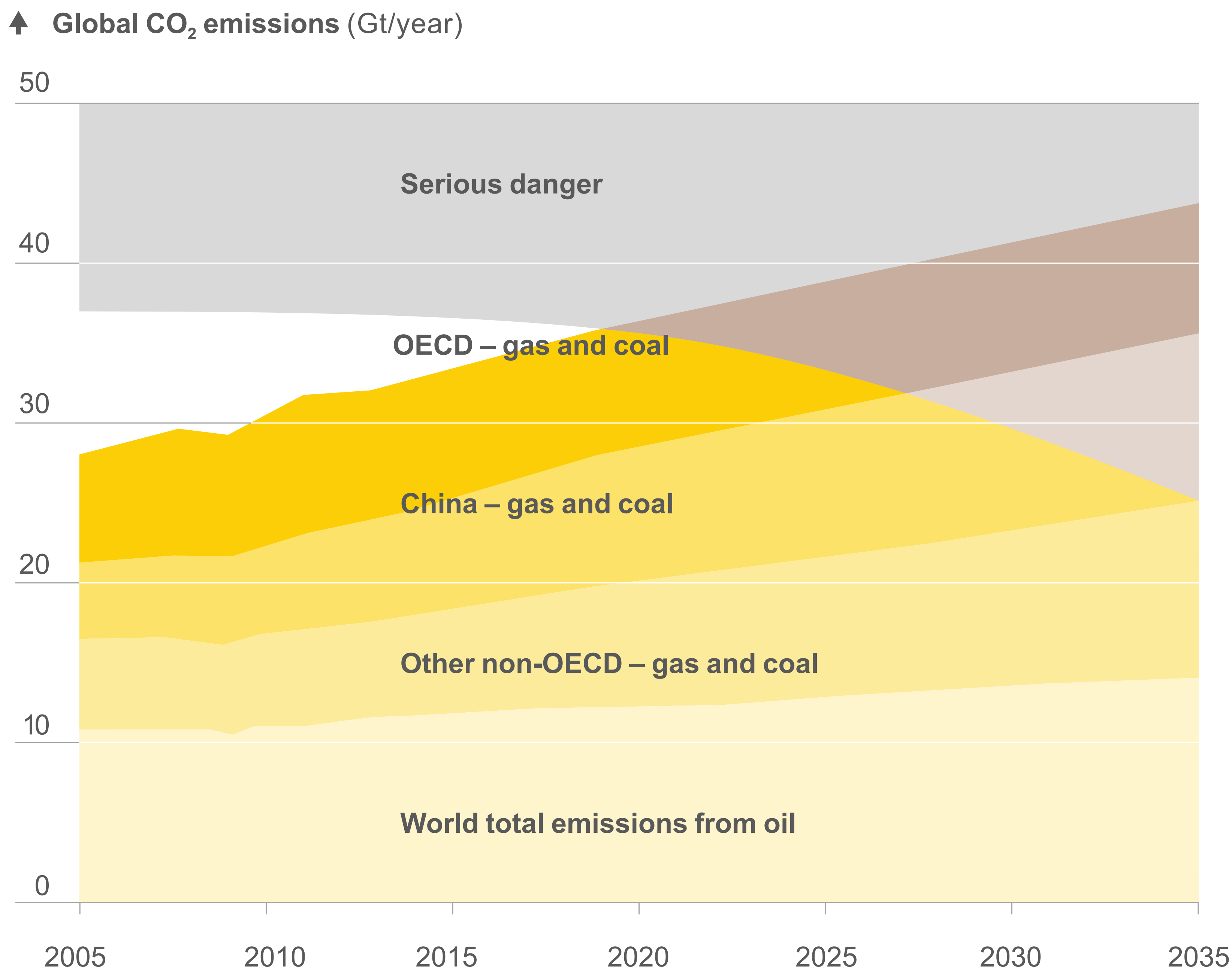

Figure 3: The emissions data of Figure 2, but now with the emissions that are most readily captured – those from gas and coal – split according to geographic region.

Chinese emissions are still rising today, as the government presses ahead with plans to bring mains electricity to the quarter of the population in central and western parts of the country that do not have it. This is being largely done with coal. The view is that social and political needs make a short-term increase in emissions unavoidable, but that before long other measures to reduce emissions will take effect.

It is possible that, as a rising economic and military power, if China takes a firm stand on emissions reduction, there could within half a decade be pressure on neighbours and trading partners to do the same. This pressure might be applied through import duties on goods from countries that refuse to manage their emissions and continue to make heavy use of fossil fuels. In short, China could turn out to have both the power and the desire to push the world towards a low-carbon economy. For the reasons given earlier this would almost certainly require the widespread implementation of CCS and it is notable that China already has a major CCS R&D programme.

Towards a second generation

The evidence that anthropogenic emissions from the burning of fossil fuel are having a strong and adverse effect on the global environment is very strong. Climate theory suggests that the longer effective action to reduce emissions is delayed, the more serious the long-term climate damage will be. The International Energy Agency (IEA) states that without CCS, the costs of tackling climate change by 2050 will increase by 40%. The problem is therefore urgent and this urgency is not reflected in the glacial progress of CCS technology or indeed in the efforts to develop alternative energy sources we see today.

Although there is understandable concern over the potential costs of CCS and other low-carbon energy sources, a study carried out by Nicholas Stern for the UK Treasury in 2007[7] showed that it was virtually certain that the long-term global costs of not taking urgent action on climate change were many times larger than those of acting on emissions and new energy sources now. The implication is clear that it would be very much in the interests of wealthy countries of the developed world to develop practicable and affordable CCS technology urgently and then make it widely available.

The relentless increase in the global demand for energy simply reflects the legitimate aspirations of developing countries to achieve living conditions closer to those of the OECD. In the absence of practicable alternatives this demand will largely be met by fossil fuels. Given that non-OECD countries are responsible for around 60% of global emissions today and virtually all the growth in global emissions will come from them, any global emissions strategy that cannot be implemented there will be of little value. There is no doubt that China will play a pivotal role.

Although the current generation of CCS technology is too expensive for adoption outside the developed world, it is hard to see any way of controlling global emissions without it. The costs of first-generation CCS will certainly fall, but however welcome this is, it is unlikely to be sufficient to make CCS affordable for developing countries, and it is hard to avoid the conclusion that novel and disruptive second-generation technologies are needed if CCS is to be cheap enough to be adopted there. However, there can be no second generation without a first. The good news is that various companies claim to have developed the technology to reduce capture costs to 20-30% of current estimates.[8] We shall see.

The development of cost-effective CCS will not guarantee timely and effective control of global emissions, but it is certain that such control cannot be achieved without it. The dilemma is that we cannot live without fossil fuels and we cannot live with them unless we have CCS.

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Ron Oxburgh is a geologist and geophysicist. As a Life Peer he is a member of the British House of Lords, where he sits on its Select Committee on Science and Technology. He is a Fellow of the Royal Society, an Honorary Fellow of the Royal Academy of Engineering and a Foreign Member of the US Academy of Sciences. During 2004-05 Lord Oxburgh was a non-executive chairman of Shell Transport and Trading.

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Notes and references

1. I am indebted to Gert Jan Kramer for an interesting and constructive discussion of ‘affordability’ as, in this context, the tolerable price difference between an incumbent technology or service and one that meets the same fundamental needs but carries additional benefits. He points out that even if something is affordable for consumers it may not be ‘do-able’ in an open market if, for example, it involves an initial investment that is seen by investors as relatively high for an unfamiliar technology.
2. http://archive.theccc.org.uk/aws/EMR%20letter%20-%20September%2012.pdf.
3. The Boundary Dam Power Station (100 megawatts coal) in Saskatchewan, Canada reports that it started operation with full CCS in March 2014. This is a world first.
4. P.J. Cook (2012). Clean energy, climate and carbon, *Carbon Management, 3 (3)*, 259-263, doi: 10.4155/cmt.12.28.
5. CCS Cost Reduction Task Force (2013). Final report. The Crown Estate, the Carbon Capture and Storage Association and the UK Department of Energy and Climate Change.
6. R.J. van Benthum (2014). *CO_2 capture by condensed rotational separation*, PhD thesis, University of Eindhoven: Eindhoven, ISBN 978-90-386-3525-5.
7. N. Stern (2007). *The economics of climate change*, CUP: Cambridge.
8. http://www.inventysinc.com/latest-news/former-us-energy-secretary-steven-chu-joins-board-of-canadian-carbon-capture-company-inventys-thermal-technologies.

Refining the role of the refinery
New challenges to old technologies

While refineries have enjoyed a long and prosperous life in the 20th century, they will survive and quite possibly thrive in the 21st as they adapt to serve in particular the transport needs of a world with 9 billion people. The feedstocks will become more varied, as will demand for their products.

> *Carl Mesters*

A new refinery is being built in Redwater, in the Canadian province of Alberta. In September 2017, after four years of construction, it will start producing diesel fuel from the region's notorious bitumen. The refinery isn't exceptional because of its feedstock or the product. Yet the simple fact that a refinery is being built is exciting. It has been almost 30 years since North America got a large, new, greenfield one.

Refining is core to much economic and industrial activity. Oil-based fuels provide 96% of transport energy. The oil-derived chemicals market is estimated at €2,700 billion ($3,000 billion) per year,[1] excluding pharmaceuticals. These chemicals form only a small fraction of all materials produced; the total mass of concrete is five times as much and that of steel four times as much, but chemicals are 5-10 times as valuable per unit mass.

While populations have grown in recent decades, and economies (mostly) with them, the number of refineries in the world has been declining. But the remaining ones have got bigger, so that capacity still grew in that period. At present, though, there is not enough demand to keep refineries working at full tilt. And the industry shouldn't expect an automatic return to the golden age of refining (which in fact lasted only from 2004 to 2007 with refinery margins well above $10 (€9) per barrel). The chemistry of crude oil and its derivatives doesn't change, but economic and social conditions do. This will force changes to both the input and the output of refineries.

Of course, it has never been otherwise. For centuries, millennia even, the 'oil industry' has been adapting, improving the processes to make oil useful, while managing changes in what came up from the earth and in the way people used the products.

According to the classical Greek historian Herodotus, the walls and towers of Babylon were constructed (long before his day) with asphalt. The material was known to his readers; there was a pitch spring on the island of Zacynthus. And, indeed, archaeological research has shown that on the banks of the Euphrates, an oil seep existed where 4,000 years ago asphalt was quarried for use as mortar. Asphalt was also used in ancient times for waterproofing containers and boats. The Egyptians used liquid oil as a medicine, and the Persian army made flaming arrows with it.

Deeper oil was sought and found as well. In Persia, in 1594 AD, oil wells were dug down to a depth of 35 metres (115 feet). As is so often the case with major technologies of the Middle Ages, the Chinese were there much earlier and better: in 347 AD they drilled for oil with hardened bits on bamboo pipes to a depth of up to 240 metres (800 feet).[2]

The actual conversion of crude oil to finished products started with the discovery of distillation: the separation of a liquid into fractions with different boiling point ranges. The general principle was discovered by Greek alchemists in the first century AD, and their techniques were later adopted in the Islamic world. By the 12th century, distillation had become so advanced that white naphtha was a common product for sale in Damascus.[3]

In 1847, the process to distil kerosene from petroleum was (re-) invented by James Young, who separated a natural petroleum seepage by distillation into a light, thin oil suitable for use as lamp oil, at the same time obtaining a thicker oil suitable for lubricating machinery. In 1848 Young set up a small business refining the crude oil.[4]

In these early days, any products other than these desired ones were simply burned. The first application of ‘cracking’ the molecules of these rejected fractions, to obtain products with lower molecular weight that could be sold and used, was in 1915.

Cracking made great strides during World War II. Just as the fear of the Germans acquiring nuclear bombs led to a massive effort in physics research, the need for a fuel suitable for aircraft led to a lesser known but comparable effort in chemistry. In a very short time, fluid catalytic cracking was developed, a process in which not only heat, but also the interaction with certain chemicals known as catalysts, helps large molecules to separate into smaller ones. Nowadays, catalytic cracking is the standard approach in almost all refineries.

Today’s refineries

Further need for differentiated products and specifications has resulted in the refinery complexes of today, where crude oil feedstocks and other hydrocarbon sources, such as biomass and natural gas, are converted into a variety of products that typically find application in the transportation sector, from fuels and lubricants to road asphalt (see Figure 1). Other products are used as raw materials for the petrochemical industry to produce commodity chemicals such as ethylene, propylene and aromatics, which are subsequently converted to intermediates such as polymers and oxygenates, which are further functionalised to a large number of consumer end products, ranging from household detergents (soap and shampoos) to fabrics and materials for construction, including houses, cars, etc.

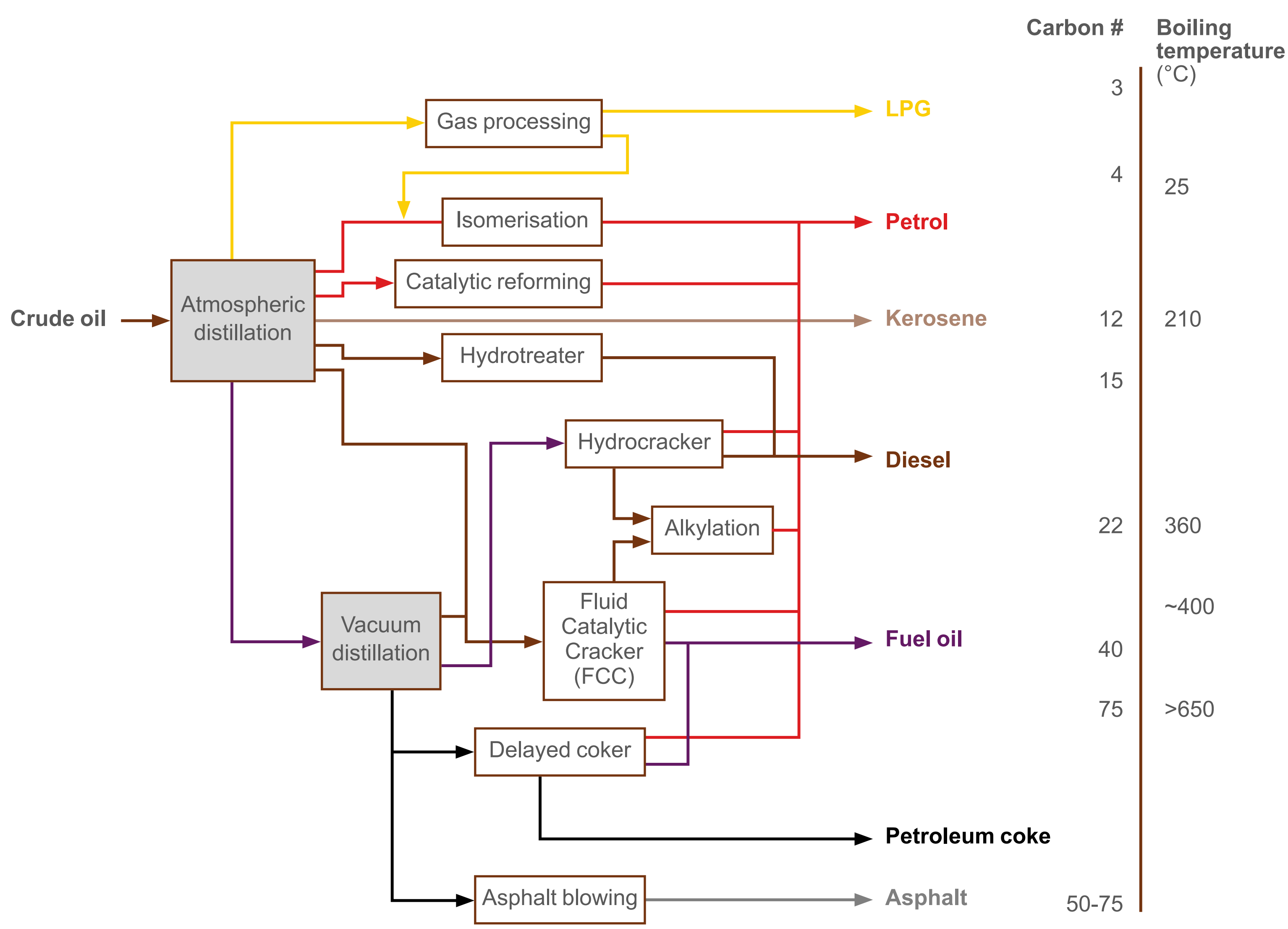

Figure 1: Simplified scheme of a refinery. The molecular weight of process streams and products increases from top to bottom. Indicative carbon numbers and boiling temperatures are shown in the scale on the right.

Any product or intermediate product in a refinery is a mixture of hydrocarbons with a specific boiling range. At the start of the refinery stream primary distillation occurs, as gas is released from the crude oil. The gas is purified and either used internally in the refinery as fuel or sold as liquefied petroleum gas (LPG).

The next higher boiling fraction is naphtha. The molecules in that stream may be structurally changed by isomerisation, which means their shape changes into a more branched configuration. This gives the product a higher octane rating, that is, it can be compressed more strongly before it spontaneously ignites. In this stage it is also possible to change the actual composition of the molecules, resulting in naphthenes and aromatics.

Depending on the complexity of the refining plant, the residue remaining after primary distillation is either sold (as marine bunker fuel or for inland power generation) or further upgraded after vacuum distillation. In that case, the vacuum distillate is typically fed into a fluid catalytic cracking unit where the large molecules are converted into smaller pieces, which typically fit the petrol boiling range but also provide valuable components for the chemical industry, such as propylene and C4 olefins.

Alternatively, this distillate stream can be ‘hydrocracked’ to provide blending components for diesel fuel. This latter process also reduces molecular weight, but to a lesser extent, and improves diesel fuel properties by increasing the hydrogen content of the products. Specific refineries might have both fluid catalytic cracking and hydrocracking units.

The residue of vacuum distillation can be converted via ‘bitumen blowing’ into a component that is blended into road asphalt, or upgraded through a variety of thermal and catalytic chemical ‘cracking’ processes to reduce the molecular weight to the range of distillate (boiling point) products such as naphtha, kerosene and gasoils, which need further treatment to improve product quality.

Economies of scale play a large role in refineries, resulting in ever larger complexes; whereas the total number of refineries has declined from 725 to 650 in the last 10 years, capacity has increased from 82 to 89 million barrels per day.[5] At present, this number represents a significant overcapacity of more than 5%, and is even higher when corrected for availability. This has depressed margins, and it is expected to get worse. To satisfy local demand, capacity is still expanding in India and China. In the Middle East, several oil-producing countries wish to increase the profitability of their own oil production. The new refinery in Edmonton in Canada will convert local bitumen. Meanwhile, in Europe demand is steadily decreasing, and in the rest of the world growth is sluggish. This is in part due to general economic growth, but also in part because some petrol from crude oil has been replaced by bio-ethanol as well as improvements in fuel efficiency.

In some respects, this rather undesirable situation would seem temporary. Looking further ahead one would expect that, with the world's population expected to reach 9 billion by 2050, more fuel for transportation would be needed, as would other refinery products and chemicals to make all kinds of products and materials, ensuring a bright future for the refining industry.

Mode of transport		Liquid fuels	Gaseous fuels				Electricity
			LPG	CNG	LNG	H_2	
Car	Short distance	++	+	+	–	+	+
	Long distance	++	+	+	–	+	–
Truck	Light	++	+	+	–	+	○
	Heavy	++	–	○	+	–	–
Rail		++	–	○	+	–	++
Ship		++	–	○	+	–	–
Aircraft		++	–	–	–	–	–

++ (Fully) compatible
+ With minor restrictions
○ With major restrictions
– Not compatible

LPG Liquid petroleum gas
CNG Compressed natural gas
LNG Liquefied natural gas
H_2 Hydrogen

Figure 2: Fuel flexibility for different applications.

But to successfully and profitably supply those 9 billion people, refineries will have to adapt, once again, to different circumstances. To get a sense of what might be coming, Shell has developed two scenarios[6] that project about the same energy consumption, and yet are quite different from one another, especially for energy use in the transportation sector. It seems plausible to expect that liquid oil and biomass will persist, and in fact will still be dominant in 50 years' time. But the scenarios differ in the number of electric cars that will hit the road, and hence the form of energy we need for transportation. A business-as-usual scenario foresees a threefold increase in transportation and a doubling of the oil use in that. But according to another, equally plausible scenario, overall transportation, although more than doubling by 2060, will, more importantly, have been largely electrified; the use of liquid transportation fuels will be lower than today, with the decline starting in about 25 years.

Very different in nature from previous 'peak oil' discussions, mainly driven by lack of new oil discoveries, in the latter scenario there will be a peak in the demand for transportation. That, if true, will ultimately limit the production of crude oil.

The drivers of these developments, deciding which scenario will come true, are on the one hand the growth of the world's population and the associated increase in distance travelled, and on the other hand local and global energy regulations and technological developments, the latter both in vehicles (drive trains, automation, including autonomous driving) and alternative energy sources. Of course, some forms of transportation will almost certainly be best served by current liquid fuels in 2050. This will be the case for long-haul transport, and particularly air transport, simply because other forms of energy storage will not be able to match their energy density (see Figure 2).

Even today, regulation is in place in regions such as North America and Europe that limits overall fuel consumption in cars by specifying overall carbon emissions for the entire fleet a manufacturer sells in a year. These vehicle specifications tend to become more stringent over time, as was very recently demonstrated by the European Union with the new 2020 vehicle efficiency requirements.[7]

Fuel choices

If an increasing concern with global greenhouse gas emissions continues to drive the utilisation of less carbon-intensive fuels, there is actually a lot of choice. Fossil fuels are not excluded from this game, for instance those with decreased carbon content, such as LPG and especially natural gas. Biofuels are important here, of course, if at least they offer a true reduction in greenhouse gas emissions, which means that in the growth and processing of biomass only a limited amount of fossil fuels may be used.

Next to global emissions, local environmental concerns can directly impact on modes of transportation and hence the fuels used. This will be the case in congested areas, such as megacities. Given that about 75% of the world's population in 2050 will live in a metropolitan area, the traffic density in terms of distance driven per unit area will increase and so will the emissions of noxious components by vehicle exhaust gases. Already, one of the major technical objectives of a refinery is to 'decontaminate' hydrocarbons to minimise such emissions, by tailoring their properties to improve the combustion process.

The process of regulation and adaptation has a long, successful pedigree

This process of regulation and adaptation has a long, successful pedigree. Removal of sulphur from fuels, in combination with flue-gas treatment of electrical power plants, has ended acid rain. And technology combinations of fuel composition, vehicle engine management and exhaust gas purification catalysts have in many places done away with local smog phenomena – although the reduction in exhaust gas emissions has been partly undone by the increase in distance travelled. Moreover, these technical solutions typically don't improve fuel economy. This is simply due to the fact that combustion for optimal power and efficiency can be achieved at a higher air/fuel ratio than is optimal for minimising emissions.

Just as with overall greenhouse gas emissions, local emissions, too, tend to be lower when fuels contain less carbon. This is not only the case for gases, but also for liquids, such as gas-to-liquids (GTL) diesel, which produces less nitrogen oxides, less particulates and even less noise. Of course, for local emissions hydrogen- or electricity-powered vehicles have the lowest impact, and it is to be expected that their use will increase substantially – although the production of electricity can cause local emissions, especially for power generation using coal.

The outlook for petrochemicals is relatively more straightforward in that the growing population will need more materials and products derived from petrochemicals, especially if average income and wealth improve. Even now, petrochemicals are showing a healthy growth rate that is actually slightly higher than the annual growth of energy.

Not all crude oils have been created equally

Typically, the products derived from petrochemicals are not directly associated with local or global emissions, although their production obviously has an environmental impact. The increasing use of products such as shampoo, detergents, plastics and the like might cause some concern regarding recycling and disposal, but that is of a different order than issues related to the use of fossil fuels in relation to transportation and the resulting greenhouse gas and noxious emissions.

The future of refining is not only about the products, the transportation fuels and the petrochemicals but also about the feedstock, which today is mainly crude oil. However, not all crude oils have been created equally. There is a large variation in properties such as density, viscosity, boiling point distribution, hydrogen and carbon content, types and levels of impurities, etc. Although the average properties may not change that much, the individual cargoes of crude will show larger variations than has been the case so far. To what extent this will progress in the future will be completely dictated by economics, including the price of crude oil but also any taxes or penalties society might put on these different hydrocarbons in relation to their environmental effects.

Various newcomers, still denoted as crude oil, will have to be accommodated. For example, the current unconventional oil and gas boom in the USA gives rise to a large supply of 'light tight oil' – oil from shale formations which exhibits large variations in composition. On the other hand, extra heavy oil as in bitumen is coming to the market.

Biomass

Then there is the increasing role that biomass is going to play. There is ethanol for blending into petrol, but also derivatives of fatty acids as a diesel component. These blending components, added because of regulatory requirements in, for example, the European Union or the USA, based on climate concerns or security of supply, are the topic of an ongoing debate. They may compete with land use for food, and it is still debated if they are really more climate-friendly than crude oil products, when all greenhouse gas emissions associated with their production are fully accounted for 'from farm to wheel'.

Biomass will not only make up a larger part of the supply of feedstocks, it is also likely to be more integrated in the production of fuels in refineries than is the case today. Currently, the production of bioethanol from fermenting sugars is done in complete isolation. Similarly, the processing of fatty acids to make biodiesel blending components is done separately. These bio-blending components are then added to the respective fossil fuel (being petrol or diesel) at a refinery or depot.

Second-generation biofuels, starting from the non-edible parts of the crop, are more amenable for co-processing in existing or modified refinery equipment, as processing them involves chemistries that are somewhat related. At this stage, though, these processes are still in a development and demonstration phase.

In other words: the technology to produce biofuels from biomass not in competition with food, or from crops grown on non-arable land, is not yet competitive. From a technical perspective, one of the difficulties of biomass is that it has a low energy density compared to crude oil. That means that if one wants to use economies of scale and process them in very large plants, there are great logistical difficulties in getting enough feedstock to this plant: the volume will be overwhelming.

A second problem is that from a chemical perspective, biomass contains at least as many impurities as crude oil. These need to be removed before or during conversion to a transportation fuel.

Another new source of energy that has made its way into the transportation sector is natural gas, either as compressed natural gas (CNG), liquefied natural gas (LNG) or as a liquid product resulting from chemical conversion of natural gas (gas-to-liquids, GTL). In addition, natural gas is being converted to methanol, a versatile chemical compound which is an emerging raw material from which a number of commodity chemicals are produced.

Using natural gas to create GTL products will become particularly relevant if avoiding particulates, nitrogen oxides and other emissions will require fuel properties that are very difficult to achieve with diesel or other fuels derived from crude oil. However, given the different nature of the chemistry involved in GTL processes, it is unlikely that such a process will be incorporated in existing refinery processes; more likely these will be separate manufacturing units.

Refining crude oil, in sum, is going to change, but more in response to social changes and demands than technological ones. In that respect, the sector is commoditised; it's not about developing new chemistry, but about doing the things we do better, cheaper, more reliably, with more automation and using more analytical data, so that we make better decisions as to what crude to process.

Biomass conversion, on the other hand, does need technology breakthroughs to produce second-generation biofuels from non-edible crops in an economically attractive fashion. But even if this can be done, their actual contribution to transportation fuels might be modest because of the logistics of the supply chain, biomass simply having too low an energy density.

In this respect it will be interesting to see future technology developments to convert biomass as well as natural gas to petrochemicals, in particular ethylene and benzene. This will still have a beneficial impact on the environment, as it will cut down on the consumption of crude oil, while fixing the carbon for the bio-feedstock in products. Meanwhile, the value added as feedstock is converted to product is higher compared to transportation. And the scale necessary to be competitive with existing processes based on crude oil is significantly smaller.

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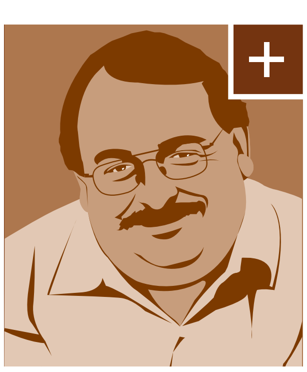
Carl Mesters is a specialist in catalysis, central to many processes in refining. He has worked on the development of major new energy projects, such as Pearl GTL. He joined Shell in 1984 and currently works as managing researcher at Shell Technology Center Houston. Mesters has been chairman of the Catalysis Society of the Royal Dutch Chemical Society. He has been a member of the scientific advisory board for NIOK, the Netherlands Institute for Catalysis Research. In 2005 he was appointed Shell's Chief Scientist for Chemistry & Catalysis.

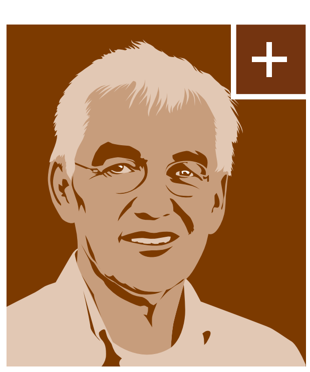
References

1. http://www.icis.com/resources/news/2013/10/18/9716315/market-outlook-global-chemical-growth-to-be-driven-by-the-us-asia/.
2. G.E. Totten. Timeline of petroleum history, http://www.astm.org/COMMIT/D02/to1899_index.html.
3. Z. Bilkadi (November/December 1984). Bitumen – a history. *Saudi Aramco World* 2-9. Retrieved February 25, 2014.
4. L.S. Russell (2003). *A heritage of light: Lamps and lighting in the early Canadian home*, University of Toronto Press: Toronto.
5. *Oil & Gas Journal*, December 2, 2013, http://www.eia.gov/forecasts/steo/report/global_oil.cfm. Retrieved February 2014.
6. http://www.shell.com/global/future-energy/scenarios/2050.html. Retrieved February 2014.
7. http://ec.europa.eu/clima/policies/transport/vehicles/cars/index_en.htm. Retrieved February 2014.

The energy density conundrum
When the days of easy energy are over

Between energy production and consumption, we increasingly need densification and new approaches to storage. This will change as much as production and consumption.





> *José Bravo and Gert Jan Kramer*

Back in the days of black and white TV, there was a man who took a shot at a rabbit and missed. Where the bullet hit the ground, he saw this black fluid ooze up. Soon after, a very rich family of rednecks moved into a mansion in a posh suburb of Los Angeles, to the amusement of millions.

The Beverly Hillbillies were the beneficiaries of a natural resource that has since been utterly depleted. Easy oil doesn't exist any more. No problem, you might think, we're doing quite well with oil that's somewhat harder to get out of the ground. But 'somewhat harder' has become 'quite hard'. And the alternatives to oil and gas, such as wind and solar energy, need equally massive deployment of equipment to deliver their energy for general use.

Looking past the differences in technology, you can tell the story of each of these energy sources in terms of their energy density. There is a big difference between a hole in the ground delivering oil and the parcel of land on which wind turbines could be built with the same energy output per day. This is not just a fact of life: it is the central theme of all energy development, from the time of the Texas wildcatters to a possible future of Saharan photovoltaics fields.

We are more used to thinking about energy density in the context of consumption. For instance, how many batteries would we need for an electric car to go as far as a regular car? Too many, is the answer so far. The energy density of gasoline and diesel is superior to that of electric charge in batteries. In fact, it has set the standard for all future products.

Getting to that density was the easiest thing in the world for the oil barons of the early 20th century – think Rock Hudson and Elizabeth Taylor in 'Giant'. Following the wildcatters, they based their business models on oil that readily came out of the ground – often with dangerous enthusiasm. Their energy source could be had at an accessible depth in a temperate climate. It was not too viscous, and didn't bring up much sand or water to be filtered out. The process of energy densification necessary to convert the natural resource into high-quality mobility products was simple distillation.

As these products became ubiquitous, older energy sources fell by the wayside, and their competitive disadvantage was precisely their lack of density: wind that allowed the ships of the colonial era in the 15th to

18th centuries to cross oceans just by setting sail. Wood that for millennia was the major provider of heat. Their lack of density made them less affordable. But these days, humanity must take a new look at what it can afford. We would like to find an energy source with a density equal to easy oil. Even more dense would be better, of course: this preference is so obvious, and so strong, that it is a theme in many science fiction movies, and has even acquired a standard chemical designation: as viewers of the movie Avatar well know, it's all about the Unobtanium.

But failing its discovery in our time, the energy industry is in the business of densifying energy. And it seems that in the journey towards sustainability of our energy system, we will have to work ever harder at this, as the energy sources that remain available to us are less dense than the ones modern society was built with (see Figure 1).

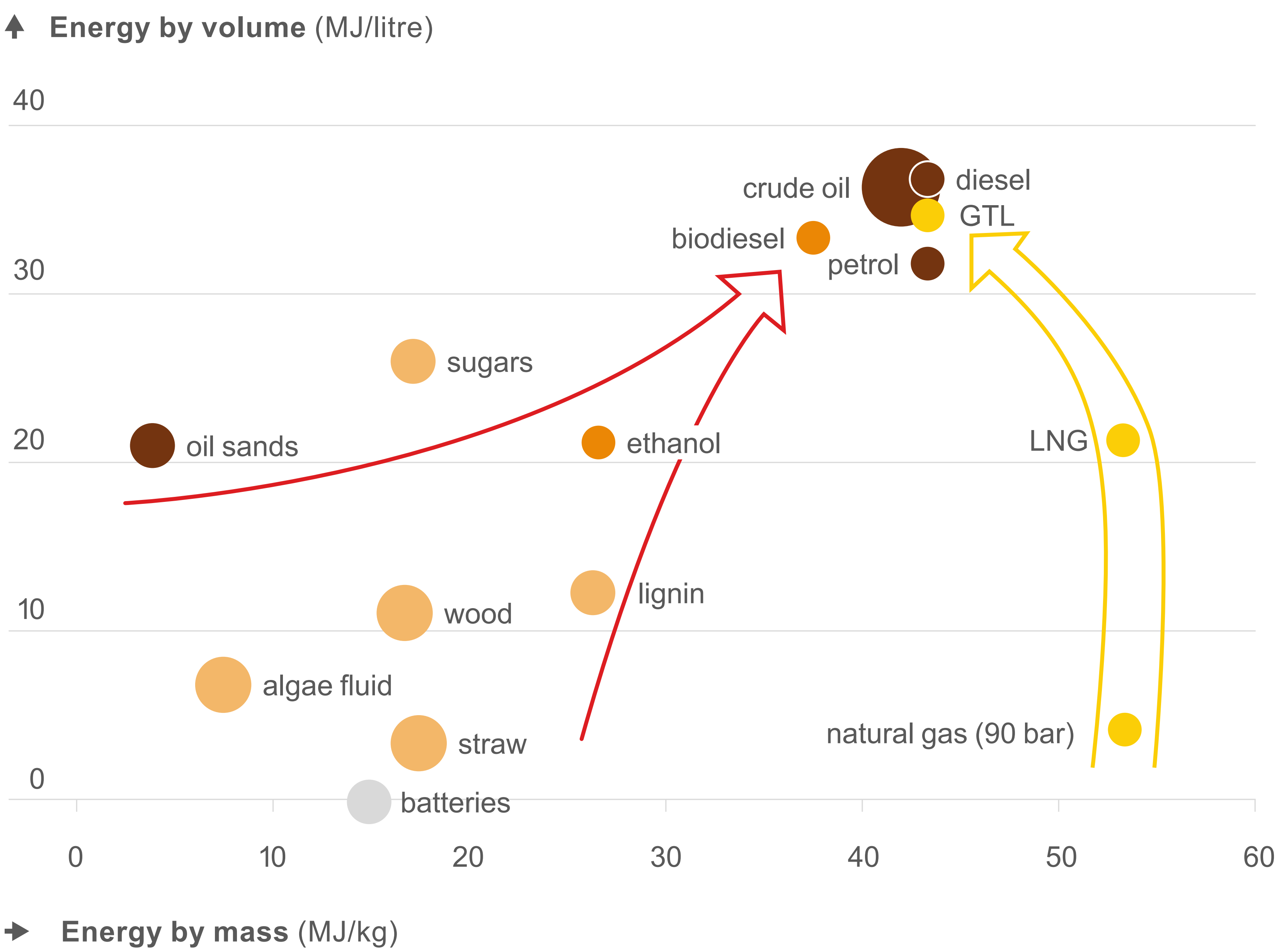


Figure 1: Comparison of the actual volumetric and mass energy content of resources and products. The journey of energy densification is a move to the upper right corner.

The conundrum

There's no reason to find fault with our technological forebears for having done the easy things first. In that respect, human technology was obeying, as all of nature does, the laws of thermodynamics. But now it has come to the end of the easy road, where it is confronted with a quadruple whammy of demands on its energy system.

Whammy number 1 is simply that the world needs more energy, as its population grows and its economy develops. But it also wants (whammy 2) energy products that are more pure than ever before: less sulphur, less soot, less emission of metals, a better cetane number. At the same time (whammy 3) the sources of energy are becoming ever more difficult to access and ever more dilute in form. And finally (whammy 4), it's not only the energy-carrying fraction of our raw materials that we have to densify. The need for a sustainable energy supply compels us to purify the ever increasing amount of waste material into levels suitable for reuse, recycling, or at least efficient and non-harmful disposal.

Sources of energy are becoming ever more dilute

This conundrum has extensive social, economic and environmental implications. Technology and its effective implementation into the system is clearly an important enabler and that is where we, as engineers and scientists, can focus our creativity and innovation impulse. But the systems we apply technology to are increasingly more complex and the development of point solutions often proves to be counterproductive. What is needed is to look at these problems and their proposed solutions from a systems point of view.

Unconventional resources

One way to look at this is that almost all the energy we can use comes or has come from the sun in one way or another. Nature has naturally densified the energy content of fossil fuels with the aid of time in a very slow process. The renewables are all solar in origin as well, but have not benefited from the natural densification process of ageing that fossils have.

The only exception to this is nuclear energy. This is a very dense energy resource, and whatever may be said against it, it also scores really well on the density of its waste products. Former US President Ronald Reagan is reputed to have said that a year's worth of nuclear power plant waste could fit under a desk.

The next densest energy resource – so far – is oil and gas, and here the energy density challenge manifests itself in various ways, as more and more is harvested as unconventional oil and gas (see Figure 2). The hydrocarbons in the oil sands, for instance, are intimately mixed with surrounded rock, sand and clay. The processes required to liberate such hydrocarbons are energy-intensive and demand large amounts of materials handling. Specific technologies we consider for use under these circumstances include mining/extraction, steam-assisted gravity drainage (SAGD), and hydraulic or heat stimulation of the reservoirs. Development of other oil resources, in particular shale gas and light tight oil, requires the use of very large numbers of wells, a very visible way for this energy resource to show its lack of density.

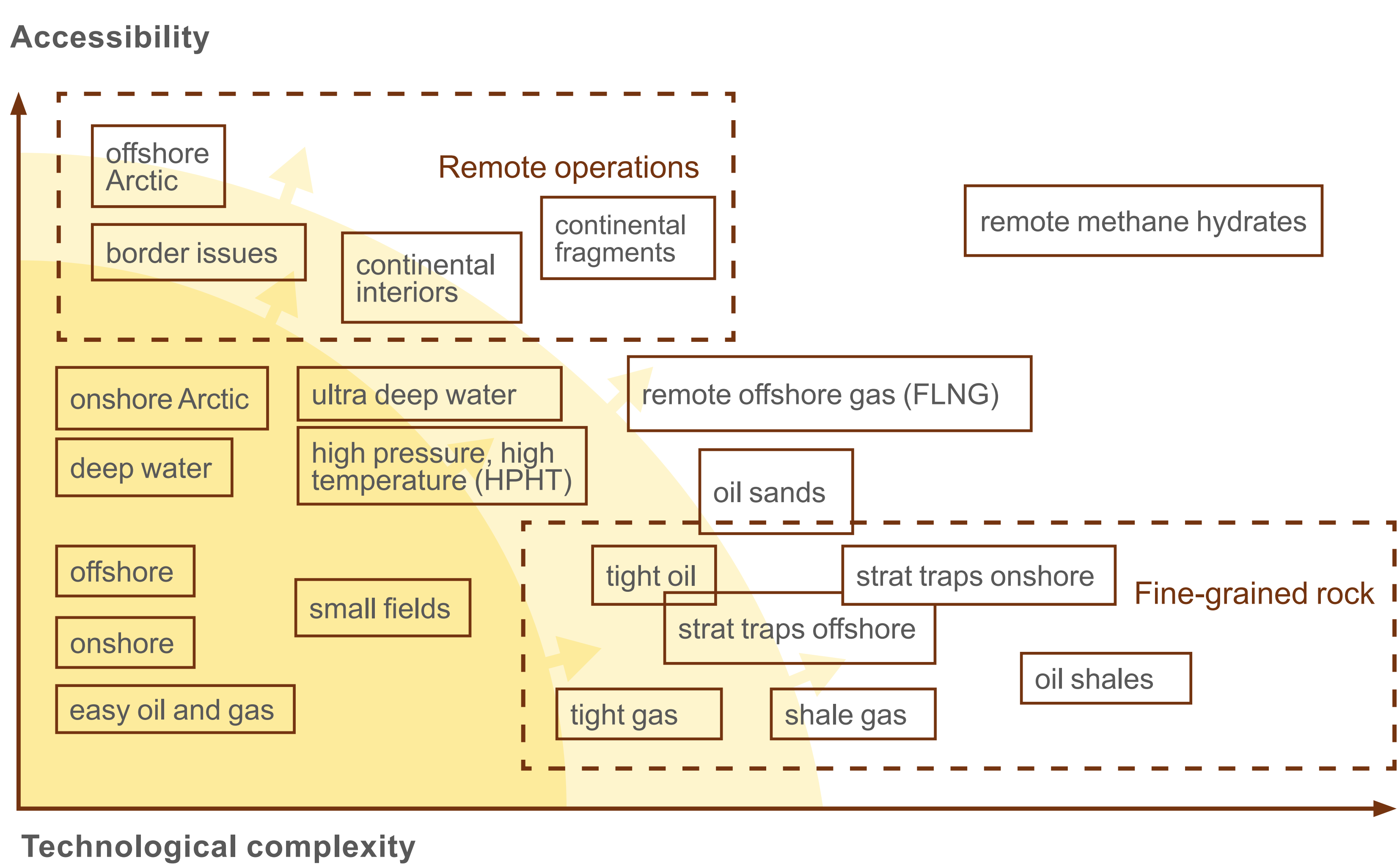


Figure 2: The relative difficulty of exploiting fossil fuel resources.

Many by-products result from the operations described above. In particular, it is a common issue that large amounts of produced and process water are often mixed with hydrocarbons, sands and clays that need to be separated. The economic impact on projects can be very severe, particularly when we see that we sometimes handle as much as ten units of water per unit of oil produced. If we look at it from the systems point of view, it is as much a water business as an energy one. And maybe that is why in the last few years activity in this sector seems to have peaked, with oil companies deciding that this is not the business they want to be in.

Of all the renewables, the energy resource most akin to oil is biomass. It was humanity's preferred energy resource until it became unsustainable, as population growth outpaced the capacity of forests. When in the 16th century London had to switch to coal, there was an almost instant call to remedy "the Inconveniencie of the aer and smoak" it created – as the subtitle of John Evelyn's pamphlet *Fumifugium* (1661) has it.

Nowadays, it is of renewed interest that there is energy available in biomass and meanwhile we have the technology – or the ability to develop the technology – to unlock it and densify it much more than was traditionally possible. Here, too, the removal of air and water, and non-energy material, are paramount. Preferably as soon as possible, perhaps even as part of the harvesting, to avoid handling of unwanted material down into the value cycle. Densification could also be accomplished by making less material unwanted: the conversion of energy precursors into energy products via catalysts and enzymes.

Systems thinking

There are textbook cases of where systems thinking has yielded successes and can yield some more. Clearly the scale required to produce biofuels in a meaningful manner has been successfully addressed in Brazil with the use of sugar cane for ethanol to replace gasoline in mobility. It is a success because the *system* of production makes sense. Brazil has the appropriate climatic conditions and the right soil for sugar cane growth. The production has a long history and has been continuously improved. Many sugar mills produce fuel ethanol and sugar side by side, and can flexibly shift between these products in response to market needs. Also, the cellulosic waste – called bagasse – is used for process heat and often electricity for export to the grid. The Brazilian sugar cane system is a good example of a sustainable renewable alternative to fossil fuels anchored in the local system. But this is not necessarily replicable to other environments.

New, low-density energy resources will turn land back into a valuable resource

For solar and wind we cannot point to a place where its deployment is already as mature as biofuels are in Brazil. It is therefore difficult to foresee how these technologies will mature as future energy *system components*. What we can see today is that photovoltaic panels work well when put on the roofs of homes and buildings. But ultimately roof space might not be enough. Wind seems to have blended well in certain relatively sparsely populated and windy places such as Denmark and Texas, but in more densely populated areas such as the Netherlands it calls up resistance, which limits deployment.

In order to appreciate the challenge of these new, dilute forms of energy, it is important to calculate the land claims that energy makes and will make. A calculation of that type has been attempted by Vaclav Smil, a Canadian geographer.[1] He remarks that classical economics, which as a science developed in parallel with modern industry, for a long time considered land a critical natural resource. In modern economics, on the other hand, it has scarcely figured. This situation is now about to be reversed once again, because the development of new, low-density energy resources will turn land back into a valuable resource.

According to Smil, and our own calculations, the world's energy production, excluding biomass, needs some 300,000 square kilometres (equal to the surface of New Mexico – see Figure 3). This is the land needed for hydro reservoirs, for oil rigs and refineries and for pipelines and transmission lines. If all the world's solar panels were lined up next to each other around the state capital Albuquerque they would still fit snugly within Bernalillo county.[2] This is going to change dramatically, if we are to rely more on renewable energy sources which are by definition dilute. In an energy scenario with a high share of renewables by 2050, the global land requirement to accommodate all energy systems would be something more like double the surface area of New Mexico (again excluding biomass). Solar modules alone would use almost all the land in Texas. This makes the extent of the logistics and densification challenge strikingly clear, especially for solar energy. The sheer effort of collecting this dilute form of energy and distributing it to densely populated areas is a major task. It also illustrates the future relevance of nuclear energy – its footprint is so small that it is lumped together with fossil in Figure 3.

The challenge of energy density comes at a time when humanity lives in higher densities than ever before. Civilisation has evolved in parallel with the increasing energy density of fuels. In the era when we warmed ourselves by a wood fire and ate the grains of the field, we needed about 1 square metre of land for each watt of energy that came available. When we tamed wind and water power, the energy yield of a square metre of land rose by a factor of 10, which allowed for larger communities. The advent of coal, oil and gas accounted for another factor of 100 improvement and heralded the era of urbanisation. Easy, more concentrated forms of energy allowed for a more concentrated community with a more complex division of labour.

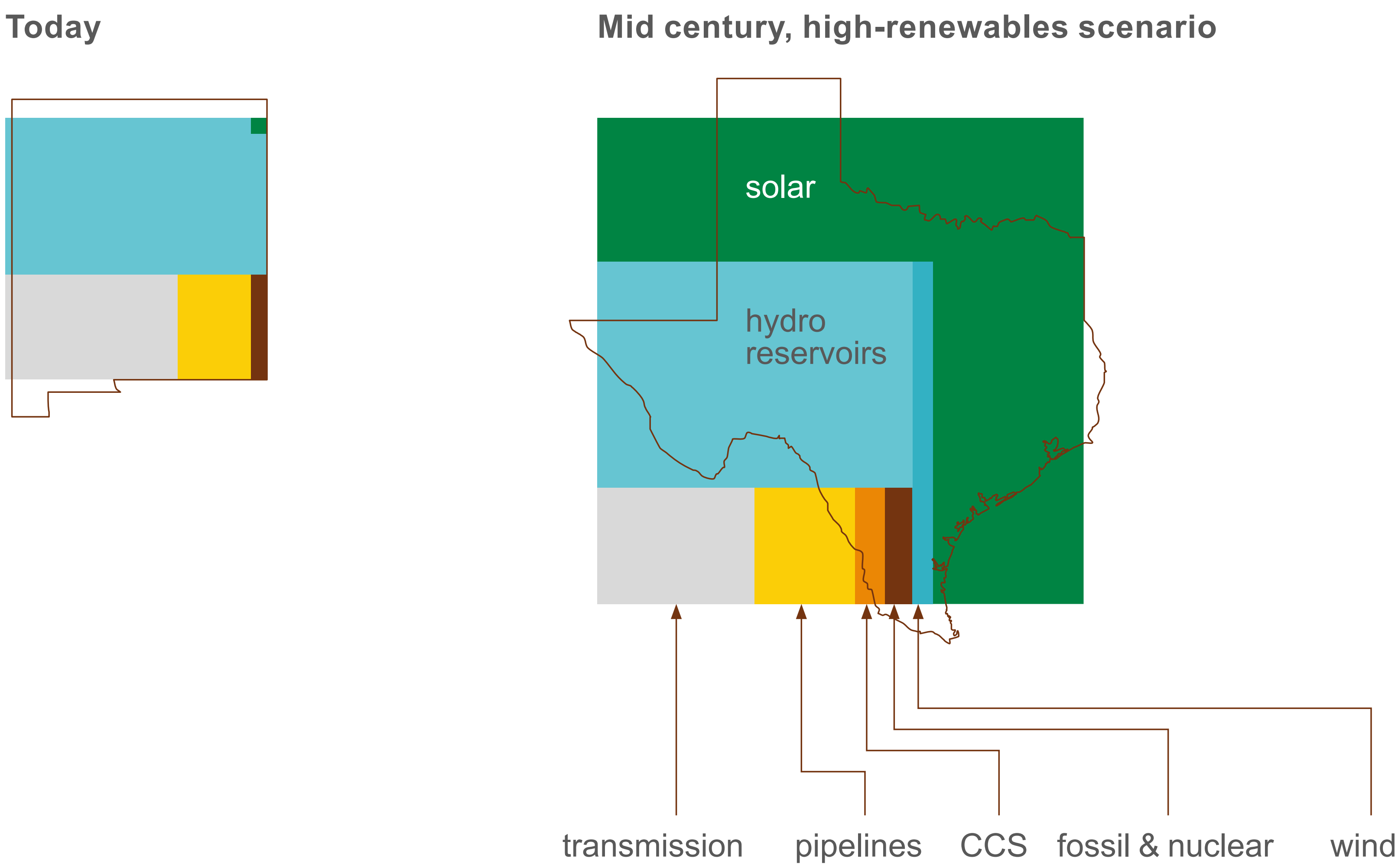


Figure 3: Rough estimates of the surface area in use for global energy production today, excluding biomass, overlaid on New Mexico (left). Similar estimates for 2050 in a scenario with a large share of renewables overlaid on Texas (right). Calculations adapted from Smil, ref. 1 (see text).

In the last century, innovation has progressively peeled away the density advantage of one energy source over another. Density is not a fixed given. Wind has cut space requirements by a factor of 2 in the past decades, although this is levelling off. Solar has halved its space requirements in the last decade and may densify further if we really need it. Eventually it is a question of the cost of space versus conversion efficiency. And even for energy sources that take a lot of space, any density can be reached by electrification of chemical densification. Innovation continues in this area. These efforts for densification are necessary to fuel society.

Related essays

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> *Oliver Inderwildi*

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> *Carl Mesters*

José Bravo is Chief Scientist Thermodynamics and Separations at Shell. He spent eight years as the Research Program Manager for Separations Technology Research at the University of Texas at Austin, USA, prior to joining Shell in 1995. He has published more than 50 technical papers and four patents in the Distillation and Extraction areas, and has published a book on the topic of separations technology.

Gert Jan Kramer is Manager Energy Futures at Shell Technology Centre Amsterdam. A physicist by training, he joined Shell in 1988 where he initially worked on classical oil industry topics such as catalysis and reactor engineering. In 1998 he became involved in research relating to hydrogen as a future fuel. Over the years his activities broadened to technology assessment across the full spectrum of alternative energies. In addition to his role at Shell he is professor of sustainable energy at Leiden University and a member of the Technical Committee of the Energy Technologies Institute in the UK.

Notes and references

1. Vaclav Smil (2007). *Energy in nature and society: general energetics of complex systems*, MIT Press: Cambridge, MA.
2. Bernalillo county covers 3,000 square kilometres, of which Albuquerque covers 500, leaving room for the approximately 2,000 square kilometres needed for today's global inventory of solar panels.

Earth sciences for the Anthropocene
An emerging discipline

Earth sciences have advanced thanks in no small part to their enormous value to oil and gas exploration. In this century they will prove essential for the assessment and management of a broader set of resources including water, geothermal heat and carbon repositories.

> *Dirk Smit*

We live in the Anthropocene – a geological epoch, characterised by man's imprint on the planet. For the first time in the earth's history, one species dominates earth systems. As the global population continues to grow and wealth increases, we are facing significant resource challenges to provide the required food, fresh-water and primary energy resources due to the sheer scale at which these have to be available.[1]

Indeed, because of this, production of resources can no longer be considered in isolation. Using a sizeable fraction of available resources has significant effects on other important life-sustaining systems. Beyond the issue of basic supply and demand, there are other problems looming: how can we optimise resource availability on both a global and local scale and how can we mitigate the expected impact of both the production and use on the local as well as the global environment?

These challenges need to be addressed by scientists in geology, ecology, biology, hydrology, oceanography and many other fields. Yet only an integrated approach can address the complex interactions of earth systems and resource production that are so characteristic for the Anthropocene. Integrating these disciplines – collectively known as 'earth sciences' – brings unique new knowledge and methods, combining physical, chemical and biological data for the interpretation of processes spanning varying magnitudes and timelines.

Earth sciences have been successful in the hydrocarbon industry where evaluating the commerciality of developing and then producing hydrocarbon reservoirs is a key competence. The need for an integrated approach has a strong analogy in the medical industry. Recently, there have been radical improvements in sub-dermal visualisation technology (such as ultrasound, mammography, MRI), allowing the collection of detailed data that has become the foundation of important medical diagnosis and decision-making methods. As the technology has advanced, more experts and specialised groups have become involved, from many different fields, resulting in more complex and accurate devices that are now even more widely used. It has also spawned the use of arthroscopic technology, creating a realm of unprecedented surgical precision that has significantly reduced negative physiological impacts on patients.

The beginnings of a similar revolution are visible in the hydrocarbon industry. The ability to gather, integrate and analyse data from many different sources allows for a better identification of new resources and the creation of sophisticated scenarios for their exploitation. Just as the medical industry was revolutionised by better ways to see inside the human body, the hydrocarbon industry will be transformed by further step changes to see inside the earth and understand more broadly the impact of subsurface resource extraction. New subsurface data collection and interpretation methods could foster other new technologies that would transform the process of hydrocarbon extraction in ways that are currently unthinkable.

With the advent of new – in particular integrated – technologies and methods pioneered and developed in the oil and gas industry, earth sciences are at a turning point.

This has a broad significance, not only for locating hydrocarbon resources. The technologies developed in the oil and gas industry are also important for the discovery of water resources. This may save lives. But it is also important for the industry itself. Water is an essential ingredient in many processes in the energy industry, which makes it only natural that the oil industry studies water provision. The seismic impact of hydrocarbon production is another important field of study, with a much broader significance than limiting the environmental damage of the industry's activities. Thus the role of integrated earth sciences is of wider relevance than 'just' for climate and environment in relation to fossil resources. It will be essential for solving the puzzle of how to meet resource demands, mitigate the environmental impact of their production and optimise availability.

Exploration of new hydrocarbon resources

To understand how earth sciences may become essential in many fields, it is illuminating to see how they have already contributed to more effective ways of discovering hydrocarbon reservoirs. The formation of oil, gas and coal depends on both large- and small-scale processes happening over widely varying time-frames, from the enormous movements of plate tectonics down to the most basic chemical reactions and physical changes that occur in the tiny pore spaces of the host rock. The combined effect of these various processes holds the key to why and how rock formations, once at the earth's surface, were transformed into the deeply buried hydrocarbon reservoirs.

Earth sciences help us to discover and exploit these reservoirs, thanks to the availability of more and better data from controlled lab experiments, computer modelling and field studies to identify the structure and characteristics of subsurface rock formations. There are now a host of data-gathering techniques that can detect the results of these processes at spatial resolutions ranging from 10^5 metres to 10^{-5} metres: satellite imaging (surface topography at the largest scale); airborne scanning for gravity and magnetic data (subsurface data on a regional scale); 3D seismic imaging (subsurface data on a local scale); and rock physics (intra-reservoir data at a molecular scale).

Robots deploy sensors on the ocean floor

As an example, let's look at a technique used extensively in the oil and gas industry to determine some of the factors that shaped and altered these ancient landscapes. The image of the subsurface shown on the left in Figure 1 is a high-resolution 3D seismic image of a field of sand dunes that are 5 kilometres below the ocean floor, which is itself 2 kilometres below the ocean's surface. On the right, a recent satellite image of the sand dunes in the Namibian desert is presented for comparison.

Seismic data used to derive this subsurface image is produced by exciting acoustic waves at the ocean's surface from many different positions. The waves propagate through the water and then through the sea floor into the subsurface. There, they reflect from the varied subsurface rock layers or 'strata' back up to the sea floor where they are detected by extremely sensitive sensors, called geophones. To eliminate noise, the sensors need to record the seismic data at thousands of locations, in a grid of typically 10 x 10 kilometres. Robots are used to deploy sensors accurately at a regular spacing on the ocean floor.

Scientists use the details of the seismic waves' propagation (for example, the wave speed, its dispersion while travelling[2]) to create high-resolution complex images of the deep subsurface strata with great accuracy. This requires massive amounts of high-performance computing power and complex mathematical models of how seismic waves propagate in actual rocks.

Figure 1 confirms the similarities in landscape between the seismic (subsurface) image and the satellite (surface) image, allowing us to reconstruct the processes that initially created this now-buried 165-million-year-old Jurassic landscape of sand dunes. Beyond that, we can use additional seismic images to determine how it was subsequently transformed by looking at the overlying, younger strata. The exceptionally high resolution of these images can reveal fine details, such as ash layers (usually tiny veneers) that indicate sudden events like increased volcanic activity. Some of these events caused climate changes resulting in major environmental shifts (for example, changes in sea level) whose impact on the landscape was significant. With this sophisticated technology, we are literally able to see 165 million years into the past in 'high definition', and thus visualise the structural complexity of these buried ancient formations.

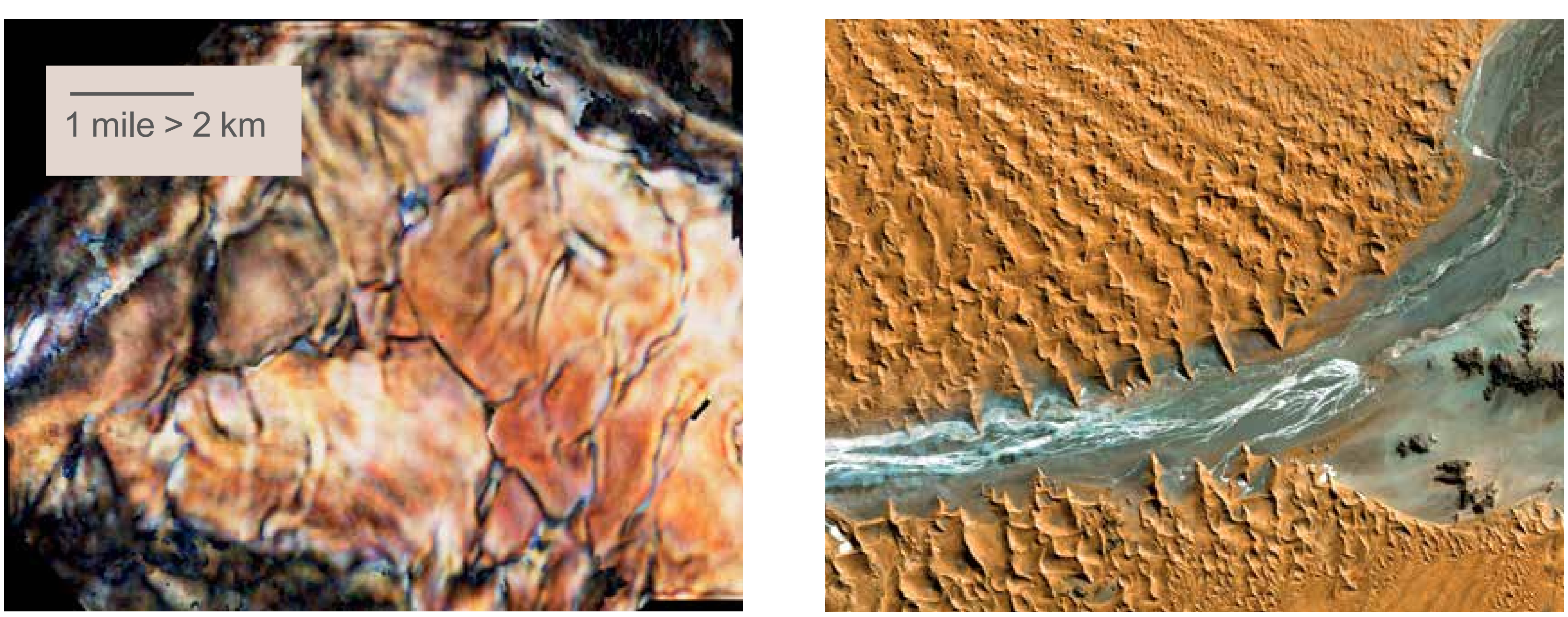


Figure 1: Left, a high-resolution seismic image shows sand dunes that were formed 165 million years ago, and then transformed into a buried hydrocarbon reservoir (source: Shell). Right, a modern-day satellite image at the same scale is shown for comparison (source: NASA Earth Observatory).

But simply obtaining an accurate image of these features and a general understanding of their evolution is usually not enough to locate potential hydrocarbon resources. How, then, do we find these? This is where data integration comes into play. One of the shortcomings of using seismic data is that it provides no information about the types of fluid that may be hidden within the formations it can image. A subsurface structure that appears promising may contain only salt water (brine) or it may contain hydrocarbons, but this cannot be determined from the seismic data alone. To identify these fluids we can use techniques that detect their electromagnetic properties. Plain salt water has a very low electrical resistivity compared to hydrocarbon-saturated brines. This can be detected using a radiotransmitter towed behind a boat which sails in a regular pattern. Antennas on the sea floor pick up tiny disturbances in the electromagnetic field caused by the higher resistivity of hydrocarbon-saturated brines. This data is used to compute a profile of electrical resistivity. The combination with seismic data allows us to identify hydrocarbon-bearing strata.

This is only one example of how integrating the measurements of different physical properties can be extremely useful. Yet combining data is often complicated, because different data-collection methods operate at different resolutions. In the example above, the seismic images of the sub-surface are of higher spatial resolution than the electromagnetic images. We face this same problem when we collect data at an even smaller scale: to fully understand how the different physical properties of the geologic formations are actually related, we must delve into the processes governed by rock and fluid physics that occur within the host rock's pore space. Scientists use high-resolution electron scanning to examine these processes at a microscopic level in a rock sample from the reservoir. Thus, data at three very different resolutions must be combined to give a picture of what lies in the subsurface.

Even with this integrated approach, it is not always easy to identify confidently a hydrocarbon-filled reservoir, as other fluid-rock interactions and other fluid types could produce the same results. As the hydrocarbon industry continues to strive for greater certainty in these interpretations, it drives important developments in the collection of the high-resolution subsurface data required for accurate imaging and methods of data integration.

Earthquake analysis

Earth sciences have also increased the understanding of seismic activity caused by oil and gas production. The extraction of fluids from a deeply buried reservoir can increase stress levels. This may induce subsidence and compaction. Usually these effects only occur at the reservoir level and are too small to be observed at the surface. Yet owing to faults present in the subsurface, this increased stress can cause them to slip, causing small local earthquakes. Recently these types of quakes have been felt in the northern Netherlands related to gas production in the Groningen gas field. Such quakes are also known in other places where large-scale extraction occurs, such as with water extraction in Spain, China and the Central Valley in California. Quakes may also occur as a result of injection – for example as recently seems the case in Oklahoma during waste water injection processes. Such subsurface instabilities may also be detrimental to the production process itself as they may lead to loss of production wells that could shear off. They may also disrupt other infrastructures and can affect the safety of those living and working in the region. In extreme cases, dams may be at risk.

Several new reservoir monitoring techniques give crucial insights on how we may be able to minimise earthquakes due to production. For example, fault activation processes may be monitored accurately through borehole measurements of tiny micro-seismic effects occurring at or near known faults in the reservoir. From these measurements, scientists may be able to conclude which faults may be under enough stress to make a failure with ongoing production likely. Yet, with these methods, it is difficult to estimate the extent of potential failure, and hence whether an earthquake is likely.

An unlikely but valuable improvement comes from satellites orbiting the earth that collect Advanced Interferometric Synthetic Aperture Radar (InSAR). Their high-resolution data can be used to observe surface compaction of just a few millimetres per year. This method has a host of potential geophysical applications, but in order for these measurements to be really useful, a high degree of integration with other data is crucially important. For example, when satellite data of a reservoir is combined with microseismic data from boreholes, and then integrated with seismic images, dynamic models can be developed that show the potential for slip along major faults as a result of increased production.

This information may then be used to decide on mitigation measures of the seismic 'tremor' effects. These developments are still in an early phase, but it is clear[3] that the use of satellite data (in the future possibly in combination with similar continuous geodetic measurements on the ground), integrated with other data sources, is crucially important to estimating and managing the economic and environmental risks associated with oil and gas production.

The data deficit

Our full understanding of many earth systems is hampered by a 'data deficit'. Portions of this deficit are simply givens: the geologic record is missing at various locations and the geologic record about the past climate is incomplete. At various points in time, significant portions of the record are lacking and must be deduced by interpolation. Fortunately, the missing portion of the record varies greatly from region to region, and often we can reconstruct some aspects of the absent sections provided we have sufficient data for sophisticated interpolation methods. But if there is insufficient data, we have no way to fill in these gaps.

Another limitation is a general lack of data from deep in the earth, far below the crust in a region called the 'solid earth'. For example, questions about the carbon cycle (important for sustaining life) require significant understanding about the solid earth, where major events in the cycle occur. Likewise, our understanding of the water cycle is incomplete, in that it extends only to shallow aquifer systems and does not include comprehensively the effects of solid earth systems. Knowledge of the solid earth – even at shallow depths – is often lacking because sampling it is very expensive and difficult to do. Hence, earth scientists have only a rather limited understanding of the physical, chemical and biological processes that shape global resources.

This 'data deficit' has been an ongoing difficulty in the hydrocarbon industry and has driven the development of new low-cost sensor systems that may be deployed in their thousands. Several initiatives in this vein are under way, both for offshore and onshore applications. Offshore, new sensor systems will detect naturally occurring seepages of gas from the ocean floor. Other sensors will allow us to analyse the chemical composition of these gas bubbles as they travel to the surface. This technology will yield additional benefits such as capabilities for gas hydrate exploration, mining opportunities for rare earths, and the collection of comprehensive data from large-scale bacterial colonies that can reveal currents that circulate between shallower and deep water.

The ultra-deep sea floor has barely been mapped

This is truly a new frontier for data collection: only a small percentage of the ultra-deep water sea floor and subsurface has been mapped. While similar measurement systems have been developed by several oceanographic institutes, their cost has long been prohibitive and thus has prevented systematic sea-floor scanning. New inexpensive sensors will help routinely scan the deep sea floor and subsurface.

An inspiring example is a competition that is now under way to create pH sensors to monitor the oceans. The Wendy Schmidt Ocean Health XPRIZE challenges teams of engineers, scientists and innovators from all over the world to produce sensors that will affordably, accurately and efficiently measure ocean chemistry from its shallowest waters to its deepest depths. Doing this is now well within reach.

Shell has now put up a reward for those who map the deep-sea bottom efficiently over large areas. This has a broad relevance. It will shed new light on the character of natural venting systems. It may teach us about the occurrence of freshwater columns, the geology of which is still poorly understood. Knowledge of the deep ocean is also of great importance for climate models.

Onshore, the industry is rapidly moving towards deployment of, for example, low-cost wireless mechanical electromagnetic systems (MEMS) for seismic data acquisition. These systems are at a fraction of the cost of conventional geophone systems and can take high-precision measurements over a broader bandwidth that includes much lower-frequency data than is usually feasible. The data they collect helps understand how the geomechanical properties of a reservoir change when extracting a fluid from it. Inexpensive sensing networks are being developed for semi-permanent down-well and surface monitoring, as well as the technology to transform their data into predictive models.

These systems are especially important because of their ability to measure low-frequency seismic effects on a continuous basis. This may allow for the monitoring of the more ductile deformation processes that may accommodate strain in the reservoir.[4] Most stress due to fluid extraction dissipates in these processes; only a small fraction is released through earth tremors.[5] This technology is still in its infancy and in limited use. The key to its success lies in making it affordable so that it can be used routinely. Other potential industrial applications of this technology include monitoring the fluid injection processes used to stimulate production in hydrocarbon reservoirs, and the hydraulic fracturing processes used in shale gas production. Yet it is also advantageous for hazard detection in global earthquake seismology.

Another example of the industry’s innovation is in the development of airborne chemical sniffing technology. Over the past decade a new airborne survey technique called ‘light touch’ has been developed for mapping naturally occurring gas seeps, which might be an indication of an undiscovered hydrocarbon reserve.[6] This technology provides high-resolution data about both the location and emission rate of the sources detected, unlike other airborne methods.

The development of a high-resolution airborne ethane sensor that will be used to distinguish gas of geological origin from biogenic gas is also well under way. The methane sensor already has applications not only for hydrocarbon detection but also to identify environmental hazards such as methane leakages due to natural gas production. This issue has been raised again in relation to shale gas production in the USA and Canada. A recent survey[7] of the Barnett Shale shows that accurate emission rates can now be measured over large areas. Leakage from the Barnett Shale turned out to be less than 1% of production, well below the upper limit of 3.2% judged as environmentally acceptable[8] in order for natural gas to deliver an immediate climate benefit over coal.

Also old, well-established techniques are refined to fill the data deficit. This is true for magnetic and gravity measurements, perhaps the oldest field-scale geophysical method in hydrocarbon exploration. Their advantages are that they are relatively cheap and easy to conduct, providing 3D information from deeply buried strata, beyond the realm of other techniques. Their disadvantage is a low spatial resolution, which is the reason why this technique has been focused on only specific geologic features such as volcanic intrusions or basement faulting. Yet the benefits of large-scale yet affordable computational methods and developments in the defence industry now becoming commercially available have recently led to improved resolution, yielding better data quality and accuracy.[9] This now makes it possible to conduct these measurements in more places: airborne, or in deep water close to the sea floor.

One application of magnetic data in particular is as a ‘deep thermometer’ in sedimentary basins, where the temperature profile (and its history) is one of the key parameters that controls hydrocarbon accumulation. Most sedimentary rocks have magnetic properties induced by the earth’s magnetic field. They disappear deeper in the subsurface, where the temperature is higher. The boundary where this occurs is called the Curie isotherm. Until now, it has been impossible to derive the Curie isotherm from airborne magnetic data. Thanks to the recent development of low-cost sensor systems[10] scientists have been able to map the Curie isotherm under a large part of the north-western USA, including Yellowstone National Park (known for its thermal geyser systems). In addition to its use as a tool for hydrocarbon exploration, this technique will be useful in the study of geothermal energy resources and volcanoes.

Water and other resources

An integrated approach to earth sciences data is potentially a boon to the production of other resource industries. The sheer size and rapid growth of the global need for resources will inevitably necessitate more and better data for their management. This is critical to helping us meet many of our global resource challenges, not only for hydrocarbons, but for water and other primary energy resources. It is also fundamental to our understanding of how human activity shapes the Anthropocene, with its impact on climate and other earth systems. The key piece to understanding the complex energy and environmental puzzle is simply more and better data.

Yet the advances in earth sciences have come at a high cost: it has always been expensive to design and develop sensing equipment, conduct complex field studies and sophisticated lab experiments, and develop high-performance systems to process and image this data. Economic incentives caused earth sciences to evolve naturally in the hydrocarbon industry. Similar incentives do not exist in academic groups and other research communities, which has left them behind in methods and knowledge. This is bound to change with the advent of inexpensive equipment and the growing understanding that in the Anthropocene no earth system can be studied in isolation. Improved interpretation and modelling methods based on more accurate subsurface data will lead to profound improvements in handling the requirements for water and other resources.

Water supply problems may in the future meet or even surpass global energy challenges. However, compared to our knowledge of hydrocarbons, our understanding of the occurrence, formation and optimal production of water is deficient. There are important technical parallels between the water and hydrocarbon industries, and it is probable that advances in technologies may be leveraged from one industry to the other. The hydrocarbon industry itself is increasingly dependent on water supply. The essay by Tom Graedel and his colleagues in this book makes clear that almost half of all energy production involves large quantities of water. That will probably only increase. This makes it all the more important to have a clear view on the availability of water for production, as well as on responsible and efficient production processes especially where water resources are scarce, such as in dry or urbanised regions.

As in the case of hydrocarbon production, understanding the geologic record is essential for large-scale water production. For example, recent geophysical data obtained from the Grace satellite over a large area of north-western India shows an alarming drop in the water table as a result of rapid urbanisation and population increase.[11] Hence, more accurate insight into the occurrence and dynamics of the earth's water reserves on a regional and global scale may be in order if we are to successfully manage these resources.

Understanding water resources and their dynamics, and insight into optimal production and management of them, is similar to understanding the same aspects of a hydrocarbon reservoir. There are important differences (for example, the availability of surface water), but there are also strong parallels, such as the way temperature and pressure in a sedimentary basin controls many of the reservoir properties. These factors are caused by mantle convection processes and by plate tectonics – both active areas of research in academia and in the oil and gas industry.

Mantle convection processes can change the earth's surface.[12] The way this affects sea levels is fundamental to understanding the paleoclimate and environmental conditions that can affect both water-cycle dynamics and hydrocarbon generation. Recent studies indicate that vast amounts of water may be hiding in the lower regions of the crust, and that these reservoirs are connected to shallow water aquifer systems, but there is little knowledge of the potential impact of these deep reservoirs on shallower water that is accessible by drilling.

One way to get a better understanding of the water system would again be through the integrated analysis of multiple data sources, in this case, long-offset seismic refraction data, and possibly high-resolution gravity and magnetic data. The recent discovery of a shallow aquifer system beneath a large part of drought-ridden northern Kenya[13] was achieved using gravity and magnetic data studies similar to those for hydrocarbon exploration, and wider use of these techniques may help in discovering additional large-scale shallow aquifer systems.

Other water resources have also been detected. A recent study indicates that large reservoirs of fresh water (with salinities < 30% of sea water) are present in the shallow subsurface on many of the earth's offshore continental shelves.[14] However, accurate mapping of those fresh-water resources and understanding their genesis and dynamics is still in its infancy. These supplies seem to be found in accretionary prisms, which are important structures in the occurrence of hydrocarbons and stable forms of methane hydrates in the shallow subsurface. The coinciding presence of fresh water and gas hydrates raises intriguing questions about subsurface dynamics which earth sciences techniques developed by the hydrocarbon industry may be able to answer.

Other techniques from the hydrocarbon and mining industry have been developed to characterise water resources, not only in Kenya, but also in north-west Africa, India and elsewhere. One example is the WATEX technology developed by RTI, a French geophysical company specializing in remote sensing techniques many of which developed or in use in the hydrocarbon industry. It uses a combination of radar imaging and satellite data, so that groundwater may be detected even where roads, rocks or vegetation stand in the way. RTI used this technology during the Darfur crisis to quickly locate water resources to help more than 2 million displaced people.

Techniques from the oil and gas industry could also help to predict the seismic effects and environmental risks associated with large-scale water production, including the occurrence of earthquakes.[15] For example, geodetic data about surface deformation (such as compaction due to groundwater level changes) may be integrated with seismic data, thus providing a more precise and accurate dynamic deformation model of a compacting reservoir.

Likewise, this data would be valuable for developing better methods of storing carbon dioxide (captured as a by-product of industrial operations) underground in depleted oil and gas reservoirs. While the industry has developed a significant body of expertise in this area, there are still uncertainties associated with the long-term safety of injecting super-critical carbon dioxide fluid into the subsurface. Current monitoring technology has not yet given a reliable assessment of potential fault leakage or activation due to the increased pressure caused by the injection process.

Finally, this new technology may play an important role in geothermal energy production. In particular, the use of low-cost, ubiquitous seismic sensor networks may greatly improve our understanding of water flow driven by heat sources in geothermal reservoirs and hydro-energy engineering issues in general. Geothermal heat production at an industrial scale has been known to cause earth tremors, to an extent that the execution of these programmes is now at risk.[16] The accumulation of subsurface stress caused by large-scale water injection and production associated with the use of heat exchange mechanisms is not well understood. While similar dynamics occur naturally at a much larger scale in areas of volcanic activity, comprehensive dynamic flow models of these systems have never been produced, despite the obvious advantages to identifying and predicting potential geologic hazards. The integrated approach of earth sciences and the advent of affordable sensor technologies may now make these types of interpretation possible.

Meeting the challenges of the Anthropocene

If we are to successfully meet the challenges of the Anthropocene, it is imperative for society to have access to more accurate knowledge about the distribution of hydrocarbon, water and other energy resources, so that diverse groups can be involved in deciding the best course for their production and management. One of the greatest trials of this era could arguably be the challenge to meet the rapidly growing industrial-scale energy demand. This must be achieved in the face of competing demands for other resources by affordable and responsible means while mitigating the environmental and atmospheric impact. An approach that employs integrated earth sciences methods may prove successful in the discovery, production and management of geothermal, hydro-electric and other primary energy sources, as well as water resources.

These are more than just engineering problems. But this fact is not widely realised, despite some fairly obvious observations: our global resources are not evenly or efficiently distributed, they are sometimes absent or transient in nature, and they may require specific materials to facilitate their production. Ultimately, when these resources are produced at scale, more fundamental questions will inevitably emerge related to their available volume, and the environmental impact of their usage and production. Answering these questions will require important societal choices based on an integrated scientific understanding of issues related to both environmental concerns and optimised production. The insights and expertise developed by the hydrocarbon industry in the realm of earth sciences represent valuable tools for making these important choices in the Anthropocene.

Related essay

Entangled circles
Energy and its resource connections
> *Tom Graedel, Ayman Elshkaki and Ester van der Voet*

Dirk Smit joined Shell in 1992 and his roles have included chief geophysicist for Shell UK and technology manager for Global Exploration. Currently he is Vice President of Exploration Technology and Chief Scientist for Geophysics. Smit also holds a visiting faculty position in the Earth Sciences department of the Massachusetts Institute of Technology in the USA and has a visiting professorship in Geoscience at the Chinese University of Petroleum in Beijing. He was awarded the Ludwig Mintrop award in geophysics by the European Association of Geophysicists and Engineers in 2002.

Notes and references

1. D. Smit (2013). Discovering the subsurface, EmTech keynote speech, see videolink EmTech Conf, MIT, MA, http://www.technologyreview.com/video/521451/dirk-smit-shell/.
2. J. Scales (1995). *Theory of seismic imaging*, Lecture notes in Earth Sciences, SpringerVerlag: Berlin.

3. Committee on Earth Science and Applications from Space, National Research Council (2007). *Earth science and applications from space: National imperatives for the next decade and beyond, A Community Assessment and Strategy for the Future*, The National Academies Press, Washington, DC.
4. M. Zoback, A. Kohli, I. Das & M. McClure (2012). *The importance of slow slip on faults during hydraulic fracturing stimulation of shale gas reservoirs*, SPE paper 155476, presented at the Americas Unconv. Resources Conf, Pittsburgh, PA.
5. N. Boness & M. Zoback (2006). Mapping stress and structurally controlled crustal shear velocity anisotropy in California, *Geology*, *34*, 825-828.
6. B. Hirst, D. Randell, B. King & P. Jonathan (2014). *Mapping sources of methane emissions over the Barnett shale*, Shell Global Solutions International BV: The Hague, the Netherlands.
7. Funded by the Environmental Defence Fund (EDF) and led by the National Oceanic and Atmospheric Administration (NOAA).
8. R.A. Alvarez, S.W. Pacala, J.J. Winebrake, W.L. Chameides & S.P. Hamburg (2012). Greater focus needed on methane leakage from natural gas infrastructure, *Proc. Natl. Acad. Sci., 109 (17)*, 6435-6440, doi:10.1073/pnas.1202407109.
9. D. Smit, E. Biegert & J. Mondt (2003). *Advances in subsurface imaging using potential field technology: Gravimetry sensors and applications*, Barbican Conference, London.
10. E. Biegert, S. Saleh & D. Smit (2013). A method to constrain a basin model with Curie depth, World-wide Patent WO2013096187, patent pending.
11. M. Rodell, I. Velicogna & J. Famiglietti (2010). Satellite-based estimates of groundwater depletion in India, *Nature, 468*, 173.
12. P. Wheeler & N. White (2002). Measuring dynamic topography: An analysis of South East Asia, *Tectonophysics, 41*, 1040-1066.
13. The Kenya aquifer (see http://www.nytimes.com/2013/09/12/world/africa/aquifers-discovered-in-drought-ridden-kenya.html?_r=0) was found by RTI, a remote sensing company, using standard oil and gas remote sensing techniques. Shell is using satellite radar imagery in an ongoing programme to monitor carbon dioxide sequestration in the QUEST project in Canada by a similar process – there the carbon dioxide may cause brine in a shallow aquifer to come closer to the surface where it could potentially be detected by satellite radar imagery.
14. V. Post, J. Groen, H. Kooi, M. Person, S. Ge & W. Edmunds (2013). Offshore fresh groundwater reserves as a global phenomenon, *Nature, 504*, 71-78.
15. P. Gonzales, K. Tiampo, F. Cannavo & J. Fernandez (2012). The 2011 Lorca earthquake slip distribution controlled by groundwater crustal unloading, *Nature Geoscience*, published online 21 Oct 2012, doi:10.1038/NGEO1610.
16. W. Ellsworth (2013). Injection induced earthquakes, *Science, 341*, 142-149.

Gauging climate records

What the Earth's past can tell us about our future

The geological record shows that the Earth's climate is capable of rapid changes and that the current rise in carbon dioxide levels has no geological precedent.

> *Bruce Levell*

Even if the greenhouse gas content of the Earth's atmosphere in 100 years' time were to be known, the corresponding climate pattern of the Earth would still be very uncertain. This may seem surprising, after the decades of hard work by scientists to measure greenhouse gas levels and model heat exchange between land, air, oceans and space. Adding to this uncertainty the range of projections for the peak greenhouse gas content of the atmosphere by the end of this century is itself very wide: 600 to 800 parts per million (ppm) of carbon dioxide equivalent might possibly cover it. Reflecting this, the estimates of climate sensitivity, that is, the temperature impact of a doubling of atmospheric carbon dioxide from pre-industrial levels (290 ppm), remain stubbornly uncertain: from 2 to 7 degrees Celsius.

These large margins of error provide scientific space for both the doom-mongers and the climate sceptics and probably contribute to the resulting lack of truly collective action. Could they be made smaller by looking to the past? What does the geological record say about how the Earth system has responded to earlier changes in the levels of greenhouse gases? What did the Earth look and feel like when these levels were very high? Has anything ever happened that was like the experiment we are currently undertaking with our planet? In short, inverting the dictum of Charles Lyell, can the past be a key to the present?

Ironically, we are – or, more correctly, were recently – living in a period of almost unprecedentedly low levels of greenhouse gases in the atmosphere. And even more ironically, as we shall see, the oil and gas reserves that we have been burning were put into rocks by nature many millions of years ago, through natural responses which cleaned up surplus carbon in the atmosphere. During periods which may be among the closest analogues to what we are about to experience, the Earth system executed natural sequestration events producing coal seams and oil and gas source rock, but on a scale and over time periods that dwarf any 'carbon capture and storage' that we might attempt.

Probing climate

Predictions of the future effects on temperature of a rise in atmospheric greenhouse gases are based on global climate models using supercomputers. Yet the geologist's instinct is to look at the past, when analogous processes were at work, and examine the preserved record in the rocks of climate change that resulted from these. Their sources of evidence for past temperature and levels of atmospheric greenhouse gases (primarily water, carbon dioxide and methane) are many and they are rapidly proliferating. For all but the last 800,000 years these are exclusively indirect measures, known collectively as 'proxies'. Among the most widely used temperature proxies are those derived from samples of carbonate shells of marine organisms. The oxygen atoms in the carbonate are a mixture of three isotopes. They were taken out of the ambient sea water, in a proportion that was determined by the water's temperature at that time and place.

Carbon dioxide levels from the past can be inferred from counting the 'stomata', the pores on the surface of fossil leaves. Their number decreases as carbon dioxide levels rise. Another way to pry that information from fossils is by measuring boron isotopes in the shells of microscopic creatures called foraminifera. Again, the proportion of different kinds of boron atoms incorporated in the shells carries the information: it is controlled by the acidity of the sea water, which is influenced by the amount of carbon dioxide dissolved in the oceans, which in turn depends on the atmospheric levels of the gas.

For the last 800,000 years we can manage without the proxies by directly measuring air inclusions in ice crystals from ice cores. This record overlaps with the proxies, which allows calibration of the proxies themselves. These proxies can give us a very detailed view, both geographically and in time, but only provided we can reconstruct both the precise age and the specific isotopic or geochemical reservoir sampled by the different methods. This is a considerable complication for reconstructing the evolution of 'global climate'. Seasonal and regional effects would have been as pronounced in the past as now, so it is hard to say whether differences between two samples represent actual climate change, let alone how rapid this change was.

This has not deterred scientists from trying. Typically, the approach adopted is to use the available data to calibrate one or more global computational paleoclimate models, and then test the model validity by further data collection. It is important that these models take into account the correct positions of continents and ocean basins, as well as their topography and the interconnections between water masses, restoring for the plate tectonic changes over the intervening millennia.

Ice cores

In comparison, the last 800,000 years offer a wealth of data on carbon dioxide levels, with much better details in the time dimension, without the need for proxies: by directly measuring air inclusions in ice crystals from cores. Combined with detailed temperature records from oxygen isotopes in the oceans this has given us a reasonably clear understanding of why the Earth's climate keeps changing. It turns out that the primary natural climate forcing mechanisms are solar, volcanic and – by far the most important – orbital.

The energy that our planet receives from the sun each day used to be known as the 'solar constant'. In fact it does vary somewhat, but if there are mechanisms in the Earth system that amplify these variations, nobody has yet discovered them. A possible exception is variation in the ultraviolet component of the sun's radiation. It is conceivable that this could, via stratospheric feedbacks, be playing a role in decadal climate oscillations. Over much longer time periods, astrophysical evolution models for the sun suggest that in the earliest history of the Earth, before about 3.5 billion years ago, the sun was fainter than today. However, for our purposes we can currently do no better than to regard solar insolation as 'constant' over any particular period of Earth history we are looking at.

Another influence on climate is volcanic activity. Over millennial timescales this forcing is sporadic and unpredictable. It may have occasionally been dramatic and it is implicated in occasional large swings in atmospheric carbon dioxide.

The most regular and persistent forcing of climate comes from the perturbations of the Earth's rotation axis and orbit. In particular, these have been shown to give rise to glacial cycles. They work primarily, at least in the recent past, through their effect on the insolation of the northern hemisphere, where the sea ice presents an opportunity for feedback. If, for instance, decreased insolation causes ice not to melt there in summer, the increased reflection of sunlight by the ice will further lower temperatures and increase ice cover even more.

Orbital metronomes

Thanks to the combined effects of these cycles we currently live in an interglacial period, a warmer period within an ice age. Comparison with orbital parameter sets for previous interglacials suggests that the current interglacial might end within 1,500 years. Yet due to the relatively weak orbital forcing associated with the Earth's present orbit shape, we can only expect an ice age if atmospheric carbon dioxide were to be no higher than about 240 parts per million,[1] which is even lower than pre-industrial levels. Present human-induced carbon levels are so high that there is no analogue in the glacial cycles of the last 800,000 years.

Several other orbital 'metronomes' are in play. A roughly 400,000-year cycle is governed by Venus and Jupiter. Given the large mass of Jupiter, this period is likely to have remained stable over the past several hundred million years, imprinting a detectable, regular cycle of climate change on the geological record of Earth and probably also Mars.

From the time of the early Earth, some 4.5 billion years ago, the overall trend of atmospheric carbon dioxide levels has been downward. Biological activity has relentlessly been converting a large fraction of the original carbon endowment of the atmosphere into rock – principally calcium and magnesium carbonates (in limestone and dolomite) and into bacterial and algal organic matter in shales and coals. But of course, superimposed on that trend are periods of high and low carbon dioxide levels.

Searching among those for analogues of the high greenhouse gas atmosphere we are creating for ourselves today is not quite as straightforward as it might seem (see Figure 1). Of course, one could choose times when absolute levels of atmospheric carbon dioxide were close to those predicted in a 'business as usual' scenario for the end of the current century – something like 600-800 parts per million carbon dioxide equivalent. Another option is to try to see what happened when carbon dioxide levels weren't particularly high or low, but were rising at the quite extraordinary rate they are at present.

Climate parallels

Somewhat reassuringly, even in periods when the geological records tell us that atmospheric carbon dioxide was up to, say, 1,000 parts per million, global average temperatures on Earth are broadly familiar. There was always some place on Earth where conditions would merit them being called 'habitable' with respect to our present experience, even if the distribution, geographically and over the seasons, would not be familiar and the habitable zone for humans could have been very small.

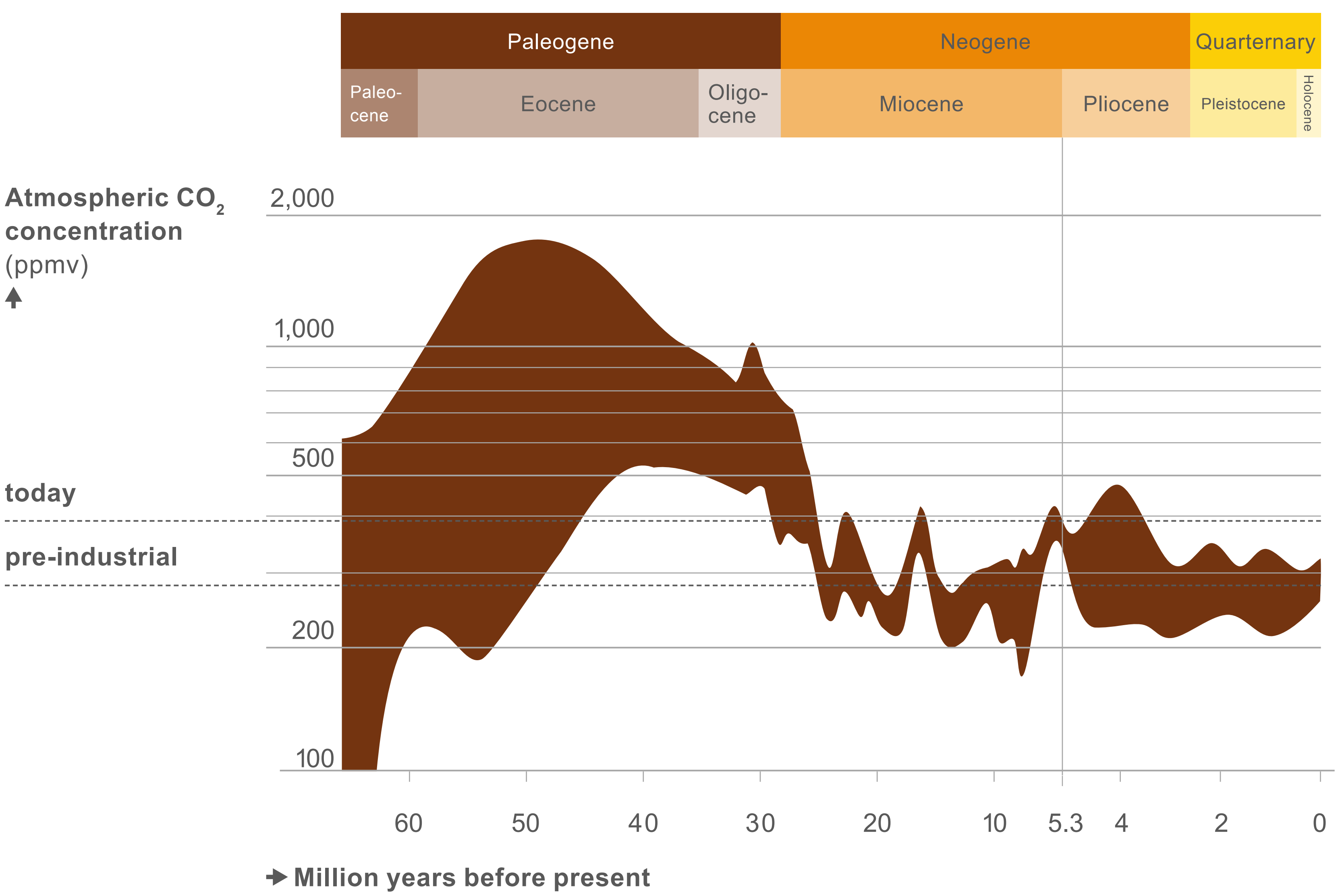


Figure 1: Historical atmospheric carbon dioxide levels. The width of the ribbon reflects the uncertainty in the measurements (one standard deviation) (source: based on Fig 5.2 of IPCC (2013). Climate change 2013: The physical science basis, CUP: Cambridge).

As far as absolute carbon dioxide levels are concerned, geologists have zoomed in on three periods in particular for their potential similarity to modern conditions. The first one is the last interglacial before the one we are in now. It occurred from 129,000 to 116,000 years ago. Reconstructions and simulations of its warmest millennia show that global mean annual surface temperatures were never more than 2 degrees Celsius higher than in the pre-industrial period of our own interglacial. During this time, atmospheric greenhouse-gas concentrations were also close to our pre-industrial level. Global sea levels were 5-10 metres (16-33 feet) higher than now.

A second candidate is the Early Pliocene (5.0 to 3.0 million years ago). This is the period preceding the current set of northern hemisphere glaciations. It was characterised by atmospheric carbon dioxide concentrations from 350-450 parts per million and global mean surface temperatures approximately 2-3.5 degrees Celsius higher than for pre-industrial climate. As such it is often picked out as a potential analogue for future climate. The continents and oceans were also pretty much the same as today's – for instance, the Atlantic would have been only some 180 kilometres (110 miles) narrower. This is an important requirement for an analogue. Ice sheets were still present, but Greenland and both the West and East Antarctic ice sheets were a lot smaller than they are now. Global sea level was not more than 20 metres (65 feet) higher than now, but how much higher it actually was, we don't know.

Despite these similarities in carbon dioxide levels and climate, the Mid Pliocene was startlingly different in a number of other respects. Isotope data from marine organisms suggest that sea surface temperatures didn't differ as much from equator to poles as they do now. And the warm surface layer over the oceans didn't reach as deep as nowadays. The problem with that is that current global climate models, using the reconstructed carbon dioxide levels, struggle to match these observations. Furthermore, the climate seems to have been quite sensitive to changes in carbon dioxide levels. A decrease of between 50 and 100 parts per million was sufficient to induce – or was associated with – a structural climate change: the world tipped into a northern hemisphere ice age.

A third candidate is the Early Eocene Climatic Optimum (54 to 48 million years ago). From that period a mineral, nahcolite, has been found which only precipitates when carbon dioxide concentrations are over 1,250 parts per million. Global mean surface temperatures were 10-15 degrees Celsius warmer than today. There were no polar ice sheets, indeed turtles and palm trees lived at latitudes of 80 degrees, far north of the polar circle.

This degree of polar warming has proved problematic to climate modellers. But because the configuration of the continental plates was markedly different from today – for example the North Atlantic was only just being opened at this time – any direct climatic analogies with the modern era are tenuous at best.

Somewhat later, at about 50 million years ago, the geological record shows an apparently rapid reduction in carbon dioxide, which is attributed to the bloom of a planktonic freshwater fern, *azolla*, over the entire surface of the Paleo-Arctic for a period of about 800,000 years. The Arctic Ocean at this time appears to have had a stable freshwater surface layer in which the fern could live. Drawdown of atmospheric carbon dioxide of perhaps up to 470 parts per million is attributed to this unprecedented carpeting of the surface of an ocean-size water body by a single species. This biomatter ended up in a regional hydrocarbon source rock in the high Arctic that was only discovered in 2006 through the International Ocean Drilling Programme on the Lomonosov Ridge.

Rapid changes in carbon dioxide

If we want to look for past rates of change in temperature or carbon dioxide levels comparable to today, due to the limitations of proxy data we are for the most part limited to the past 800,000 years, for which we have the ice core records. Rates of change of carbon dioxide in those cores are to the order of 10 parts per million over 100-year periods. Those are 100 to 1,000 times slower than what we observe now.

As for temperature changes during that period, perhaps the most alarming are the so-called Dansgaard–Oeschger events. These were first recorded in the Greenland ice cores and have subsequently been found in cave and oceanic records. They show temperature increases at quasi-periodic intervals of about 1,500 years over the last glacial period (100,000 years).

The temperature follows a sawtooth pattern: 5 degrees Celsius of warming over a few decades, followed by slow cooling. Their origin is not understood.

Not knowing even an approximate rate of change for earlier times isn't to say we aren't aware of any dramatic increases in the absolute amount of carbon dioxide in the atmosphere in certain periods. These have been detected as 'carbon isotope excursions', sudden changes in the geological record of the proportion of heavy versus light carbon atoms.

These excursions indicate major disruptions of the carbon cycle and can have a variety of causes. In some cases, more heavy carbon isotopes would have been released to the atmosphere from volcanoes or metamorphosed limestones. In other cases, more light carbon would be released in the form of biologically sourced methane or carbon dioxide.

The most extreme isotopic excursion currently known in the entire carbon isotope record of the Earth is from the Late Precambrian, about 560 million years ago. The 'Shuram excursion', a dramatic shift to isotopically light carbon, discovered first in Oman by Petroleum Development Oman and subsequently found globally, is still unexplained.

The most recent major carbon isotope excursion was the Paleocene-Eocene Thermal Maximum event, about 56 million years ago. This event was marked by a massive carbon release, and a global warming estimated from proxy data to be 4-7 degrees Celsius. The carbon release was 4,500-6,800 billion tonnes, comparable to the total carbon that is in all currently available fossil-fuel reserves. But it happened over 5,000 to 20,000 years – translating into a rate of emissions of between 0.5 and 1 billion tonnes per year,[2,3] which is only one tenth of today's emission rate.

Ironically, such emission events often resulted in warming of the oceans and increased biological productivity there. This would eventually cause the bottom waters to be depleted of oxygen and hence organic matter being preserved: not being oxidised or eaten. This in turn resulted in the formation of the rich source rocks which generate much of today's oil and gas.

Unprecedented climate experiment

All these attempts to compare past climate with present conditions were motivated by our need to catch a glimpse of the future.

In particular, we'd like to deduce from them the climate sensitivity, the shorthand way of getting from a change in carbon dioxide level to a global temperature increase. Estimates for modern conditions range from a 2 degrees Celsius temperature rise, for a doubling of carbon dioxide from pre-industrial levels, to a 7 degrees rise.

This sensitivity is the net result of a host of processes, and its value will depend on the starting conditions, such as carbon dioxide, temperature, geography and the Earth's orbital parameters. At the moment, the atmosphere is thought to hold some 56% of the available carbon dioxide from all sources. This proportion is unlikely to have been the same during previous spikes in greenhouse gas emissions, and for that reason alone the sensitivity will on those occasions have been different.

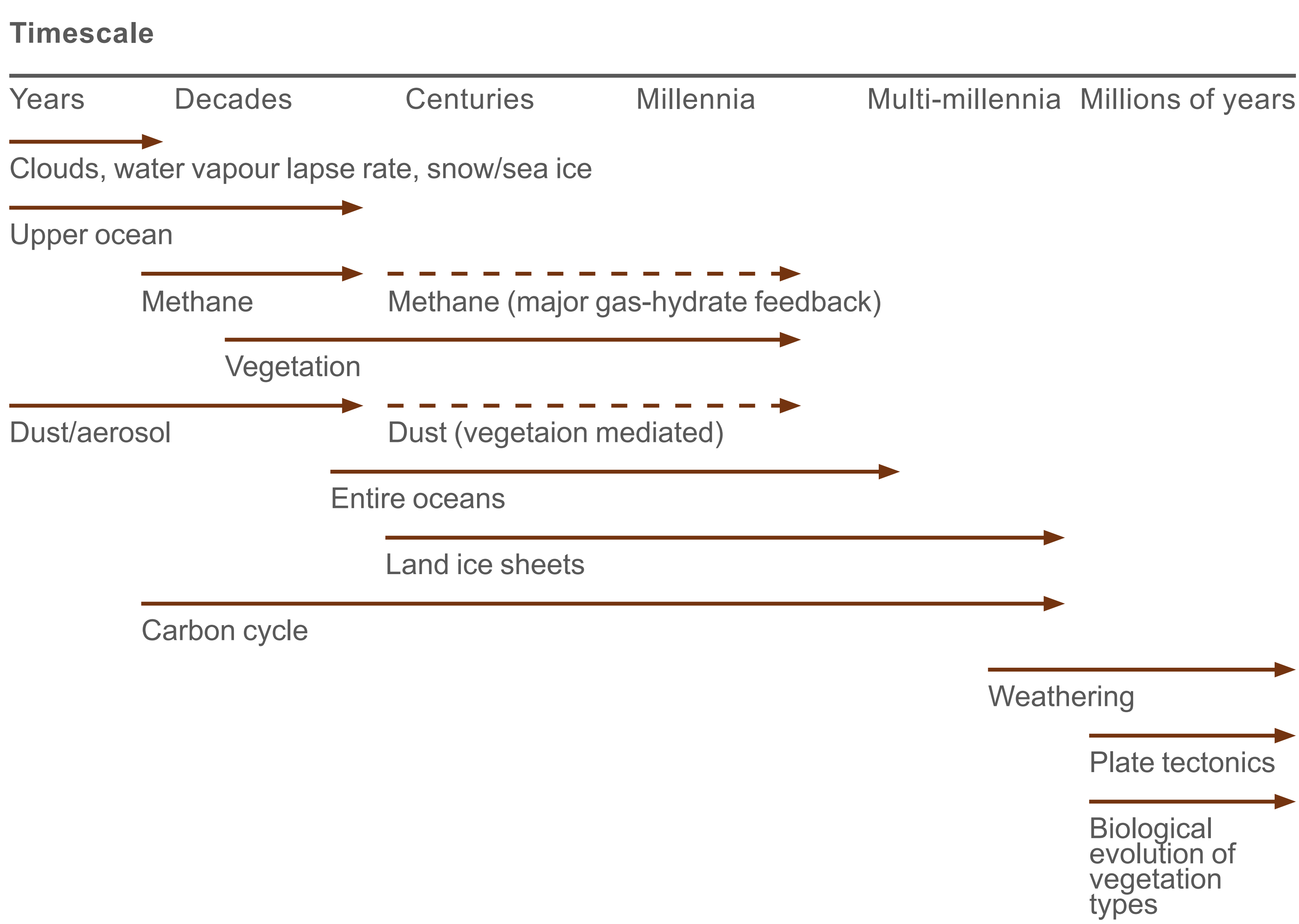


Figure 2: Timescales relevant for climate feedback mechanisms (source: reproduced with permission from *Nature*, *491*, 683-691; see also Further Reading).

In addition, faster rates of greenhouse gas emission not only will obviously lead to higher levels of carbon dioxide, but perhaps more surprisingly also to higher sensitivities. This is caused by the feedback loops that are involved.

So, in fact, there are both fast and slow climate sensitivities (see Figure 2). And which one we are measuring depends on which timescale we are studying. Geological studies perforce deal with slow climate sensitivity, as they lack the time resolution to do otherwise. Hence extrapolation of their results to predict our own future on a decadal timescale is unwise.

So how will the Earth's climate fare in the next century? The work on the geological record to date sheds little quantitative predictive light on the consequences of the current atmospheric experiment. The geological record shows that the Earth's climate, in terms of surface temperature distributions and the temperature structure of the oceans, is capable of rapid structural changes which we often can't explain.

Furthermore, changes are happening to this complex non-linear system consisting of oceans, atmosphere, lithosphere and biosphere, at what is quite likely to be an unprecedentedly high rate. The past cannot, unfortunately, be a guide to the future, but by this result alone it is emphatically warning us.

Bruce Levell is a geologist and visiting professor at the University of Oxford. His research focus includes fluid flow in sedimentary basins using a combination of geophysical and geological data and investigations into Precambrian deposition, in particular shallow marine and coastal processes in Precambrian seas. Before moving to Oxford in 2013 Levell was Chief Scientist Geology and Vice President Emerging Technologies at Shell.

Further reading

- PALAEOSENS project members (2012). Making sense of palaeoclimate sensitivity, *Nature, 491*, 683-691, doi:10.1038/nature11574.
- H. Brinkhuis et al. (2006) Episodic fresh surface waters in the Eocene Arctic Ocean, *Nature, 441*, 606-609, doi:10.1038/nature04692.

- H.C. Jenkyns (2010). *Geochemistry of oceanic anoxic events, Geochemistry Geophysics Geosystems, 11 (3)*, doi:10.1029/20009GC002788.
- IPCC (2013). *Climate change 2013: The physical science basis. Working Group I contribution to the IPCC 5th Assessment Report – Changes to the underlying Scientific/Technical Assessment*, CUP: Cambridge.
- R. Caballero & M. Huber (2013). State-dependent climate sensitivity in past warm climates and its implications for future climate projections, *Proceedings of the National Academy of Sciences, 110 (35)*, 14162-14167.
- J.E. Hansen & M. Sato (2013). *Climate sensitivity estimated from Earth's climate history,* http://www.aecb.net/draft-paper-climate-sensitivity-estimated-from-earths-climate-history-by-james-e-hansen-and-makiko-sato/.
- A.V. Fedorov, C.M. Brierley, K.T. Lawrence, Z. Liu, P.S. Dekens & A.C. Ravelo (2013). Patterns and mechanisms of Early Pliocene warmth, *Nature Geoscience, 496*, 45, doi:10.1038/nature12003.

References

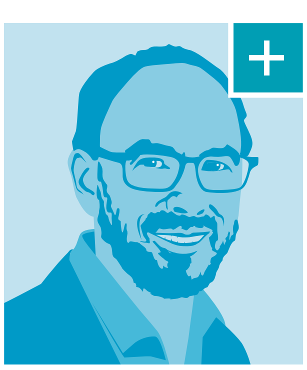
1. P.C. Tzedakis, J.E.T. Channell, D.A. Hodell, H.F. Kleiven & L.C. Skinner (2012). Determining the natural length of the current interglacial, *Nature Geoscience, 5*, 138-141, doi: 10.1038/NGEO1358.
2. K. Panchuk et al. (2008). Sedimentary response to Paleocene-Eocene Thermal Maximum carbon release: A model-data comparison, *Geology, 36*, 315.
3. R.E. Zeebe et al. (2009). Carbon dioxide forcing alone insufficient to explain Palaeocene-Eocene Thermal Maximum warming, *Nature Geoscience, 2*, 576-580.

Renewables and more

Relying on renewables alone presents a formidable challenge. How do they compare to nuclear fission and fusion? And how viable is the large-scale use of bioenergy?

The multi-terawatt challenge
Preparing photovoltaics for global impact

Photovoltaic solar energy will soon enter the era of self-sustained growth, limited by integration rather than by system cost. We need to prepare now for truly large-scale deployment.



> *Wim Sinke*

As photovoltaic solar energy technology matures, it gradually moves away from incentivised markets and becomes a competitive option with enormous potential for major commercial markets worldwide. This creates business opportunities beyond imagination, but also brings along new challenges. Realising this potential requires continued cost reduction but not, as is often stated, a technological breakthrough. The technology is already available in a variety of forms that, by further improvements and combination, could yield the necessary cost reduction already. However, the many new options that are under development hold out the promise of a still broader or accelerated deployment of photovoltaics. For photovoltaics to truly flourish, however, more emphasis should be placed on its electrical, physical and societal integration. This would pave the way for photovoltaics to have a large impact on a global scale, making it an important building block for a future sustainable energy system.

In fact, a combination of factors has determined the course of photovoltaic technology from its earliest days. John Perlin, in his book *From Space to Earth*,[1] describes how the modern solar cell became a success in space shortly after its invention. Large-scale terrestrial applications of photovoltaics were also already envisaged in those early days in the 1950s. Terrestrial success failed to materialise, however, because of high prices and a lack of urgency. Without a mass market for the product, prices would remain high – a stalemate that lasted a number of decades. Yet through dedicated stand-alone products, photovoltaics served small, high-value markets such as rural electrification, telecoms and recreation. On top of that, there were many demonstration projects, with photovoltaics on rooftops, ground-based power plants and other grid-connected and stand-alone applications. This allowed the sector to grow steadily, build a track record and gain experience. A robust, predictable, but rather slow process.

The development of photovoltaics gained impetus with Germany's '1,000 roofs' programme in 1991, followed by the '100,000 roofs' programme in 1999 and an optimised feed-in tariff system in 2004. This moved the market away from complex stand-alone applications selling only small units in relatively small numbers and with wildly varying support schemes, if any. The German incentive model for grid-connected photovoltaics applications was simple and extremely effective. It created a gigawatt-scale market for a range of system sizes and types. In modified forms it was adapted by several other countries. This helped photovoltaics grow rapidly (see Figure 1).

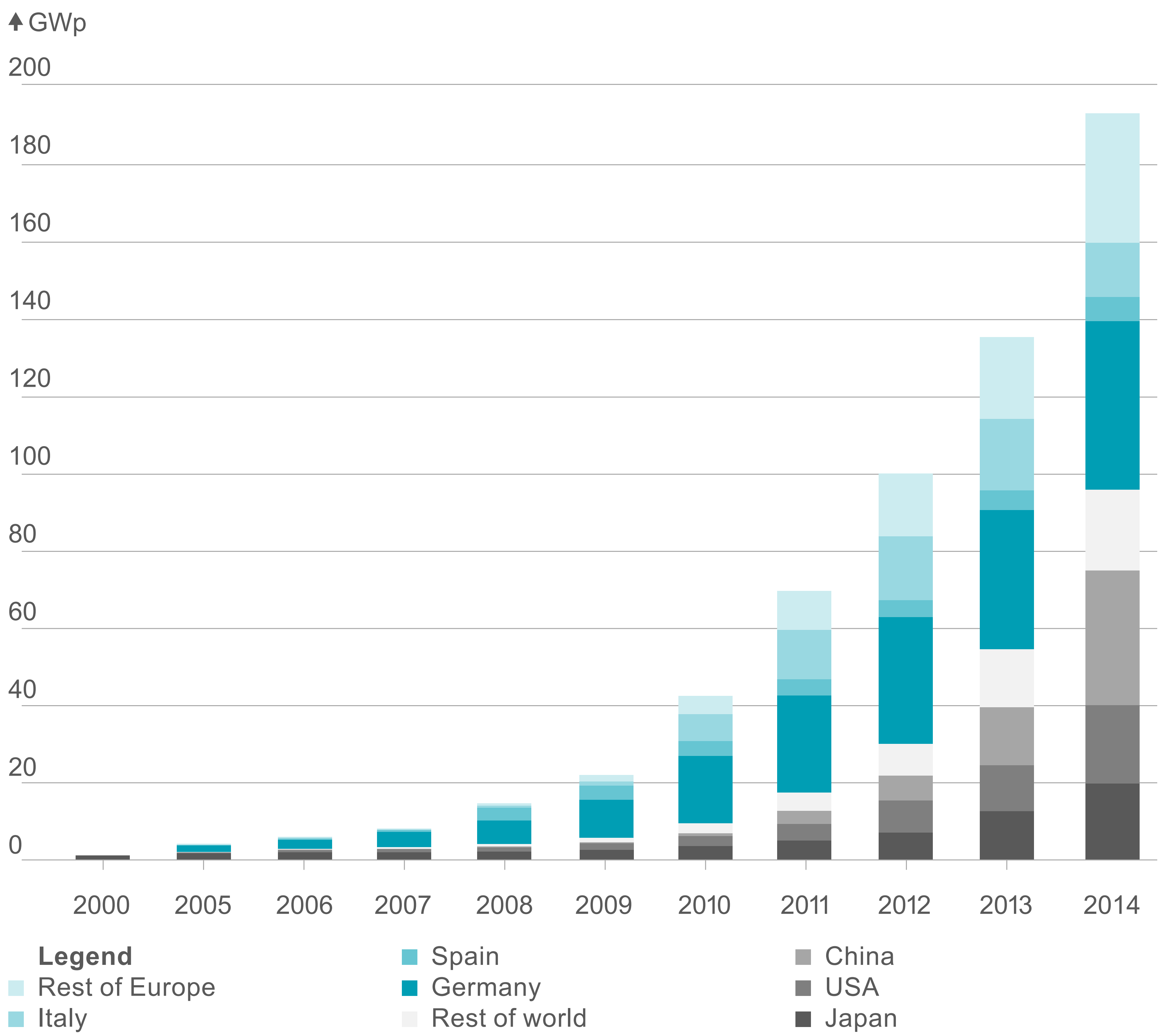


Figure 1: Cumulative photovoltaic installations in GWp (PV Status Report 2014, Report EUR 26990 EN, EU: Luxembourg).

Today the global market is dominated by residential rooftop systems (typically 1-10 kilowatt-peak[2] (kWp)), larger building-added systems (10 kWp to 1 megawatt-peak (MWp)) and ground-mounted power plants (100 kWp to 1 gigawatt-peak (GWp) or more).

The success of this large-scale deployment may in turn finally spur the development of stand-alone applications, particularly in cases where this is hampered by high prices. At current and future low price levels, reliable photovoltaic products holding the potential to change rural life are feasible, especially in the many regions of the world where electricity is rare or completely absent.

The development of photovoltaics in the past decade has been driven by incentives that create immediate business opportunities. The incentive schemes themselves, on the other hand, are usually motivated by the promise of real impact in the longer term. Yet there are very different ideas about what is meant by 'impact' and what 'longer term' it will take to have its full effect.

The term 'impact' can, for instance, be related to total global electricity consumption. If it is loosely defined as a 25% or more share of future consumption, it requires 10 terawatt-peak (TWp) of photovoltaic systems,[3] approximately two orders of magnitude more than the current installed capacity.[4] If 'impact' is measured against total *energy* consumption, an even higher installed capacity would be needed. Such a definition becomes particularly relevant when electricity from photovoltaics is also expected to replace other forms of energy (fuels and heat), for example through power-to-gas, electric vehicles and electric heat pumps. The level of 25% is not meant to suggest that the contribution of photovoltaics should in any way be limited to that. On the contrary, the global potential of photovoltaics is practically unlimited and its role could become much bigger.

And what would the 'long term' be, over which this impact might be realised? Over the past few years photovoltaic solar energy has become increasingly popular, due to cost reductions and price erosion. Although this made margins shrink or even disappear and slowed down global photovoltaics innovation, it has boosted the photovoltaics market, reaching a share of almost 1% of global electricity consumption in 2014. In Germany and Italy, the contribution of photovoltaics now exceeds 5%, double the average of the European Union. The cost of photovoltaic electricity has decreased to a level that competes with retail electricity prices in many countries. In the well-developed market of Germany, generating costs in

2013 averaged between €0.10 and €0.12 ($0.12 and $0.14) per kWh for residential systems and between €0.08 and €0.12 ($0.09 and $0.13) per kWh for large systems, in spite of Germany's modest insolation levels.[5]

This has brought self-sustaining markets closer, a long-cherished dream of the photovoltaic sector and its customers. Sustainably priced turnkey photovoltaic systems with generation costs as low as €0.04 to €0.08 ($0.05 to $0.09) per kWh are projected for 2020,[6] which overlaps with the range of today's commercial electricity prices. Photovoltaics may therefore enter commercial electricity markets sooner than many people have expected. After that, system prices and, consequently, generation costs are expected to further fall to €0.02 ($0.02) per kWh in sunny regions.[7] Solar electricity will then become competitive in terms of generation costs in most of the total global electricity markets, even without carbon pricing. Photovoltaics thus gradually leaves the era of incentive-driven markets and enters the era of self-sustained growth, starting to make significant contributions to the energy system.

Diversifying technology

The development of photovoltaics builds on a broad and still-growing range of technologies. The commercial modules available today are based on silicon wafers, similar to those used in the micro-electronics industry, and on several types of thin film, with efficiencies from 7% to 22% (see Figure 2).

A wide range of new photovoltaics technologies is under development. One category aims at ultra-high efficiencies by using a larger fraction of the solar spectrum and reducing losses as much as possible. The usual approach is to adapt the cell to the solar spectrum. This can be done by combining materials (sub-cells) with different absorption characteristics in tandem or 'multi-junction' designs, but there are several other possibilities. An alternative approach is to adapt the spectrum to the cell, using 'spectrum shapers': materials that convert high-energy photons into two or more low-energy photons or vice versa, to create a better match between the light spectrum and the sensitivity of the solar cell. These are 'efficiency boosters' that could be added to existing solar cells and modules.

Nanotechnologies have recently brought new options for design of (synthetic) materials and devices to reach the old goal of full spectrum utilisation with low losses, for example by using quantum dots and nanowires.

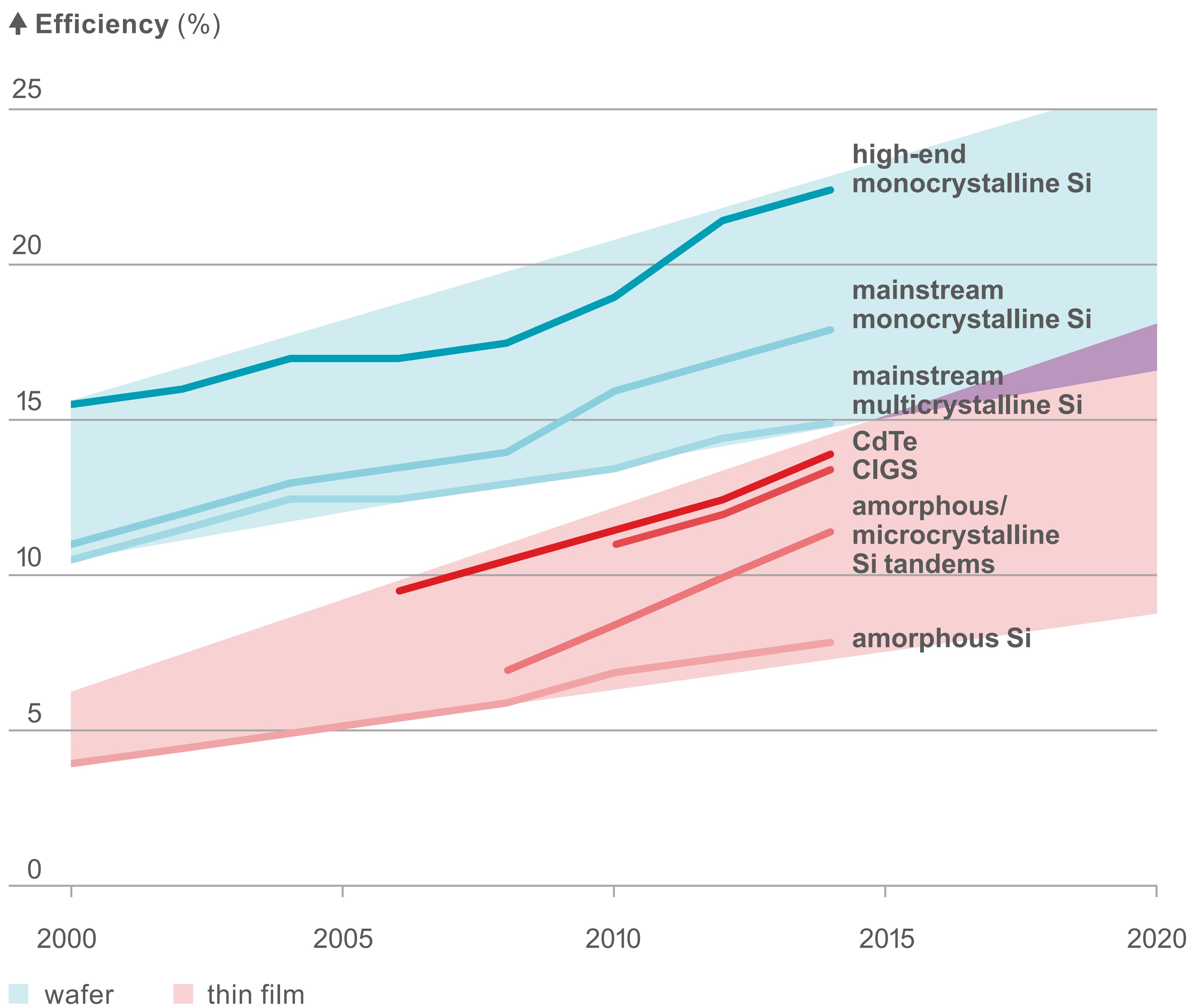


Figure 2: Typical commercial module efficiencies.

Concentration of light by lenses or mirrors is another way to increase efficiency, although not as drastically as by using multi-junction designs. Concentration only works on direct sunlight, not on the diffuse light that is scattered in the atmosphere. This implies that concentrator modules have to track the sun on its daily path. The fraction of diffuse light in the total amount of sunlight ranges from less than 20% in sunny regions to more than 50% in moderate climate regions. In concentrator modules, the active cell area is much smaller than the light-receiving area (which now consists of lenses or mirrors). This allows for the use of more complex and costly cells, such as high-efficiency multi-junction devices. It is therefore not surprising that record-high efficiencies are achieved for concentrator modules, since they combine the benefits of multi-junction cells and light concentration. Current laboratory concentrator cells have efficiencies up to 45% (the world record for photovoltaic conversion), while commercial concentrator modules reach 25-33%.

Commercial module efficiencies of 40 to 50% should be possible

By applying nanoscale 'photonic' patterns for advanced light management to solar cells, it may be possible to achieve efficiency gains similar to those for light concentration with lenses and mirrors, although probably again at the cost of not being able to utilise diffuse light. Another advantage of light management could be that all sunlight can be absorbed in extremely thin layers of material, using light trapping. This would drastically reduce consumption of expensive active cell materials.

Eventually, conversion efficiencies of 60 to 70% for laboratory cells should be possible, enabling commercial module efficiencies of 40 to 50% or even higher. Today, however, only multi-junction devices operating under concentrated light have demonstrated very high efficiencies (> 40%) in practice. Nevertheless some other approaches will probably reach maturity too, further broadening the range of photovoltaic options. Wafer-based silicon/thin-film hybrid modules, which combine the best of two (commercial) worlds, are now under development as medium-high efficiency candidates for '1 sun' operation.

The second category of technologies under development aims at ultra-low costs or new applications. Obviously, high efficiency is still desirable, but it is often not yet possible or even not desirable to address both aspects to the same extent at the same time. Cost reduction per unit area is primarily a matter of materials and processing. This involves reduction of materials consumption and the use of low-cost materials, as well as the development of very high throughput, preferably non-vacuum processes. Examples include organic solar cells (using polymers or small molecules), printed versions of existing thin-film technologies, and several quantum dot based devices. Recently so-called perovskite-based solar cells have also attracted great interest. These promise to be low-cost, and in laboratories a rapid advance in efficiency has been obtained – to as high as 20% by the end of 2014. Yet the long-term stability of perovskite-based solar cells and modules still needs to be demonstrated. Moreover, current best-performing perovskites are not yet fully sustainable since they contain hazardous elements. These issues need to be addressed when perovskites are considered for very-large-scale use.

Ultra-low-cost technologies, however, need a sufficiently high efficiency to become attractive (see next section), as well as large-scale production to demonstrate their cost potential. This represents a serious barrier to market introduction, which may be overcome with speciality markets as stepping stones towards large-scale deployment. Examples include devices with low weight and flexibility, semi-transparency, tuneable colour or freedom of form. If these markets are big enough they may even be the final target market for the technologies involved.

The value of efficiency

Higher efficiencies allow for more photovoltaic power to be installed if the available area is limited. This is the case in densely populated regions and in constructed environments in general. Reaching ambitious targets for the contribution of photovoltaics to the total electricity consumption (for instance 25%) typically requires areas comparable to the total net area available on roofs and façades at current efficiency levels.[8] The potential of photovoltaics in such cases is therefore dependent on the efficiency of commercially available modules and systems.

Building a ‘turnkey’ photovoltaic system out of modules has costs associated with it. Some of these costs are related to the area needed for a given system power and hence to the efficiency of the modules.

This is the case for costs of land or roof preparation, system installation labour, support structures, cabling, etc. Moreover, the costs of operation and maintenance such as land use and module cleaning in dusty regions also are area dependent. Hence the statement dating back to the early days of photovoltaics that very-low-cost modules are only useful if they have a certain minimum efficiency. Even if low-efficiency modules were available for free they would not give low-cost electricity in a system, it was argued. Although this is far too simplistic in view of the wide variety of system types and cost structures, high efficiency is clearly advantageous, as it enables more compact and thus cheaper systems and lower-cost electricity generation, all other parameters assumed constant. This argument can also be reversed: high-efficiency modules may be somewhat more expensive than lower-efficiency modules, since this will be compensated by lower costs to build the complete system.

Cheap low-efficiency modules don't give low-cost electricity

A similar argument holds at the level of solar cells. More efficient cells allow construction of modules with a higher output power for the same area. In this way the costs associated with module materials can be reduced. Finally, at the deepest level, a higher cell efficiency helps to reduce the amount of cell materials needed and to increase manufacturing throughput, again all other factors assumed constant. Efficiency is therefore the universal lever for cost reduction of photovoltaics: it works at the levels of cells, modules and systems.

Although the cost of (that is, the initial investment in) a photovoltaics system is clearly a very important parameter in the cost of photovoltaic electricity generation, it is not the only one. Cost of capital and the depreciation period chosen, insurance, system lifetime, reliability and stability, cost of operation and maintenance and of replacement of parts and specific output[9] (expressed in kilowatt-hours per year produced per watt-peak system power installed), are all important as well. Differences in cost of capital can lead to the surprising fact that electricity from photovoltaics may be cheaper in cloudy Germany than in sunny Spain.

Photovoltaics *is* the breakthrough

The broadening range of technologies in research and commercial production makes photovoltaics a robust option for the future. If several technologies fail or have to be rejected for some reason, there are sufficient others left to carry the development further. All the more reassuring is that current technologies could already advance photovoltaics to multi-terawatt scale. Halving the cost of today can be reached with ambitious further development and deployment of technologies that are already commercially available. In addition, combinations of such technologies are expected to come into play. Photovoltaics therefore does not need a technological breakthrough to become really big, contrary to what is often believed. Photovoltaics *is* the breakthrough. Yet new technologies can help bring the costs down even further, increasing the efficiency to higher values, broadening the range of applications and thus accelerating photovoltaics deployment. All of this is very welcome in view of the need to fight climate change, secure energy supplies, provide access to energy in rural areas, and more. Novel photovoltaic technologies, even if their development risk is high, are therefore essential. The world can and should afford this modest investment in its energy future.

If a breakthrough is needed, it is in integrating photovoltaics into the energy system. The 5% share in countries like Germany and Italy has been reached without major modifications to the grid system and electricity market (apart from the feed-in tariff). A 5% share of photovoltaics in the total consumption of electricity implies that at noon on a sunny day as much as half of the power produced may come from photovoltaics. The reason is that photovoltaics systems do not operate at peak power continuously. Their average power production is 10-25% of peak power, dependent on the annual amount of sunlight available. There is little reason to doubt that this share can and will be repeated on a global scale, where 5% (requiring 1 TWp) would correspond to 5-10 times the current installed capacity. This level may be reached in the early 2020s.[10] It is expected that beyond this level of penetration new challenges will gradually appear. Several studies show that substantial further growth will first require adaptations of the electricity grid. As a first step, its flexibility should be enhanced, for instance by adding intelligence to match supply and demand, or by using local storage. These technical measures have to be accompanied by suitable market conditions. In the long term a transformation of the energy system as a whole is needed, which may include large-scale storage and conversion of power to fuels.[11] Photovoltaics thus enters a new phase if it is to supply well over 5% of total electricity. Electrical and physical integration as well as societal acceptance will largely determine further growth, as will sustainability and total quality. This will change photovoltaics from a technology-driven development with mostly 'one size fits all' products to an application-driven market, with differentiated products. If growth will be limited by integration rather than cost, it becomes essential to consider the complete set of requirements for large-scale use of photovoltaics and to prepare for the multi-terawatt-scale application expected after 2020.

Photovoltaics does not need a breakthrough. It *is* the breakthrough.

Triple integration

There is no consensus yet on the strategies and policies needed for further integration of photovoltaics in the energy system to achieve growth into the terawatt regime. The world seems involved in a big experiment in large-scale deployment of photovoltaics, with some countries providing valuable experience and results to many others. Issues related to electrical integration and market integration have received broad attention, especially where the limits of the current system are felt most prominently. We can only be thankful for the lessons learnt from Germany, a leading global laboratory in this respect.

Physical integration into cities, infrastructures and landscapes has so far received much less attention. Yet if photovoltaic technology is going to provide terawatts of electricity, it will be literally everywhere and we have to make sure that people like it. The biggest mistake is to take public and political support for granted. The ‘not on my roof’ or ‘not in my backyard’ syndromes need to be and *can* be prevented. A unique property and valuable asset of photovoltaics is that it can be applied in an aesthetically pleasing way as building-integrated photovoltaic (BIPV) systems and infrastructure-integrated (I^2PV) systems, or as ground-mounted power plants using landscape architecture. Well-integrated systems should not be considered a costly niche, but a necessary building block for very-large-scale use and a requirement for societal acceptance. It is not rocket science to develop the products and approaches needed, but it is not trivial either, especially since flexibility and versatility of use have to be combined with standardisation and sufficiently low cost. Possibly some of the new technology options discussed before fit well here.

In summary, a key notion is that a very-large-scale deployment of photovoltaics will rely on more than low cost alone. Such a deployment is only possible if systems can be integrated into the energy system, into the physical environment and into markets and society. This is the ‘triple integration challenge’.

Follow the sun?

Large-scale deployment of photovoltaics on a global scale should perhaps start with the question where all these systems can best be placed. The German success is remarkable, considering the country’s moderate levels of insolation. Shouldn’t photovoltaics be installed in sunnier regions, as some argue? Indeed, a photovoltaic unit can deliver two to three times more energy in sunny countries. The centre of gravity of photovoltaics deployment will therefore no doubt move gradually from the moderate regions where markets kick-started its development in the past decade to more sun-blessed regions, although not necessarily only the ‘sunbelt’. In these regions, economic growth and increasing electricity consumption will necessitate new generating capacity, which can be partly filled in with photovoltaics. Photovoltaics is attractive for these regions due to its relatively low and still decreasing costs and sustainable nature. Moreover, large-scale roll-out can build a new economic sector, creating jobs and generating welfare and wellbeing. In a somewhat different form, these are also drivers of the recent ambitious photovoltaic deployment in the USA and China.

It is unlikely, however, that all photovoltaic installations will be constructed in the world’s sunbelt. Large-scale deployment in arid regions has its technical and economic challenges. Operation and maintenance costs of photovoltaics may become very significant when frequent cleaning and other forms of maintenance are needed. High levels of insolation are therefore not enough to ensure low generation costs.

For that matter, relying on sunny regions is in fact undesirable. Such a concentration would leave the attractive photovoltaic potential of moderate regions unused. Moreover, with generating costs between €0.02 ($0.02) and €0.05 ($0.06) per kWh, the cost of long-distance transport becomes significant, apart from the fact that a whole new transnational infrastructure would be needed. Generation close to the consumer therefore has big advantages.[12] On top of that, distant generation would lead to a new form of energy dependence.

‘Desert photovoltaics’ may well become an important part of the global market, but global photovoltaic deployment will be diverse, with regional use and export from countries with high insolation. Export will not always necessitate cables. In the longer term, solar energy may be used for fuel production, with power-to-gas, power-to-liquid and perhaps even direct solar fuels.

Sustainability

Integration of photovoltaics into society requires a vision that is expansive both in space and time. A view on spatial planning is required, as discussed above, but also a vision about the production and replacement of photovoltaic panels once they are deployed at scale. Photovoltaics are inherently renewable, but this does not make them automatically fully sustainable. Although the amount of energy used in production was a major issue in the early days of photovoltaics, this is no longer the case. The energy consumption expressed as the system's energy payback time has come down as a natural consequence of technological improvements and cost reductions. It now typically stands at 1-2 years of a system lifetime of 25 to 30 years,[13] and this continues to be reduced. The payback time of future systems may be as low as 0.5 years or less. If photovoltaic systems are produced using solar energy in a so-called solar breeder,[14] the energy payback time will no longer be a sustainability issue.

A more pressing sustainability issue is therefore the use of materials. Major studies over the past few years[15] have emphasised the importance of choice of materials in the development of improved and new energy technologies, including photovoltaics. Strategic considerations related to long-term availability, but also prices on the actual market may steer developments, as is the case for the use of silver as a contact material in silicon photovoltaic cells. The combination of increased silver prices and reduced overall module production costs has turned silver usage into a significant cost component, driving the development of alternatives, mainly in the form of copper-based metallisation techniques. Since availability and price of critical materials present a risk factor, the photovoltaic sector also embraces hedging strategies. A prominent example is the development of zinc-tin as an alternative to indium in specific thin-film solar modules. This alternative is still technically immature and has much lower levels of efficiency, but that is why development has started early. Commercial technologies are not created overnight.

Taking sustainability a step further, it is important to start considering 'design for recycling' as another aspect of 'design for sustainability'. Photovoltaic modules are currently designed to 'last forever' and are therefore difficult to take apart and recycle. It is still an open question whether it is possible to ease recycling without sacrificing quality and lifetime. It also remains to be seen whether it is preferable – from a sustainability point of view – to aim to reclaim valuable and toxic materials or to avoid their use entirely. The establishment of the PV CYCLE organisation[16] was an important initiative in the context of recycling of commercial photovoltaic modules. Since sustainability is a necessary requirement for very-large-scale use, it may be considered the third major driver of photovoltaic technology development, next to cost reduction and performance enhancement.

Quality

Eventually, private and professional users will determine the future of photovoltaics. Newspaper headlines about quality issues, such as those we saw in 2013 when global overproduction was at its peak and module prices reached a minimum, do the photovoltaic sector no good, even if these problems are far from representative of the photovoltaic product portfolio as a whole. They also demonstrate that it is not trivial to make a product that operates reliably for decades and is very cheap at the same time. Users and potential users are uncertain about quality and confused by the different certificates, labels and warranties they find. The crucial difference between high technical quality, high efficiency, and high energy yield is usually only clear to insiders. For instance, high-efficiency modules can be poorly manufactured and hence rapidly degrade or fail, while low-efficiency modules can be highly reliable and durable. The photovoltaic sector works hard to improve transparency, independence and coherence, but there is still much to be done. Further explicit product differentiation and corresponding labelling may also help users to make the best choice for their application. Deserts are very different from roofs in north-western Europe. Terawatt-scale use of photovoltaics requires quality control and assurance at all levels.

Continued cost reduction and sustainable pricing will help the global photovoltaic sector enter the terawatt age within a decade. This brings the inspiring and challenging perspective of a self-propelling market, no longer limited in growth by prices. Yet to sustain this dynamic, it is crucial to address *all* challenges in a timely manner. The next potentially limiting factors should by then already have been addressed in a joint effort of industry, research and other stakeholders.

Related essays

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Wim Sinke is Manager Program Development at ECN Solar Energy in Petten, the Netherlands, scientific advisor at the FOM Institute AMOLF and professor of Photovoltaic Energy Conversion at the University of Amsterdam. He is director of the TKI Solar Energy national public-private partnership for solar energy innovation. He is also co-chairman of the European Photovoltaic Technology Platform.

Notes and references

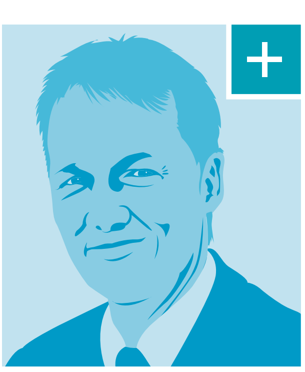
1. J. Perlin (1999). *From space to earth: The story of solar electricity*, Earthscan: London. See also Perlin (2013). *Let it shine: The 6,000-year story of solar energy*, New World Library: Novato, CA.
2. The power of photovoltaic cells, modules and systems is expressed in terms of watt-peak (Wp), i.e. the power produced at full sun (1,000 watt/m² intensity). Note that the total amount of sunlight received per year varies significantly per region of the world, whereas the maximum intensity of sunlight does not: it is approximately 1,000 watt/m² ('1 sun') everywhere.
3. Assuming an average capacity factor of photovoltaic systems of 15-20%, 1 gigawatt-peak (GWp) of photovoltaic systems will produce ≈1.5 terawatt-hours per year and it takes 12 terawatt-peak (TWp) of installed photovoltaic capacity to generate an amount of electricity equal to current demand (18,400 terawatt-hours in 2011: IEA 2013). Assuming a growth in electricity consumption by a factor of 2 to 4 or even more in the long term we would thus typically need 10 TWp to cover 25% of (future) demand. This back-of-the-envelope calculation does not consider losses related to transport and storage.
4. In 2013 cumulated capacity reached 135 GWp. IEA PVPS Report T1-22:2013 (2013). *A snapshot of global PV 1992-2012*, IEA-PVPS: Paris.
5. See, for instance, C. Kost et al. (November 2013). *Levelized cost of electricity renewable energy technologies*, Fraunhofer Institute for Solar Energy Systems: Freiburg.

6. This is based on a price of €0.8 ($0.9) per Wp with costs of capital in a reasonable range; the upper and lower limits are determined by insolation. See, for instance, European Commission, *Solar Europe Industry Initiative,* see www.eupvplatform.org and setis.ec.europa.eu and US Department of Energy, *SunShot Initiative,* www1.eere.energy.gov/solar/sunshot. System prices at or below €1 per Wp have been reached in selected cases in 2012 and 2013 already, but generally not at sustainable margins and certainly not on average.
7. This corresponds to €0.30-0.40 ($0.34-0.45) per Wp. See IIASA, Vienna (2012). *Global Energy Assessment – Towards a Sustainable Future*, Chapter 11: Renewables, www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/Home-GEA.en.html, and Fraunhofer Institute for Solar Energy Systems and Agora Energiewende, *PV cost vision 2050 – Scenarios on the future cost development of photovoltaics*, available on request.
8. Taking the example of the Netherlands and estimating the area available on roofs at 400 km², there is room for 40-80 GWp of PV systems at typical current efficiency levels, if *all* the area can be used effectively (which is probably a theoretical case). These systems would generate 30-60 TWh (taking into account the use of non-optimal locations), i.e. 25-50% of 2012 electricity consumption (and a smaller fraction of total energy).
9. The specific output (kWh/Wp/year) is primarily determined by the amount of sunlight available (the insolation), but also, to a lesser extent, to the photovoltaic module technology used, the system design and other factors.
10. A. Gerlach and Ch. Breyer (2012). *Global grid parity dynamics on a national and regional level*, 27th European Photovoltaic Solar Energy Conference, 4467-4492.
11. Federal Environment Agency, Germany (2013). *Germany 2050: a greenhouse gas-neutral country*, www.umweltbundesamt.de.
12. European Photovoltaic Industry Association (2012). *Connecting the sun: Solar photovoltaics on the road to large-scale grid integration*, www.epia.org/fileadmin/user_upload/Publications/Connecting_the_Sun_Full_Report_converted.pdf.
13. See M.J. de Wild-Scholten, various publications on www.smartgreenscans.nl/publications.html.
14. See, for instance, www.nytimes.com/1982/02/28/business/other-business-a-solar-factory-to-make-solar-cells.html.

15. US Department of Energy (2011). *Critical materials strategy,* Nova Science Publishers, Inc.: New York; R.L. Moss, E. Tzimas, H. Kara, P. Willis & J. Kooroshy, Joint Research Centre of the European Commission (2011). *Critical metals in strategic energy technologies*, Report EUR 24884 EN, EU: Luxembourg; American Physical Society and Materials Research Society (2011). *Energy critical elements: Securing materials for emerging technologies,* APS: Washington, DC.
16. PV CYCLE (www.pvcycle.org) "as the leading take-back and recycling scheme in Europe, offers waste treatment and WEEE compliance solutions for all commercially available photovoltaic (PV) technologies" (text taken from the website).

Renewables on an oil and gas scale
One million barrels of oil equivalent from wind

Looking at offshore wind on a truly large scale today seems daunting and unaffordable, but looking back in 25 years' time it may appear much more attractive in energy security, economic and environmental terms. Wim Thomas weighs the main dilemmas.



> *Wim Thomas*

In Dutch political parlance, if you want to signal that you want to go big on an issue of urgency over a long time horizon, you call for, or even better present, a 'Delta Plan'. The name comes from the successful effort the Dutch made to secure their low-lying land against storm surges after the 1953 tragedy in which 1,840 people lost their lives and some 100,000 lost their properties. It took half a century and €8 billion ($9 billion) in 2015 money – about twice as long and twice as expensive as originally thought – to strengthen the coastal defences.

In view of that history, weather-related events, rising sea levels and long-term thinking are normal problems for the Dutch. Interestingly, at the same time as work on the Delta Plan was beginning in the early 1960s, the Netherlands was creating the backbone of its current energy system: the gas grid that brings gas from Groningen to all Dutch homes, businesses and industry. Half a century on there are two good reasons to rethink the Dutch energy system. First, the giant Groningen gas field will inevitably decline in production in the next decade. Second, there is the question of energy security, in combination with Dutch and the European Union's renewable energy and carbon reduction targets.

The easy answer is to diversify the energy mix. But neither nuclear nor coal with carbon capture and storage have much public appeal. Gas-fired power generation clearly has potential with over 60% market share, but natural gas will increasingly be imported after 2020. The next appealing option, not always enjoying broad support, is renewable power. Within that category, photovoltaics is still acceptable, but onshore wind increasingly faces opposition, although it contributes no more than 4% to the Dutch electricity mix.

Yet large-scale offshore wind could do the 'heavy lifting' on its own. Can it be done? Could the Netherlands cater for most of its future energy needs from this renewable source just over the horizon? Largely invisible, except to sailors and fishermen, just as today's energy system is largely invisible, is a Delta Plan for offshore wind possible for the Netherlands?

Let's first come to grips with the scale. The Netherlands Wind Energy Association quotes that a single 3 megawatt wind turbine at the coast serves about 2,000 households, so we might be tempted to think that fewer than 4,000 of these will do the job for the Netherlands' 7.5 million households – which is more or less the Dutch government target for wind. However, household electricity consumption represents only 3% of Dutch energy consumption. So much, much more wind resources will need to be developed to become a substantial part of supplying the total final energy consumption in the Netherlands of about 2.6 exajoules per year today, which is about 1.25 million barrels of oil equivalent per day.

Most activities of a major oil company are not on the 1 million barrel per day scale, but in some cases they are. The Groningen gas field has produced more for many years. Yet at the time of its discovery in 1959, there was no large-scale gas infrastructure, nor a market for so much gas. A joint venture between Shell, Exxon and the Dutch state was established to solve that problem. Together they built a formidable new gas infrastructure, which is now central to Dutch energy security and many neighbouring countries. For the Netherlands, such an undertaking was in the national interest, and also a good fit economically. The Dutch are still quite dependent on this huge reserve of natural gas. Natural gas is the dominant primary energy source at 45% market share, while oil has a 39% share, coal 9%, nuclear 1% and all the renewables together about 6%, of which biomass plus waste is the largest at 4%, while wind is just 1%.

But the days of large domestic gas production are numbered, with the Groningen field coming to the long tail-end of its life cycle (see Figure 1). For the state, this means the gradual loss of around €12 billion ($13 billion) annual upstream tax take, to very little by the 2020s. After that, the Dutch will need to get used to paying for importing gas to the tune of some €10 billion ($11 billion) per year, assuming today's prices and no switching away from gas. This will affect the government budget and the country's balance of payments. These costs might actually be much higher as prices may rise under stiff competition for fossil energy resources, particularly from the emerging economies in Asia-Pacific.

Quite apart from cost, energy security remains a concern. The world saw a geopolitical conflict flare-up in Europe between Ukraine and Russia in 2014, the source of 30% of the European Union's gas imports. So if Dutch fossil fuel resources are dwindling, and as the Netherlands has so much offshore wind potential, why not start a Delta Plan for wind?

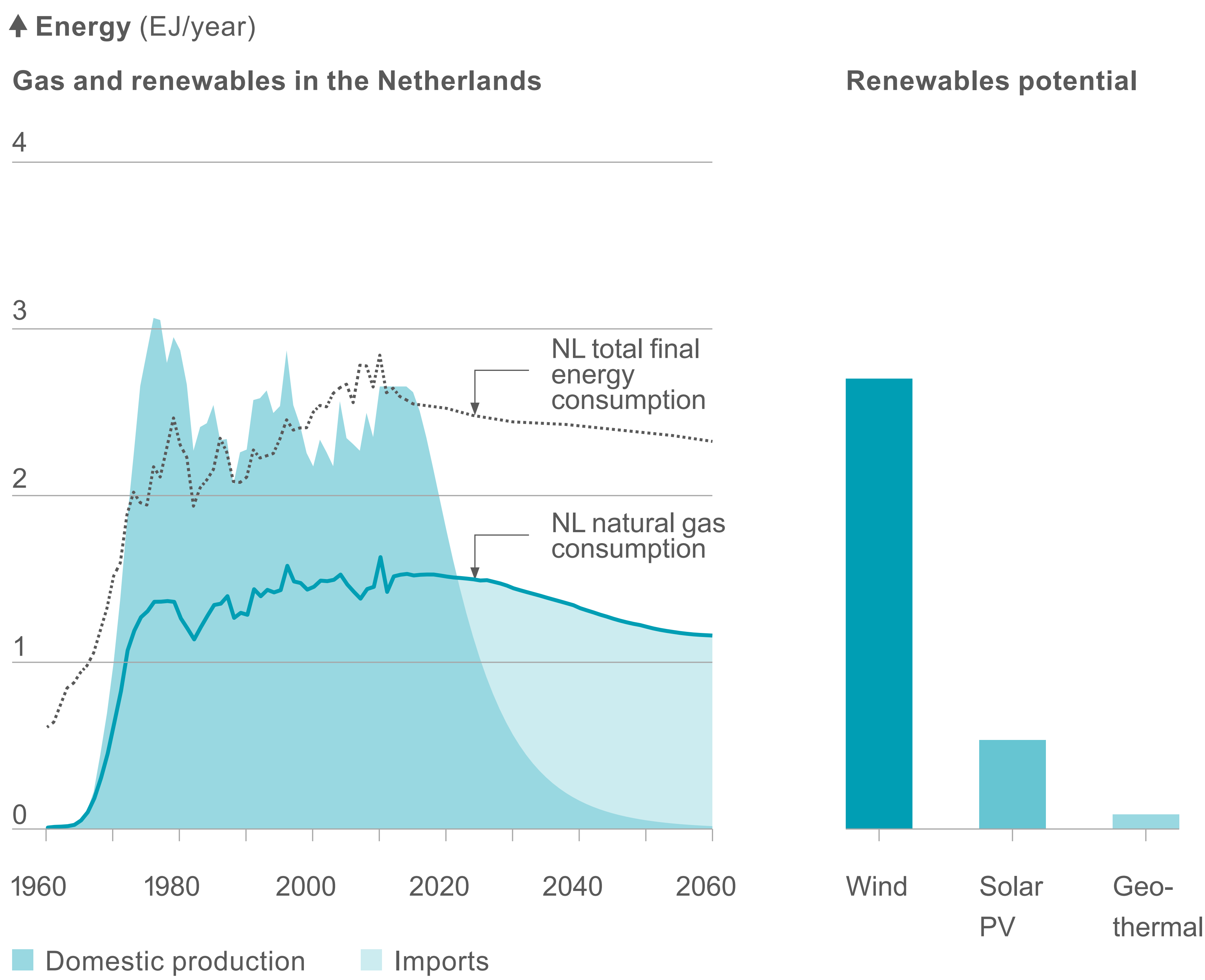


Figure 1: The Netherlands' natural gas balance over time, and the Dutch renewable energy potential for three major resources.

Wind Delta Plan

According to the European Environment Agency[1] and an Ecofys study,[2] the Dutch wind resource potential about equals its entire total final energy consumption. However, most renewable resources produce electrons, while the overall energy system will need molecules as well. So not all this renewable potential can be used for the Dutch energy system, but let's do a thought experiment to unearth how much of this potential could be realised to supply the Netherlands, building renewables at the scale of oil and gas projects, and what political, societal and economic dilemmas need to be overcome.

A 'Wind Delta Plan' is not for the faint-hearted. The counterpart of a 1 million barrel per day oil or gas project turned into electricity would be an offshore wind farm in the North Sea with an installed capacity of some 120 gigawatts. It would have some 34,300 turbines of 3.5 megawatts peak capacity operating at 25% load factor, taking into account the variability of the wind. These need to be placed over a sea area of 12,000 square kilometres, or 21% of the Dutch offshore Exclusive Economic Zone. For comparison: solar would require some 275 gigawatts installed capacity on 2,700 square kilometres, roughly 10% of the land surface of the Netherlands. Clearly that footprint would pose a problem for the Netherlands, and the potential for solar is much more modest at around half of that. An oil or gas project that would produce this amount of electricity would be super-compact: it would just need a few hundred wells, and have a footprint of a few square kilometres.

If the offshore Wind Delta Plan could start in, say, 2017, and build out over the next 20 years to 120 gigawatts, it would cost up to €360 billion ($400 billion) at today's prices. Over the first 20-year period, that would mean building 1,700 turbines per year, or 140 per month, which is about five times what is installed now in the Netherlands over a whole year. This would mean about €18 billion ($20 billion) investment per year, around 3% of the Netherlands' GDP in 2012, or well over half the total annual investments of a large international oil company.

The economic life of a wind turbine itself is about 20 years, but the Wind Delta Plan will need to be designed such that the supporting infrastructure of pylons, in-farm electricity distribution lines, substations and transmission lines to shore will be robust enough for the next generations of wind turbines as well, extending the infrastructure lifespan to at least double that of a turbine. For example, the offshore infrastructure in the oil and gas industry is often built robust enough to withstand 40 years or more. Although this would burden the first cycle with some upfront additional costs, it would significantly reduce overall investments for a second 20-year cycle wind generation project, all the more when the wind industry delivers on its promise to reduce cost and increase the overall efficiency of the turbines. This will make a big difference: the same 120 gigawatts would need only 12,500 pylons for 6 megawatt turbines at a 40% load factor. As this is only one-third of the number of pylons required in the first cycle, an attractive option is to limit the first-cycle development to this number of pylons required for the second cycle. This will make the initial investment drop by almost two-thirds – as does the power output – but it would give the industry more time to 'learn by doing' to reduce installation and operating costs, while the cost to the end consumer can be more gradually introduced. The second-cycle investment costs could be about a half to a third of a full-blast first-cycle project of 120 gigawatts.[3] The first cycle delivers less than half the amount of electricity for each euro or dollar invested than gas-fired power. However, the second cycle could be as effective if the projected improvements are indeed realised, but otherwise could still be a third less investment-effective than gas-fired power at today's gas prices.

Both the huge size of this undertaking and the very-long-term management that it requires suggest that this new infrastructure is best designed integrally to avoid under-designing that may later bring prohibitive additional costs, and as a 'backbone' to a future, more renewables-based infrastructure. Given the complexities and the large financial exposures, the government could decide that this would be best built and operated by a 'national system operator': a company or a consortium that is familiar with large-scale, complex infrastructure and offshore operations. Once the backbone is built, smaller operators can more easily enter the market, as we have seen in the North Sea for oil and gas developments.

However, extensive planning and infrastructure adaptation will eventually also be needed across national boundaries. An offshore electricity ring, connecting countries around the North Sea, built step by step to connect markets and to deal with intermittency has, for instance, been proposed as part of the Zeekracht concept of the architecture and urban design partnership OMA.[4] Nevertheless, this ring will still not be sufficient when really aiming at the largest scale.

The amount of electricity would vastly surpass even the peak electricity demand in the country – by a factor of five. Therefore, any Wind Delta Plan should also include a plan for large-scale storage of electrons. Pumped hydro-storage options are limited, as an elaborate plan from the early 1980s shows ('Plan Lievense'). The only long-term route will be the application of hydrogen, utilising surplus wind electricity (along, quite possibly, with surplus photovoltaic electricity) for the electrolysis of sea water to generate hydrogen.[5] This can be stored, for example in depleted gas fields, for later use as fuel in different sectors, or to be converted into electricity again at more opportune times and places. Luckily, the Netherlands already has an extensive offshore and onshore natural gas grid in which 5% or even 10% hydrogen could be spiked without too much adaptation. Building a dedicated grid to deliver the hydrogen to land is another possibility. This would make it available for use in fuel cells that power cars and trucks. The transport market could pay a premium for hydrogen, as it competes against petrol and diesel, which would be much needed to make the hydrogen development economically attractive.

The Netherlands' energy use transformed in three decades

What will the Dutch energy system look like in the 2040s with such large-scale renewable energy production? The overall share of renewables in primary energy will have increased from 6% to just under 50% of the overall energy mix. Carbon dioxide emissions from energy will be half that of 1990. Oil imports may be some 30% less and gas consumption 45% less. Electricity consumption will become 2.5 times higher than today – without a Wind Delta Plan it would only increase by 10%. And about a fifth of all wind electricity produced will need to be converted into hydrogen.

This shift to electricity and hydrogen is only possible with a profound change of the type of energy used throughout society. A third of all cars will use hydrogen and a fifth electricity (measured by distance travelled). Trucks will deliver a fifth of all tonne-kilometres using hydrogen. The chemicals sector will remain 98% dependent on fossil fuels as a feedstock, but other sectors will see strong growth in electricity use at the cost of oil and gas. Industry will be over 80% electrified from around a third today. The Dutch will need to chuck out their high-efficiency gas boilers and cookers in favour of (also high-efficiency) electric heating and cooking. Electricity use in heating and cooking will see its market share grow to two-thirds, while natural gas will see its share tumble to a third from just under 90% today. This means new investment in boilers and machinery in factories, buildings and homes, but that will be a natural replacement process at the end of the useful life of appliances. Utilities and retail filling stations, however, will need to invest heavily to strengthen distribution networks and bring new fuels to market, while car manufacturers will have to develop cost-competitive fuel-cell cars and trucks. This will make total investments much larger than ‘only’ for the Wind Delta Plan, but it will also stimulate the economy overall.

The character and the sheer size of investment are in a quite different league

A new league in energy investments and operators

The execution scale of this project would be unprecedented as a ‘single’ project, but companies the size of an oil major would be at least familiar with managing, executing and operating such a project, and its involvement could give confidence to financial markets familiar with investing many tens of billions of dollars a year with a long-term investment horizon. Yet the character and the sheer size of investment would be in a quite different league from what is usual in this business, let alone what its traditional investors may think of changing course.

Cash flows and profit margins with renewables today are much lower than with oil and gas. Even compensating for depletion of oil and gas fields, offshore wind requires three to four times more capital for producing the same amount of energy.[6]

In general, this gives less room for manoeuvre to governments that want to implement renewables on a large scale. In the absence of a market-driven price for carbon dioxide, governments need to resort to subsidies of many billions over tens of years, while they see their tax base from fossil fuels dwindle at the same time due to less consumption as a result of efficiencies and fuel switching. There is no social dividend available for immediate distribution, other than job creation, and thus less compensation for the consequences that will be felt by everyone in the form of gradually higher energy bills and the footprint of renewables encroaching on their doorsteps.

But the long-term perspective of renewables could look much better, especially once the new supporting infrastructure is built and largely amortised. Whereas oil and gas fields deplete, renewables by definition do not, although replacement investments will be continuously required. The initial small, if any, profits in renewables may still be attractive to some investors with a long-term horizon, stretching well beyond the first 20 years.

So how could this giant undertaking be financed? Certainly the present subsidy system will not be able to cope, nor is it a robust longer-term basis for political, legal and financial decision making, as experienced in Spain when the government had to rein in earlier commitments under the pressures of the financial crisis. The most important element in this framework will be regulatory predictability over time, recognising that the system needs to evolve, particularly with regard to market structures and margins. This needs to serve as the foundation for a competitive market for wind turbine operators, the wholesale electricity market and the gas market.

Two crucial elements in this new market design are to socialise the new infrastructure and not exempt wind and photovoltaics operators from the costs of the intermittency of their electricity production. It could be a similar approach that local and national governments have traditionally followed, investing in water, electricity, sewage, roads and other infrastructure to attract industry and housing. The cost to the government, and thus to the public, is recovered later through taxes both from operators and consumers and, more generally, through increased economic activity in the sectors and regions involved.

To put the wind turbines in place, the Dutch government will need to spend €2.2-3.1 billion ($2.4-3.5 billion) each year, a project almost 10 times bigger than the original Delta Plan. Initial investments could come from using part of the present natural gas tax income. But after 2020, when this source of income is expected to dry up, offshore wind will have to be taxed to continue financing a steady expansion of the backbone infrastructure. Spain has already set a precedent with a 7% sales tax levied on onshore wind electricity. A 10% royalty on all electricity sales from offshore wind should be sufficient. For the offshore wind operators using the infrastructure, this will affect their profits, which will be challenging in the first 20-year cycle of the project. But subsequent cycles, with mature infrastructure and improved wind turbines, could be cash generators at the scale of oil and gas projects, with attractive profitability – if regulators allow it. For that reason, offshore wind operators must be able to obtain licences for at least two or even better three cycles, 40-60 years, to have long-term incentives for economic attractiveness.

Hydrogen infrastructure will ultimately be required to cope with the intermittency, costing an estimated extra €5-10 billion ($5.5-12 billion) at today's cost levels. This would result in an even more marginal first cycle for the industry. In that case, the 10% royalty would have to be (partly) waived. But ultimately, the prize for the government could be sufficiently attractive, with tax takes maybe even double those in the 'electricity only' case.

Could it be done without subsidies? In principle, yes, if wind operators received a carbon dioxide credit of at least €40 ($45) a tonne on top of the wholesale electricity price. In this case, too, the cost would ultimately be paid by the end consumer. This is a real political dilemma – how to convince people that an inexorably rising electricity bill is actually a good thing. On the other hand, overall efficiency gains are projected to halve our energy needs over the next 50 years. So if people's cost per unit of energy doubled over time, they would still pay more or less the same amount. As a proportion of their income, which is projected to be higher in real terms in line with economic expectations, energy could even become less of a burden. However, the pain is likely to be in the short term, while the gains will for now have to remain a belief for the future.

The Wind Delta Plan is only possible if the government can provide a long-term framework in which the technological and economic cycles can play out in a reasonably predictable fashion. If it succeeds in this, its reward will be the development of a completely new industry, potentially creating a huge new export sector for the Netherlands, comparable to its dredging sector. Ultimately, this will generate significant tax income over time directly from the projects, perhaps up to a third to a half of what now results from Groningen gas, creating some 40,000 direct permanent new jobs[7] and indirectly some 100,000 jobs.[8]

Daunting, yet affordable

So these are the main political, societal, financial and market issues, dilemmas and building blocks of ‘renewables at the scale of oil and gas’. It is a huge undertaking, being complex, costly and difficult, but not necessarily unachievable or unaffordable. The Dutch are used to thinking long term. The ‘Energy Agreement’ (*Energieakkoord*) that was concluded in the Netherlands in 2013 aims at a scale which is ‘only’ just 12 times smaller than the Wind Delta Plan, with 10.5 gigawatts of wind power in 2023. Some 4.5 gigawatts will be offshore wind – 3.5% of the Wind Delta Plan. It is a good first step. Yet the plans laid out in the Energy Agreement will probably be carried out on a project-by-project basis, without necessarily leveraging synergies of scale and integration, nor being part of a greater plan for an infrastructure backbone which is robust enough for future technical and regulatory progress.

Looking into the future from today’s perspective, ‘renewables at the scale of oil and gas’ seem daunting, but looking back from the mid 2030s it may appear much more attractive, not only in terms of our energy security, but also environmentally and economically. The Netherlands will remain dependent on fossil fuels but is uniquely positioned with one of the best wind resource bases in the world, an industry that has the experience with these scales and timeframes and an electorate that is increasingly engaged in dealing with the energy challenge.

The decisive questions are: will there be a meaningful market-driven long-term price for carbon dioxide; will the Dutch public accept higher prices for electricity and support successive governments in embarking on such a grand scheme over many decades, including the socialising of the new infrastructure; will the market design be sufficiently attractive for all involved to build and finance it all; and will the Netherlands remain competitive, or even better pull ahead in economic development as a result? But foremost, will the Netherlands have the courage to embark on another Delta Plan, this time on an even larger scale?

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Wim Thomas is Chief Energy Adviser at Shell. He leads a team responsible for worldwide energy analyses and long-term global energy scenarios, and advises Shell companies on a wide range of energy issues, not just oil and gas, including global supply and demand, regulations, energy policy, markets, pricing and industry structure. He has been with Shell for some 30 years. He is chairman of the UK National Committee of the World Petroleum Council and a former chairman of the British Institute of Energy Economics.

Notes and references

1. EEA (2009). *Europe's onshore and offshore wind energy potential*, EEA Technical report No 6/2009, EU: Luxembourg.
2. Ecofys (2012). *Renewable energy resource assessment and country-level assessment of long-term global bioenergy potential.*

3. This is all very dependent on cost assumptions, cost deflation or inflation over time and capital cost discount factors. For these round figures $4 million/MW is assumed for the first-cycle 3.5 MW turbines at LF 25%, and $2.5 million/MW for 6 MW turbines at LF 40%, as well as a 20% uplift on first-cycle costs to pay for making it suitable for the second-cycle, stronger turbines, and a 3.5% discount factor.
4. Office for Metropolitan Architecture, Seapower, http://oma.eu/projects/2008/zeekracht.
5. IHS-CERA (September 2013). *Bottling the wind: Power-to-gas as an enabler of renewable electricity*.
6. Based on net present values at 3.5% discount rate to reflect cost of capital and risks.
7. Based on the announcement of the Moray Firth 1.8 GW projects (Scotland).
8. Based on numbers for Spain, onshore wind operators (BBC news article, April 23, 2014).

Nuclear power at a crossroads
Conditions for a revival of the industry

The future of nuclear power will be determined by the effectiveness of the industry and the institutions that govern it, since these will ultimately determine public trust without which a nuclear renaissance cannot occur.

> *Chris Anastasi*

Nuclear power will continue to provide electricity throughout this century, but it is uncertain if it will make a significant contribution to the world's energy supply. Will it persist as an essential part of the global energy mix, or will it gradually decline and become negligible as plants are shut down without replacement? The answer to this question relies on a number of important factors, any one of which may limit the advancement of the nuclear industry, at least until breakthrough technologies are developed and deployed.

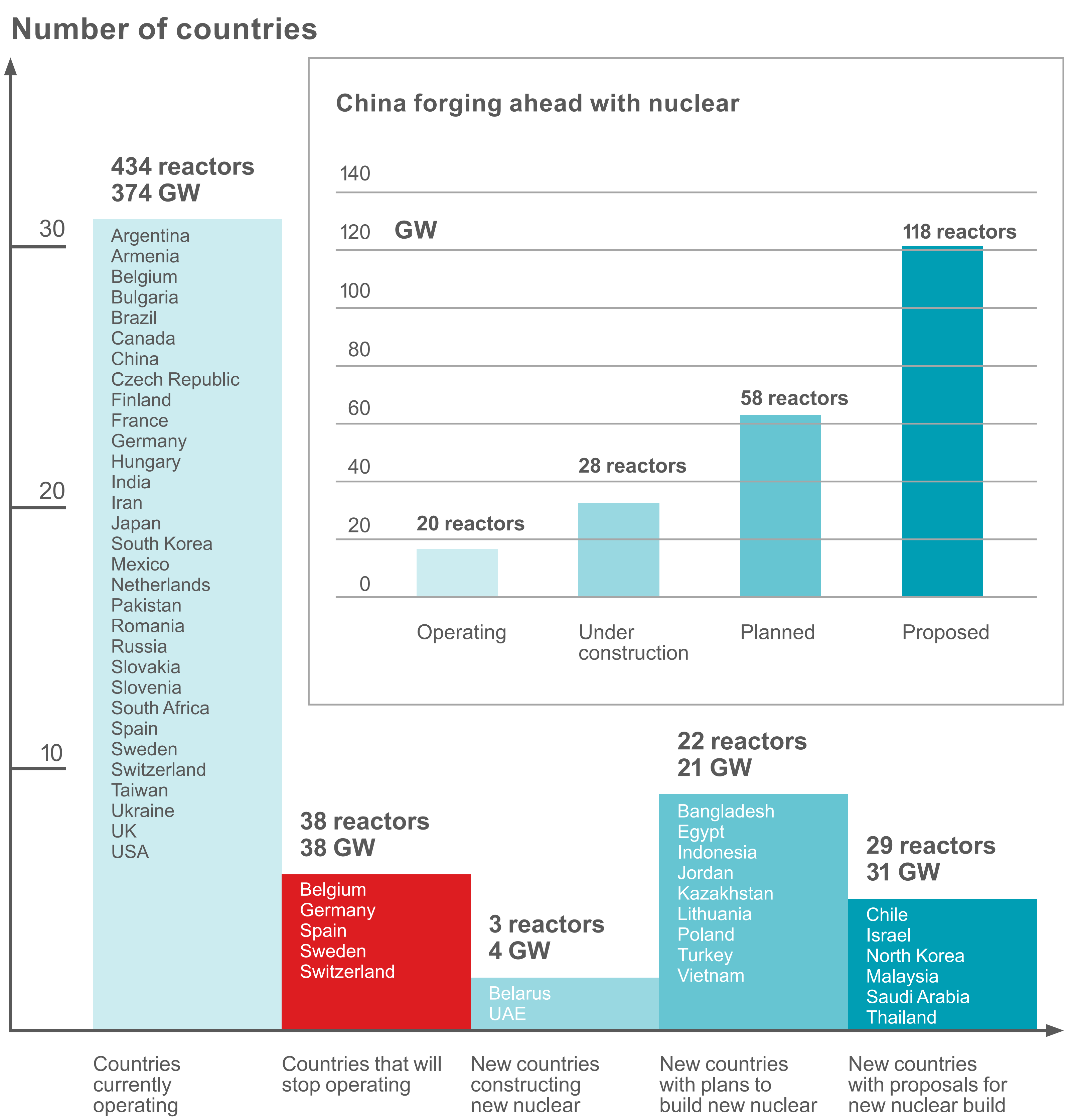


Figure 1: Nuclear power today and in the future.

The current role of nuclear power generation must be viewed within the wider global energy context, since this is the bedrock on which the future of this technology will unfold. The impact of a small number of critical accidents over the last 60 years is significant. It is fair to say that a nuclear renaissance was under way during the first decade of this century, but it was interrupted by the earthquake and tsunami on the east coast of Japan in March 2011 and the crisis those events precipitated at the Fukushima Daiichi plant. These incidents reopened the debate on the future of nuclear power in many countries, and the industry remains under scrutiny today. Of the 31 countries that currently generate nuclear power, five have decided to phase out this technology, and Japan may one day follow suit.

A number of countries remain undeterred, and will continue to build new plants; the UK is expected to replace its ageing nuclear fleet, and China is forging ahead with ambitious plans that (if realised) will make it a dominant force in the nuclear industry (see Figure 1). But for a global renaissance, the industry needs to gain public confidence and show that nuclear power satisfies the basic tenets of sustainable development.

Nuclear power generation is a mature industry which has delivered large quantities of baseload electricity since the first civil nuclear reactor began operating in 1956 at Calder Hall in the UK. Today, almost 60 years later, there are 434 reactors operating in 31 countries around the world, with a combined generating capacity of 374 gigawatts electrical. Seventeen other countries from Eastern Europe, the Middle East and Asia are either constructing new nuclear plants, or have plans or proposals for new plants. The existing global fleet of plants generated about 2,500 terawatt-hours or about 11% of the world's electricity needs in 2012. Nuclear power currently constitutes only about 5% of the world's total energy supply, and this percentage has remained virtually static for about 20 years. Despite the fact that its contribution is relatively small on a global scale, in some countries nuclear power constitutes a major electricity source.

There are a range of factors that will determine the future of the nuclear industry, including technical issues, political agendas and public opinion. For nuclear power to remain a significant factor, the industry must craft a credible argument that clearly portrays nuclear power as a viable, sustainable energy resource for the future, and not just an option of last resort. In order for any type of development to be considered sustainable, it must meet the needs of society today without sacrificing the needs of future generations. This principle provides a solid basis for the three ‘pillars of sustainability’: the economic rationale, environmental footprint, and social impact.

There are many who believe that nuclear power technology can never meet the criteria for sustainable development. Others believe that the sustainable development debate actually provides an opportunity to take a more holistic view of this technology, to highlight both its advantages and its disadvantages. There is no analytical formula based on a detailed description of each ‘pillar’ that can be used to evaluate whether a technology or industry is sustainable. There are both objective and subjective factors to be considered: quantitative measurements and data, as well as the more qualitative political, philosophical and emotional issues. The constituent elements of each pillar must be assessed as positive or negative, and their perceived importance will vary across different groups. The current cultural climate and state of social development will also have a key influence on these evaluations. Thus, the industry must gain the public trust that is crucial to the nuclear debate by providing better information about the nuclear process to all stakeholders, in an open and transparent approach.

Place in the energy mix

Is there a sound economic rationale for the further development of nuclear power generation? There is little doubt that large quantities of affordable, reliable electricity are fundamental to supporting society’s economic growth and the quality of life of its citizens. It powers industry and commercial activities, heating and lighting for homes, and mass transportation, water and sanitation, all essential in modern society. Nuclear generation contributes a significant share of the electricity supplied in the countries where it operates. For example, France generates 75% of its electricity from nuclear plants, while China's nuclear capacity, at just 2% of total electricity, is projected to grow rapidly. On average, in the 31 countries that host nuclear plants, almost 24% of their total electricity is derived from nuclear power. Germany relies on nuclear sources for 16% of its electricity and must look to other technologies once it decommissions its nuclear plants. Other countries find themselves in a similarly serious situation: Spain and Switzerland depend on nuclear power for 36% of their electricity while Belgium's nuclear-generated share is just over 50%. It will be no easy task for any of these countries to find viable alternatives to nuclear power generation, and meeting the demand for electricity using other resources may result in increased carbon emissions over the short term.

It falls to governments to support the deployment of nuclear technology

Some have suggested that nuclear power is not sustainable because it is too expensive. The construction of a new nuclear plant must make economic sense, and the same holds true for any type of power plant. Building a new nuclear power station represents a capital-intensive infrastructure project, and three parameters play key roles in determining its economic viability: the interest rate for securing capital, the cost of fuel for the market's benchmark technology (usually gas), and the cost of handling carbon emissions. Financing these projects can be difficult in liberalised markets and so it falls to governments to support the deployment of nuclear technology with a variety of financial instruments to effectively reduce the cost of the required capital.

At low gas prices and carbon costs, gas remains the preferred energy source; at high gas prices and carbon costs, nuclear is favoured. The greatest influencers in making this choice are the availability and cost of gas resources, and the importance of the decarbonisation agenda. Despite a continuing healthy reserves-to-production ratio, competition for gas supplies is expected to increase as global demand grows in future decades. The shale gas revolution in the USA has signalled the potential of gas derived from unconventional sources and this will contribute to the world gas supply. Gas prices are currently low, but they are expected to show a net upward trend driven by increasing demand over the operational lifetime of a new nuclear build.

Despite the lack of an international agreement on climate change for the post-2020 period, the pressure to reduce worldwide carbon dioxide emissions remains. As the impact of climate change becomes more tangible, politicians will eventually reach consensus on a plan that is likely to increase the cost of carbon and place additional economic pressure on the use of fossil fuels. There remains the potential for the emergence of a truly disruptive technology that will reduce the importance of the carbon-free benefits of nuclear power generation. Carbon capture and storage (CCS) technologies are currently being developed to address the issue of increased carbon dioxide emissions produced by the use of fossil-fuel sources, but the complexity and cost of these projects has resulted in slow development. Pilot projects at a meaningful scale are on the horizon, and these will provide the information required to go forward with this technology.

In this light, it is plausible to expect that nuclear energy generation can compete economically with leading alternative technologies in the medium to long term. A further benefit – security of supply – is not formally valued today, but will serve to broaden the economic appeal of nuclear when it is recognised in the market.

Emissions and waste

What about the environmental impact of nuclear power generation? Most discussions about the sustainable development of energy sources are primarily focused on climate change. The carbon produced by conventional energy generation methods will persist in the earth's atmosphere for centuries. Although the nuclear industry was developed primarily to deliver large quantities of baseload electricity to aid economic development, and not as a way to address climate change concerns, this is a technology that can do both. Nuclear generation does not emit the large quantities of carbon dioxide that result from energy generation using fossil fuels. Assuming a conservative value of 500 grams per kilowatt-hour of carbon dioxide for electricity derived from fossil sources, the global supply of 2,500 terawatt-hours of electricity produced annually using nuclear power avoids the production of 1.3 gigatonnes of carbon dioxide each year. To put this number into context, this is equivalent to removing about a quarter of all carbon emissions produced in the USA. The nuclear power sector has arguably been the single greatest contributor in efforts to curtail carbon emissions over the past 60 years. Without it, the detrimental impact of atmospheric carbon would be much greater today and in the future.

There is little doubt that governments, and the people they represent, are likely to view the nuclear option as more favourable when the threat of climate change is imminent. But they do so reluctantly, primarily because progress in resolving the long-term nuclear waste issue has been slow. With the possible exception of one or two countries, government and industry have done a poor job of explaining these issues and their potential solutions to the public, despite the fact that opinion polls confirm this is a key concern.

The issue of inter-generational environmental equity is a key principle of sustainable development. It is reasonable to expect that the generation that receives the benefit of the electricity generated should also be responsible for dealing with the by-products of its production. While the actual management of some nuclear wastes may be delayed until the future, producers have a current obligation to develop, fund and implement a practical solution for this task. The industry wants to do this; the question remains one of how to advance this debate. Discussion must occur on three levels: technical, social and political. In the past, the industry's focus has been mainly technical, showing that its solutions are safe and feasible, but this has been demonstrated only to a relatively narrow group of stakeholders composed of regulators, academics and peers.

Positions on the long-term safety of storing nuclear waste are polarised. At one end, some NGOs maintain there is no safe way to dispose of highly radioactive waste and therefore its production should stop, while at the other end, the industry contends that the technical aspects of this problem are well understood, and that solutions for safe disposal already exist. The public is not educated on these issues, and so its opinion has vacillated as people try to decide whether the NGOs are more trustworthy than the industry. A long-term, concerted education programme is needed to put the nuclear waste problem and its implications in perspective, and convince the public that nuclear waste can be handled safely and responsibly. At the outset, the industry could explain that the volume of waste is relatively small, that it is not uniquely hazardous, and that most of the waste has a relatively short half-life. People need to know that the industry stores and monitors its wastes safely, that it oversees their long-term management, and that these activities are routinely scrutinised by an independent and a highly competent regulator.

Public involvement and consensus are crucial

The development of waste-disposal facilities in Finland and Sweden has shown that public involvement and consensus are crucial, with government acting as a key facilitator. In Finland's case, many lessons have been learned from the operation of two waste repositories for low- and intermediate-level waste over the course of 25 years, and this knowledge has been instrumental in gaining public confidence in a proposed long-term solution. This experience is encouraging for the industry, but it can be difficult to leverage this type of success across countries and cultures. Nevertheless, the practical knowledge gained can be adopted across national boundaries.

Timely resolution of the waste-disposal problem will not only make the safe storage and management of existing wastes practical, but will foster the development of future disposal strategies. If left unresolved, this issue could present an ongoing, significant barrier to the construction of new nuclear plants.

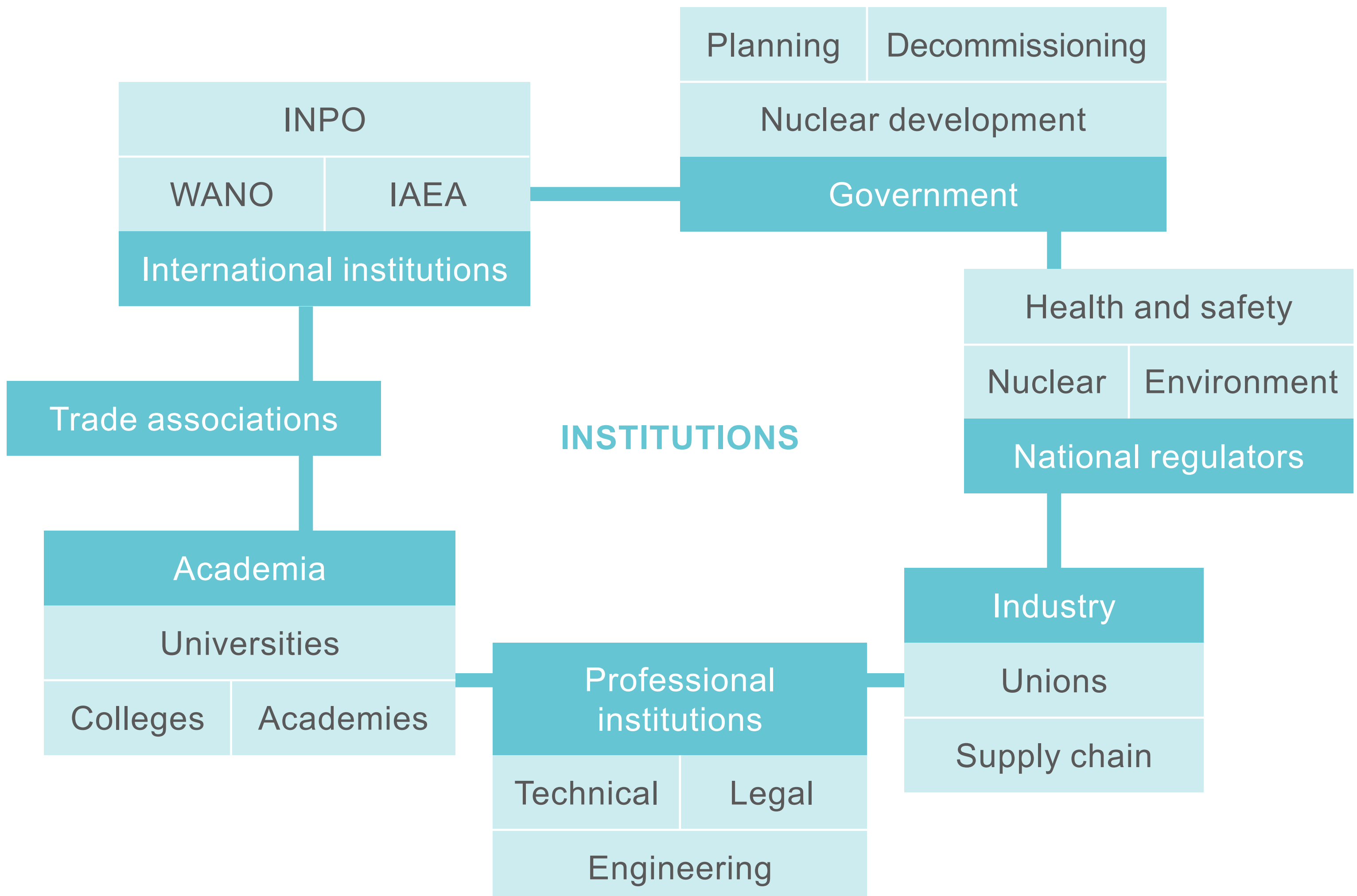


Figure 2: Strong institutions are essential for new nuclear build.
Note: WANO, World Association of Nuclear Operations; INPO, Institute of Nuclear Power Operators; IAEA, International Atomic Energy Agency.

Acceptance

How does the development of nuclear power affect society? This question is perhaps the most difficult to answer because it involves contentious issues including concerns over dangers from radioactive emissions and accidents, plant security, and the proliferation of nuclear weapons. The role of institutions that provide operational guidelines on both a national and international level is critical in this area (see Figure 2). The industry's track record for avoiding radioactive releases to the environment from normal operations is very good. A strict regulatory framework, rigorously enforced by an independent regulator, ensures that the radioactive dosage to employees and the public is kept well within safe limits – as people go about their normal daily lives, they are likely to receive more radiation exposure from natural sources than from nuclear power stations.

Communities that host nuclear plants tend to have a better understanding of nuclear safety and more confidence in the way the industry conducts its operations. This has been achieved through regular meetings where industry can inform and discuss issues with its local stakeholders. But these efforts should be extended by the numerous institutions that play a role in the industry to increase awareness in the broader population.

Some significant accidents during the past 60 years have damaged the nuclear industry's reputation for safety and delayed its advancement. Like most accidents, these did not result from a single issue, but from a confluence of issues that contributed to a severe outcome. And these causes were not purely technical in nature – they included poor management decisions and operational hubris. To its credit, the industry has responded to these problems by acknowledging that nuclear technology is unique, requiring its own global institutions (see Figure 3).

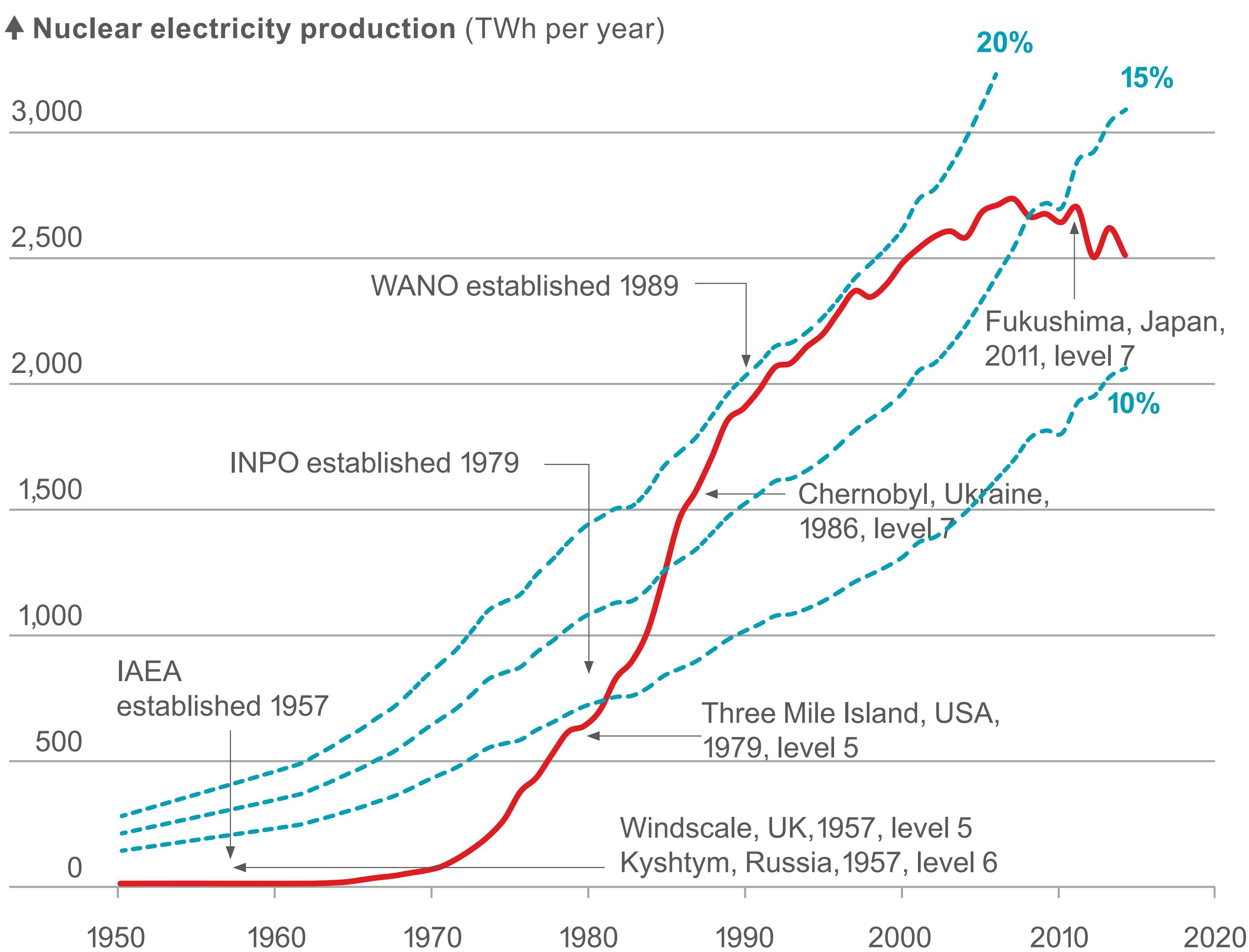


Figure 3: The journey of nuclear. Institutions enabled its growth while incidents hampered it. The red line shows the growth of nuclear electricity production compared to percentages of the world total electricity production (blue dashed lines).

The Institute of Nuclear Power Operations (INPO) was created after the Three Mile Island accident, and the World Association of Nuclear Operators (WANO) was created after the Chernobyl accident. These institutions have improved the industry's performance considerably by promoting a 'safety-first' approach, establishing questioning attitudes, and encouraging constant examination as part of ongoing organisational learning. A strong commitment by their leaders to furthering these aims, independent of economic, political or other consequences is crucial.

Former US Vice President Al Gore, a long-time environmentalist, visited post-accident Chernobyl in the summer of 1998. In a speech during that visit he proposed that nuclear energy could remain a viable energy option in the future if the industry could meet its challenges: "Nuclear power, designed well, regulated properly, cared for meticulously, has a place in the world's energy supply."

The industry currently operates under a regulatory regime in which security and safety share top priority. Public opinion will improve with the industry's continued effort to maintain this culture of high security at the operator and state levels, and with the ongoing development of international co-operation programmes where scrutiny of practice is encouraged. Peer reviews by international experts provide independent scrutiny of nuclear operational practices and a powerful method for sharing operating information, and this practice is accepted worldwide. This aspect of nuclear culture is an essential prerequisite for countries developing new nuclear projects, as well as an important practice for the countries who now provide it.

A number of developing countries around the world are turning to government-operated civil nuclear power both to meet the growing domestic demand for electricity and to limit reliance on foreign conventional fossil fuels. A fundamental challenge for these countries is their capacity for sufficient technical and institutional support of the industry. This is important throughout the nuclear cycle, including plant construction, operation and decommissioning, and the management of waste. Developing strong institutions to oversee these activities takes time, as does establishing a culture in which nuclear operators engender trust in the public at local, national and international levels. The possibility that civil nuclear power facilities could be used to develop military programmes raises another key concern about nuclear development – nuclear weapons proliferation. For this reason, strong international co-operation is vitally important; all countries who operate nuclear facilities must become members of a community that accepts the need for transparency and peer group scrutiny. Public confidence relies on the implementation of these safeguards.

To adopt nuclear power, strong and enduring institutions are needed

Today, nuclear power generation is at a crossroads with the scale of its contribution to the future energy mix uncertain. The long operational lives of nuclear plants suggest that this technology will be contributing to the world electricity mix throughout this century. It is possible that some countries (notably the major developing countries such as China and India, and established nuclear countries such as the UK and France) will continue to construct nuclear power stations in an effort to diversify their electricity mix or to replace ageing plants. There may also be a handful of additional countries that will develop nuclear power facilities for the first time. These countries must first establish strong and enduring institutions for their new nuclear industry, and it is incumbent on the existing nuclear community to share its knowledge and provide support for these new members.

There are a number of studies describing possible future scenarios for nuclear power. Shell's two New Lens scenarios, Mountains and Oceans, describe the energy landscape over a period from 1960 to 2060. These scenarios present similar predictions of overall energy consumption rates, with fossil fuels continuing to play a dominant role, but there are differences including the relative contributions of the three main fossil fuels (coal, oil and gas), and the contribution of low-carbon technologies. The Mountains scenario suggests that nuclear generation will increase threefold, while Oceans suggests a doubling over the same period. But in both of these scenarios, the future contribution of nuclear power to the world's energy is expected to remain low, at around 10% in Mountains and 5% in Oceans. The high-level message of this analysis is that nuclear may well play an important role in some countries, but it will constitute only a small portion of total global energy.

Climate concerns which, in the past, convinced many that nuclear should be part of the future energy mix, appear insufficient to encourage a full-blown nuclear renaissance today. Instead, the industry is undergoing a far less dramatic period of recovery and rehabilitation as it seeks to prove itself once again in the public eye and secure a position as an important player in the future energy landscape.

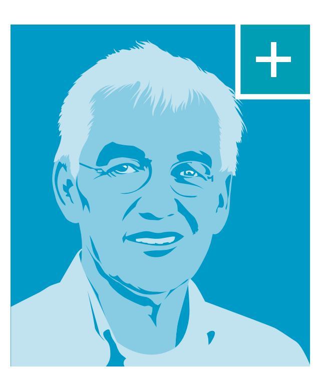
Chris Anastasi worked in Shell's scenarios team in the 1990s and has been a member of a number of Government Committees and Advisory Boards, in the UK and elsewhere.

The cradle of new energy technologies

Why we have solar cells but not yet nuclear fusion

New energy technologies can only slowly conquer the market and require large investments in money and energy to gain a hold. A comparison of nuclear fusion and photovoltaics shows that they do not differ in the size of investments needed, but in the nature thereof.





> *Niek Lopes Cardozo, Guido Lange and Gert Jan Kramer*

If you wanted to provide all toothbrush owners in the world with a brand-new toothbrush, how fast could you do that? Our guess: in about three months. Because that is the time after which a toothbrush needs to be replaced, and the toothbrush industry is tuned to exactly that production capacity. If you wanted to provide all house owners with a new house, that would obviously take a lot longer. It would probably be more like 50 years. The world's house-building capacity, set to the replacement rate, is simply not great enough to do it much faster. This is not because a house is bigger and more expensive than a toothbrush, but because it lasts much longer. For toothbrushes and houses this is obvious. Now let us look at energy.

Energy is – by a wide margin – the single largest market in the world. The capital stock that makes up the energy system, from oil rigs and refineries to power plants, wind farms and solar panels, has a lifespan of 20-60 years. House-like, not toothbrush-like.

Many people will tell you that photovoltaics, once they reach grid parity, will conquer the world market like a prairie fire, like smartphones did. Yet there is an essential difference. A smartphone, with an economic life of two years, is toothbrush-like, while solar panels, with their lifetime of 30 or more years, are house-like. So are all the other components of the energy system. Their lifespan is almost invariably measured in decades.

Scaling it up

How does the long life of power installations affect the speed at which the transition to new energy sources can be achieved? And is this different for different energy technologies? To answer these questions we consider two extremes: the large, centralised nuclear fusion energy and small-scale, distributed photovoltaics. We will illustrate the manner in which these energy sources become established.

Photovoltaics and nuclear fusion have more in common than it would seem. To start with, they are both relatively new technologies. The use of coal and crude oil, as well as the harnessing of the powers of water and wind, all go back to ancient times. But the photo-electric effect that underlies solar photovoltaic cells, as well as the idea of nuclear energy gained from joining (or splitting) atoms, are both 20th-century novelties. The first was explained and the second was predicted by Albert Einstein in the same year, 1905, his *annus mirabilis*.

It took half a century to turn revolutionary physics into dependable technology. Nuclear fission got there first, thanks to the imperatives of World War II and driven by the military-industrial complex in the subsequent decades. Photovoltaics were arguably just as challenging, but sizeable support for their development came only decades later. The first solar cell was created in 1954 by Bell Laboratories, a uniquely productive institution that owed its existence not to the military, but to the telephone monopoly granted to AT&T. Solar cells were further developed with government aid, for potential space applications, but suffered from inadequate financing from the 1970s to the 1990s. Photovoltaics only became industrialised in the early 2000s, when Germany bought wholesale into the technology.

Nuclear fusion, on the other hand, only started its life as a research programme around the time the first solar cells entered the market. And although this notoriously challenging technology saw a very rapid development – the ‘power multiplication’, i.e. the ratio of produced fusion power to the power needed to run the reactor, doubling every 1.8 years over a period of three decades – it had to go a very long way. With the construction of the international reactor ITER, fusion presently leaves the laboratory and makes the transition to a more industrial development programme.

It might seem that the winner and the loser can be called. Now that solar energy is starting to have an impact, fusion is still, as the joke has it, “50 years away, as it has always been”. But that critique may be too easy. In the longer run – 50 years from now – we may want to tap the promise of fusion as well. As we will see, research is followed by investment. This is a ‘breeding’ phase, as it were, and only thereafter can its benefits be reaped. Solar energy is well into its breeding phase and fusion is just at the beginning. Yet, if fusion gets its chance, in spite of its multi-billion dollar projects, its total development cost may not be much different from photovoltaics. In fact, as we shall show, the development costs for *all* energy technologies are similar. A $1,000-2,000 billion (€900-1,800 billion) upfront investment is needed to bring a technology to 10% of its potential.

The starting point for our analysis is a paper co-written by one of us in *Nature* in 2009, in which 'laws' of new energy technology deployment were put forward.[1] Based on an analysis of historical data, it is shown that the introduction of a new energy technology – be it nuclear fission, photovoltaics, concentrated solar power, wind or biomass – is always characterised by two phases (see Figure 1).

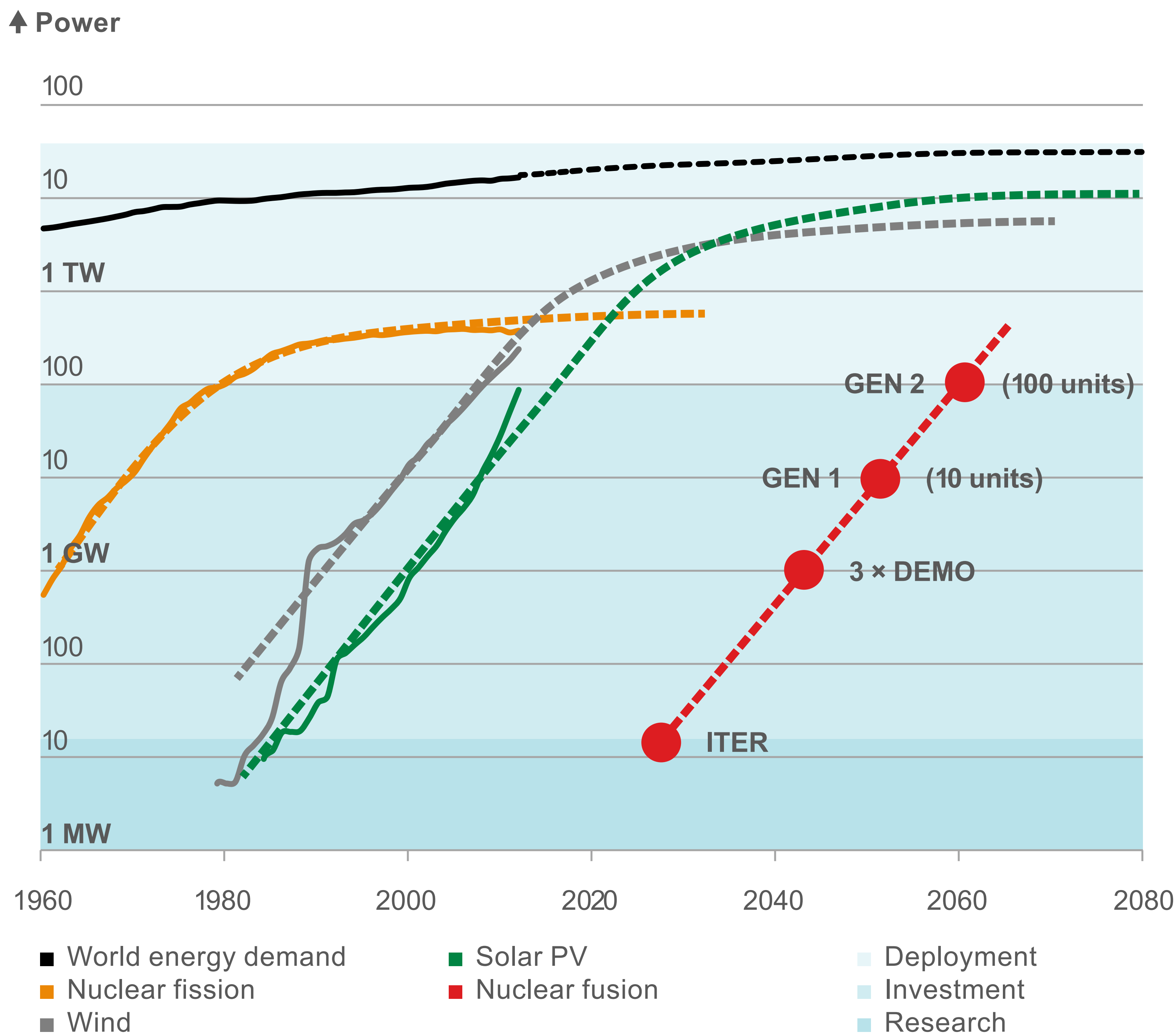


Figure 1: Deployment rate for different energy technologies. The dotted lines represent the deployment according to the model discussed in the text. The drawn lines are the actual deployment rates based on OECD and IEA energy statistics. Note that 'Power' on the vertical axis denotes the average energy delivered to society per unit of time. The installed capacity is usually larger because of a low capacity factor (PV, wind) or low availability as in the case of first-of-a-kind installations such as ITER for which 10% availability is assumed here.

The technology first shows an exponential growth, during which the installed power doubles every three to four years. This can go on for decades and bring the technology from laboratory scale to something that is visible on the radar of the world energy market, typically at 1% of world energy demand. The technology has reached ‘materiality’, in the words of this *Nature* paper. Even though 1% may not sound like much, a significant industry has by that time already been established. To illustrate this point: the worldwide investment in photovoltaics was €90 billion ($100 billion) in 2012. This is slightly more than 1% of the world’s expenditure on energy, yet the total contribution of photovoltaics to the global energy supply is only 0.1%.

Around the time that materiality is achieved – as observed in the *Nature* paper on the laws of new energy deployment – a transition occurs. The growth is no longer exponential, but linear. This linear growth phase lasts another few decades, after which the installed base levels off and the ascent from development to market saturation is completed (see Figure 2).

All stages of this process may be understood from the prudent investor perspective: before anything else the technology needs to be made practically viable through research. The first stage of the development is a phase of rapid exponential growth, limited mostly by the capacity of the market to build successive generations of ever-improving technologies. The second stage is a build-out phase, where the full benefit of the technology is enjoyed at the same time that the growth becomes more measured (linear) so as to avoid overbuild. Finally, the growth levels off when the final market share has been reached. This is a simplification, but what is lost in richness is compensated for by the fact that it allows us to express a highly complex process in a few simple mathematical equations. This leads to some interesting and non-obvious conclusions.

The development is best analysed backwards. Start with the saturated state and ask the question: what is the fastest way in which that saturated state could have been reached? To answer that question we must evaluate which constraints limit the pace of deployment. The most logical constraint is that investors don’t want to shut down good production capacity during its lifetime because it is no longer needed. Given that constraint, the fastest route to the saturation level is linear growth. Any accelerating growth wastes time at the beginning and any growth that slows down wastes time at the end. The question remains: what is the speed of this linear growth? The answer is: the replacement rate in the saturated state. Because that is the largest production capacity that you will ever need, any capacity in excess of that would need to be dismantled after the installed power has reached the saturation level. The linear growth and saturated state are therefore characterised by a single characteristic time: the lifespan of the installation.

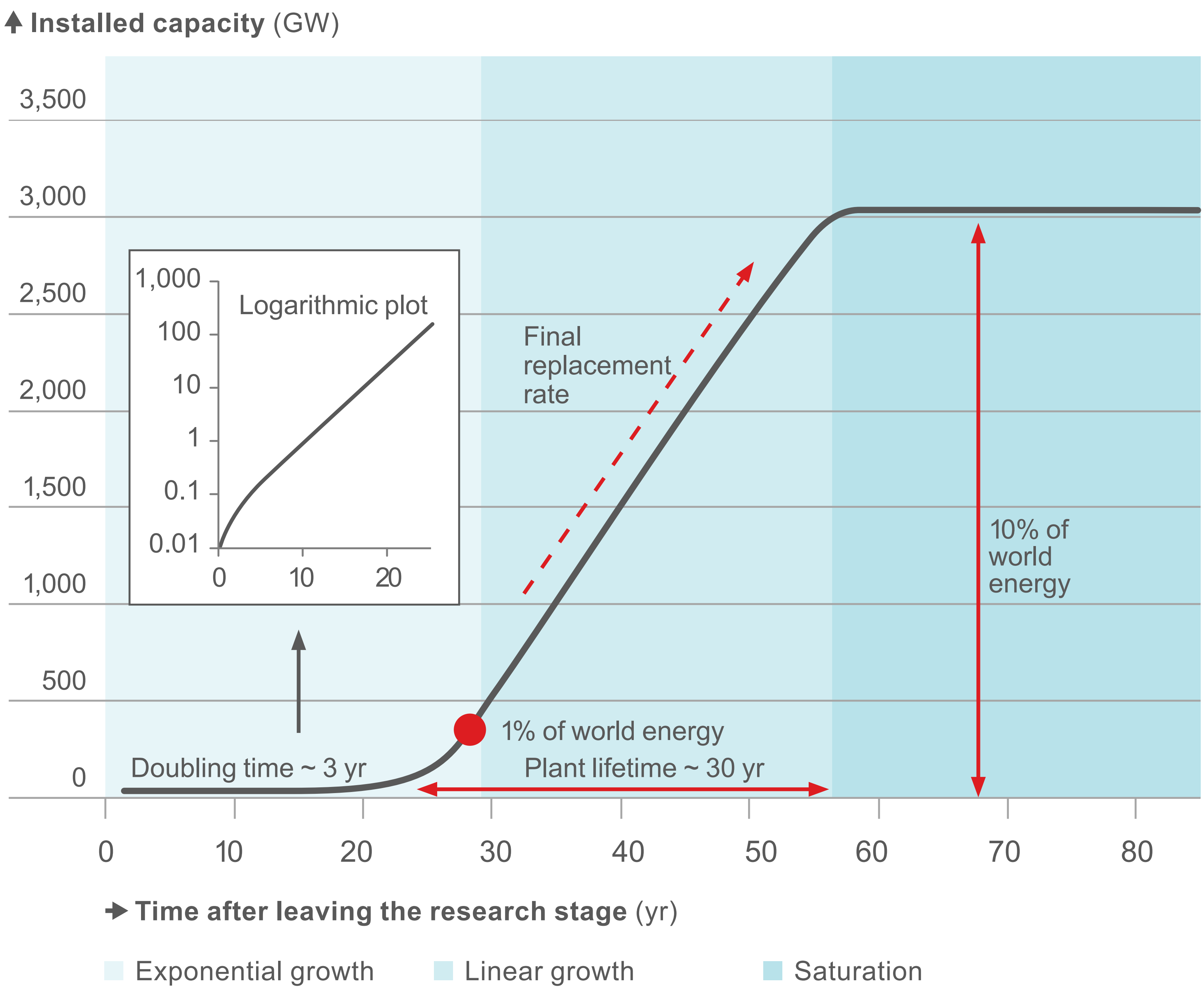


Figure 2: How energy technologies grow. Three phases in the deployment of a new energy technology.

It is obvious that one cannot start the linear growth at full speed on day one. The technology and industrial capacity first need to be built up:

factories, dedicated machinery, infrastructure, supply chain of materials, mining of raw materials, and a trained workforce. The development of these components is what the initial exponential phase achieves. It is there because it is the fastest way to build that industrial capacity. This 'growth of growth' occurs in practice whenever growth can feed off its own consequences. The buzz around a movie reaches more people each day because more people have already seen it. In its simplest form, this pattern of 'growth getting bigger because of growth' needs only one number to characterise it: the doubling time.

New energy technologies don't reduce carbon emissions during their exponential growth phase

The exponential growth of production capacity will stop once the required capacity for linear growth has been reached. It follows from the mathematics of the growth model that the transition occurs when the installed power is at a fraction of the saturation level given by the ratio of the doubling time to the lifespan.[2] For power installations with a lifetime of 40 years and exponential growth with a doubling time of three years, the changeover from exponential to linear growth occurs at about one tenth of the saturation level. This is consistent with the observations in the aforementioned *Nature* paper on the laws of new energy deployment.

These numbers are very different for the market of short-lived products, such as smartphones. They can grow exponentially right up to their saturation level, because a huge replacement capacity is needed. That is why the introduction of photovoltaics is fundamentally different from that of smartphones.

So, we have seen that maximum growth is dominated by the lifespan of the power installations. The exponential growth phase has no function other than to build up the technology and industrial capacity. In fact, during the entire exponential growth phase, new energy technology, such as solar panels or anything else,[3] don't contribute net energy, nor do they reduce carbon emissions. That is an unavoidable consequence of the mathematics of exponential growth. At its core is the fact that, for instance, in order for a solar panel to exist, we must produce it, and this activity takes energy. This will, in today's world, always involve the emission of a certain amount of carbon dioxide. Even if the factory runs on renewable energy, that energy then can't be used to prevent carbon dioxide emissions elsewhere. So every solar panel leaves the factory with a 'debt to society'.

For photovoltaic energy to be a net energy producer, this debt will have to be paid over a period that is shorter than the panel's lifetime, leaving it free to contribute to emission reduction during the rest of that time. The payback time of a solar panel is a perfectly acceptable two to three years in sunny regions, out of a total lifetime of 30 or more years.

However, as long as the production of solar panels is growing exponentially, by definition it keeps doubling. Suppose this doubling period is three years, equal to the energy payback time. If the factory is very small and initially produces one solar panel, it starts life with one panel's worth of 'energy deficit'. After the doubling period, when the first panel has just compensated for this deficit, two more panels leave the factory, so the total deficit is now twice as large. One doubling period later, the first panel will have produced one panel's worth of surplus energy. The two others will have paid their own way, and four new panels have appeared, for a total of three panels' worth of debt. That's not a very large debt for seven panels to cover. They can do it in one more 'doubling period', but only if in that period the number of panels doesn't double. That is when exponential growth stops and the growth becomes linear.

On the other hand, in order to have any impact, this transition should come late in the process, so that the technology can grow as long and as fast as possible. A new energy technology that leaves the lab when the total of its prototypes produces 10 megawatts of effective, year-averaged power, and starts its exponential growth, must grow by a factor of 20,000 to reach the 1% of world demand mark. That corresponds to more than 14 doublings. Even with a sustained doubling every three years, that still requires 40 years of exponential growth before the world can reap any rewards from this technology. Since photovoltaics are now growing exponentially, it is certain that despite many hundreds of billions of dollars spent on the production and installation of solar cells, it has produced no net energy. It might not seem that this is true. Germany, for instance, may claim that solar panels have a noticeable share in its electricity production. However, this doesn't take into account the energy investment in the countries that produce the panels, mostly China and South Korea.

Long-term investments

Indeed, when the statistics are examined globally, it follows that photovoltaics has not produced any net energy. This may seem puzzling, since the photovoltaics business is thriving, with a global production of €100 billion ($120 billion) per year. This paradox has two possible answers with some political implications. Critics say that this market is created by subsidies. Supporters say that a €100 billion ($120 billion) business cannot be subsidy-driven, and so the benefits must be real. Who is right?

The answer may be found by adding up all the numbers: cheap energy rates for the photovoltaics industry and direct government support for them; direct subsidies for solar panel owners, or tax breaks, or guaranteed prices for what they deliver to the grid. This is a complex exercise in which each number can be challenged.

We can also take the macro-route. Since we have established that the entire photovoltaics industry does not produce net energy as long as it is growing exponentially, it clearly cannot be making money by selling it. Who, then, pays the bill? Governments, investors, taxpayers, society at large. The most important point is that the cost of development of a new energy source is an investment. It is the investment society must make to develop a future clean energy source. A good investment, but one that is large and precedes the return by several decades.

How big an investment are we talking about? If 'materiality', the end of exponential growth, is reached at 1% of the world energy demand, that is 200-300 gigawatts, and this installed effective power was realised at the competitive 'overnight capital investment' of $5-7 (€4.5-6) per effective watt, then the investment is $1,000-2,000 billion (€900-1,800 billion).

In short, each new energy technology will need an investment of this order of magnitude during a period of decades of exponential growth, no matter how we do it. This will only start to pay off in the decades that follow. This is also true for the expected pay-off in the form of emission reductions.

With this perspective, fusion energy doesn't seem much different from photovoltaics. Both the investment needed during the non-productive development phase and the time required to bring it from laboratory to materiality are similar. But whereas the prototype solar cell was on the market 60 years ago, fusion is only now building the proof-of-principle machine ITER.[4] It does weigh in at 500 megawatts of thermal power, so fusion comes in a few big steps rather than many small ones.
The roadmaps for the development of fusion power that have been established in China, South Korea, India and the European Union together foresee a few electricity-producing demonstration plants around 2040-2050, followed closely by the first generation of commercial fusion plants. This development would correspond to an exponential growth with a doubling time of 3-4 years, which is very much in line with the generic picture sketched above. This would bring fusion energy to materiality around 2060-2070, some 40 years later than photovoltaics. The expected total investment over that period of exponential growth is similar to that of photovoltaics or any other power source.

Having said this, it is good to point out that new energy technologies, the ones that are presently being invented in the laboratory, in turn have a large time lag. They still have to start their exponential growth and should not be expected to contribute significantly until some 50 years from now. We should always keep in mind that the solar cell was operational 60 years ago, and the technology of windmills goes back centuries.

Risky steps

Back to our guinea pig technologies. It is clear that photovoltaics are taking off rapidly, while fusion is still in the transition from research to development and is perceived to still have significant technical uncertainties. What is the origin of this difference? In the first place, the extreme requirements of the fusion process, starting with the burn temperature of hundreds of millions of degrees, meant that fusion was still in the research phase when photovoltaics had long since become a commercial development, albeit for niche markets. So fusion lags behind, by decades. But there is another important difference. The physics of the fusion process prescribes the minimum size of a reactor for it to produce net energy, and this minimum has turned out to lie around the one gigawatt power level. Hence, the development of fusion energy necessarily comes in single large steps. ITER is not the final fusion reactor design. Significant breakthroughs are still needed, in particular in the field of materials. Unlike the case of solar photovoltaics, where the working prototype was already available on a small scale and improvements were implemented gradually during the process of scaling up, the development of fusion power critically depends on the success of these single big steps. This is, in a technological sense, a much more risky way of proceeding.

Fusion power critically depends on the success of single big steps

The financial perspective on these developments is very different, too. The perception is that photovoltaics is a market-driven, commercial development, even though we have seen that the technology is not yet producing net energy and that the development relies on investments by governments. With fusion, on the other hand, every step in the development process is a large one. Even if the required investments in the present stage of the development are tiny compared to that in photovoltaics, the risk associated with the investment is large. These differences make the development of a ‘many-small-steps’ photovoltaics-like technology much more manageable than that of breakthrough technology such as fusion energy.

To further illustrate this issue, it is useful to look again at the characteristics of the exponential growth model. With each doubling period, it’s not only the number of, say, solar panels that becomes twice as large, but also the production capacity, and with that investment. This is the mathematical property of exponential growth: if the installed power grows exponentially, then so does its time derivative, the production capacity. Of the entire investment in the development of a new energy technology, about 50% is made in the last few years before materiality is reached. From that perspective, there is every reason to try and speed up the earlier phase, when investment is still at a much lower level. The earlier in the development, the more time can be gained at the lowest cost. There really is no good reason not to leapfrog a few development generations by taking higher risks. Those risks are tiny compared to the gains, both societal and economical, that can be achieved by reaching the productive phase earlier.

Even more effective, though much less controllable, is the acceleration in the research phase prior to exponential growth. Research budgets are but fractions of the turnover in the industrial implementation phase. This is especially true in the highly conservative energy industry.

This strongly suggests that a good energy policy puts considerable emphasis on speeding up the research phase and developing different options in parallel.

It is only well into industrialisation, that is during the exponential growth, that it becomes important to select what have then emerged as the most promising technologies. Yet it is more difficult to accelerate during this latter phase, where industrialisation takes off. If we could force, for example, the exponential growth to continue for just one more doubling period, presumably by subsidising investment in more production capacity, it would double the final growth rate, and halve the linear growth period. But at the end of linear growth, half of the world's production capacity of the particular energy technology would have to be shut down, and the work force sent home. Remember we are speaking of the largest economic market in the world. So the acceleration would have been achieved at an enormous expense.

Is there no way, then, to speed up the linear growth phase? The concept of 'fastest growth' does in fact suggest a way that may be counterintuitive: *disposable* energy solutions. If the length of the linear growth phase is equal to the economic lifetime of the installations producing the energy, then if we want to shorten it, we should make those installations less durable. Think of a lifetime of a few years rather than decades. Like a smartphone – indeed, like a toothbrush. Research might focus on low-cost-not-good solutions rather than shoot for highest performance. Photovoltaic paint that you have to reapply every few years, cheap bio-based solar panels, bacteria that turn your swimming pool into a gas plant. It's speculation, perhaps, and a kind of paradox, but one has to trust the mathematics.

In conclusion, the development of an energy technology needs a large investment over decades in which no net energy is produced. This investment is more or less the same for different technologies. Yet the scale of the technology matters. Not for the total cost, but for the risk associated with the development. In that sense, investments in fusion energy are of a different nature from those in solar panels. The market will favour the latter, but governments – who eventually pay the bill and bear the responsibility for the future generations – need to make their own assessments and policies.

Related essay

The multi-terawatt challenge
Preparing photovoltaics for global impact
> *Wim Sinke*

Niek Lopes Cardozo took up the full-time professorship of Science and Technology of Nuclear Fusion at Eindhoven University of Technology, the Netherlands, in 2009, after having headed the national fusion research programme at the FOM Institute for Plasma Physics (now DIFFER) since 2001. He recently initiated a dedicated two-year MSc programme on fusion. He established and chairs the European Network for Fusion Education, the FuseNet association. He is presently chairman of the executive board of the Dutch national organisation for fundamental physics research, FOM, and chairs the interdisciplinary 'sustainable energy' research activity of the national science council NWO. In addition to teaching and research, Lopes Cardozo has engaged in outreach, particularly to secondary school students. In 2003 he was awarded the Royal Dutch/Shell Prize for sustainable development and energy.

Guido Lange was, at the time of writing, a student in Applied Physics at Eindhoven University of Technology in the group of Niek Lopes Cardozo. He has done research on the KSTAR tokamak in South Korea. He took the initiative to Team Energy, a think-tank at that university. He has also done an internship at Shell's Energy Futures department.

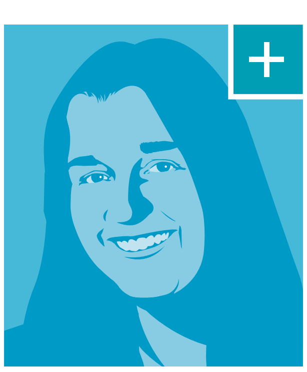
Gert Jan Kramer is Manager Energy Futures at Shell Technology Centre Amsterdam. A physicist by training, he joined Shell in 1988 where he initially worked on classical oil industry topics such as catalysis and reactor engineering. In 1998 he became involved in research relating to hydrogen as a future fuel. Over the years his activities broadened to technology assessment across the full spectrum of alternative energies. In addition to his role at Shell he is professor of sustainable energy at Leiden University and a member of the Technical Committee of the Energy Technologies Institute in the UK.

Notes and references

1. G.J. Kramer & M. Haigh (2009). No quick switch to low-carbon energy, *Nature, 462*, 568-569, doi:10.1038/462568a.
2. To be precise, the transition occurs when the total installed power (P) has reached the level $P = (P_{saturation} \cdot \tau_{doubling}) / (\ln(2) \cdot \tau_{replacement})$ where $P_{saturation}$ denotes the total installed power in the final saturated market and $\tau_{doubling}$ and $\tau_{replacement}$ are the doubling time during the exponential growth and the lifespan, respectively.
3. Strictly speaking, energy production is only negative if the doubling time is shorter than the energy payback time (which is the case for photovoltaics). Yet, if there is a net positive production, its contribution to the total energy production is negligible. Even in the last few years of the initial exponential phase, energy production is very low compared to the linear phase.
4. The experimental fusion reactor presently under construction in the south of France, ITER, is designed to produce 500 MW of thermal fusion power – ten times more than the power needed to run the device. A worldwide collaboration shares its construction costs of more than €10 billion ($12 billion).

Fuel for thought
How to deal with competing claims on biomass

In order for bioenergy to make a significant and sustainable contribution to future energy supply, a simple 'more is better' approach will not work. It is necessary that the world comes to grips with the competing claims for food, feed, fibre and fuel. This requires an approach that is both holistic and tuned to local conditions.



> *Iris Lewandowski and Angelika Voss*

Viewed from a satellite, the earth looks to be in good shape. One viewing of NASA's famous Blue Marble animation of the seasonal ebb and flow of vegetation on our planet is enough for us to be impressed by the primeval force that is photosynthesis, fixing 60 gigatonnes of carbon every year. It would seem that this force, which has sustained nature and humanity since time immemorial, holds the key to solving two of this century's main challenges: mitigating climate change and feeding its growing population. Photosynthesis should be amply able to produce both the food and the fuel humanity needs.

From up close, there seems to be rather less cause for optimism. In Mexico, irate consumers have blamed rising tortilla prices on American ethanol production from maize (known there as corn). In Germany, the expanded cultivation of the same tall crop is lamented as the *Vermaisung* (the 'corning') of its lovely countryside. Detailed research into the production of biomass as a source of energy shows that for many situations, the promised benefits turn out to be ambiguous and dependent on local conditions.

Clearly therefore, if biomass[1] is to have a long-term role in the world's energy supply, a simple 'more is better' approach will not work. Instead, it needs a holistic approach that includes the agricultural and forestry sectors to ensure sustainable biomass production. How such an approach should look depends on local conditions. Therefore governments should plan carefully and fully involve the local stakeholders, before initiating or stimulating specific programmes and projects. Whether biomass can reach its full potential depends on our ability to establish production chains that not only are sustainable, but also bring into balance our need for all the things biomass has to offer: food, feed, fibre and fuel.

Fuelling controversy

Traditionally, biomass has been an energy source for cooking and heating in the home, and in many developing countries it still is. For that reason, the lion's share of total biomass energy usage today comes from wood or charcoal burning in stoves. Though renewable in principle, this use of biomass is often not sustainable, for example if local natural resources are depleted or natural forests are destroyed.

Modern bioenergy – non-traditional and often large-scale extraction of energy from plant material – is a recent phenomenon. In the last two decades, many countries decided to support or even mandate it. As a result, 1.5% of global electricity generation and 3% of total global road transport energy now comes from biomass.[2]

Not all of this came about out of concern for climate change. In Brazil, the expectation was that it would create many jobs in rural areas. In the USA, energy self-sufficiency and farm support was a much stronger driver than greenhouse gas mitigation. And even in the European Union, where climate is indeed a driver of biomass policies, overproduction in the agricultural sector was an important consideration as well.

Yet what was regarded by many as a good thing to support at the beginning of the 21st century has only a decade later become controversial. Especially heavy criticism is directed at dedicated food crop production for energy or for fuels, often for ethical reasons. Other aspects discussed critically are limited or no reduction of greenhouse gas emissions, undesirable direct or indirect land use change, harsh working conditions in plantations and negative impact on biodiversity.

It should be noted that these criticisms are mainly linked to the agricultural sector, and reveal a number of unsolved sustainability issues that concern this sector in general: low productivity, fertiliser use, pesticides and unfavourable land-use changes. The controversy about biomass production has actually greatly contributed to the discussion of the need for sustainable methods in agriculture.

There are of course also many situations where biomass has brought definite benefits. For example, carbon sequestration through the cultivation of perennial crops, such as switchgrass and miscanthus, which has a positive effect on the atmospheric carbon dioxide balance, escaped many of the criticisms mentioned above. The discussion also shows that sustainability of biomass production is closely related to crop types, production methods and the region. It emphasises how important it is to put ‘the right crop in the right place’.

Not just agriculture

As these examples make clear, the word 'biomass' can stand for many different crops or biogenic materials, grown under different regional conditions and therefore with different sustainability profiles.

Forestry is a non-agricultural primary sector with a high biomass supply where dedicated biomass is produced for both material and energy purposes. It is generally more accepted as a bioenergy resource. Sustainable forestry management practices have been developed over the last 150 years in Europe and other developed regions and a number of certification schemes have been established and are well accepted. There is no competition with food or feed. Yet, increasing biomass use for energy or new material applications needs to be balanced with the traditional industrial wood demand and with important biodiversity functions of (production) forests.

A good example for synergy between biomass use and wood products use is the Alholmen power plant in Pietarsaari (Finland). This facility is located next to a pulp and paper mill and uses not only the residues of the pulp mill but also about 300,000 bales of forest residues per year. The wood supply infrastructure for the pulp mill is also used for the biomass supply chain to the power plant.

The acceptance by governments and societies of certain plant species as sustainable biomass resources very much depends on their suitability as foodstuff and their need for good agricultural land (see Figure 1). Biomass types generated from organic waste, field or process residues, are generally more accepted as sustainable, and are already used for bioenergy (electricity and heat) production. However, on a global scale the availability of waste and residues is relatively limited and studies on biomass potentials consider in the longer term dedicated energy crops as the most important contributor to biomass availability because of their larger potential.[3,4] It is also expected that these dedicated crops will primarily be high-yielding short-rotation trees and perennial grasses producing non-edible biomass.

A potential way out of this conundrum is the production of a plant that does not depend on agricultural land: algae. However, at the moment the implementation of large-scale algae installations for biofuels is not in sight.

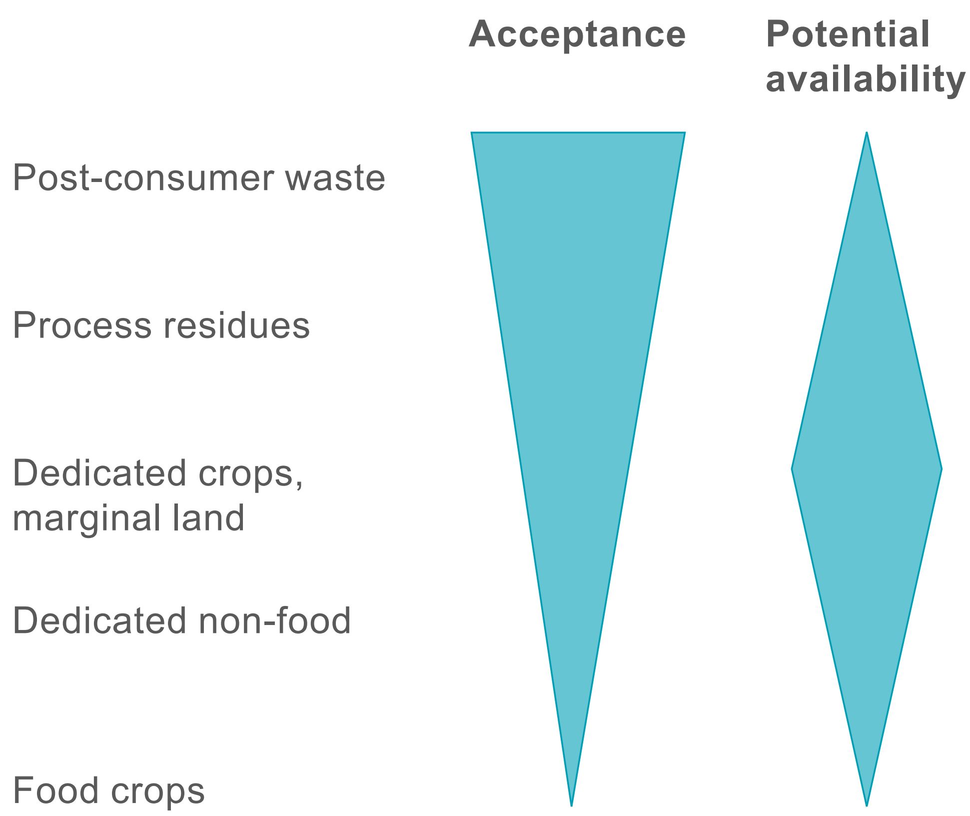


Figure1: Biomass categories and trends in their public acceptance and potential availability.

This is because significant development is still required to breed strains of algae which perform well beyond the laboratory scale and produce high enough yields of the target material (mainly oil). Efficient extraction methods also need to be developed.

The first commercial application of the technology might well come in a food context after all, with the algae producing high-value niche products such as vitamins. The exploitation of algae for large-scale biomass production, without impact on agriculture or fresh water, will take more than a decade and is very uncertain.

There is no simple solution

Given these drawbacks, one might think that biomass and bioenergy are too complicated and be tempted to abandon them, looking for other solutions to reduce greenhouse gas emissions. But the case for such defeatism is not as solid as it looks.

First of all, other renewable energies and options for reducing greenhouse gas are not without their issues either. For example, wind energy and photovoltaic technology are criticised for their intermittency, their lack of storability, and the varying wind and sun conditions across the globe. Combining the continued use of fossil fuels with carbon capture and storage is another possibility that has many unsolved problems, as is also the case for nuclear. There is no one solution to the problem of sustainable energy production and there will always be trade-offs.

Second, biomass also has distinct advantages. In contrast to wind and solar, biomass produces energy that is storable, and in addition it is the only renewable way to produce directly molecules that can be used for the production of chemicals and other materials.

Third, biomass production is potentially a means to expand the economic productivity of the rural sector beyond food production and thereby provides additional income to farmers. What these opportunities are is fundamentally determined by local circumstances. It follows, and we will come back to this later, that global biomass potential is really the bottom-up summation of local opportunities that farmers can develop, rather than the top-down potential identified from the analysis of satellite images.

Finally, biomass production for energy and material uses can create synergies in agricultural development that improve the food supply. As money is invested in land amelioration, equipment and education for farmers, the overall increased efficiency and output of agricultural production will improve both the production of biomass for energy and food or feed.

Lessons from biofuels for bioeconomy

Not only is the world developing new forms of bioenergy. It is also developing new biomaterials and biochemicals to complement the traditional forms of biomaterial use in the form of wood and fibre. All this is set to grow and therefore biomass will become an important part of the world's resource mix. It is high on the agenda of several countries. Specific strategies for a 'biobased economy' have recently been developed by the European Commission, the USA, Canada, Australia, Finland, Sweden and Germany. All these countries investigate the switch from an economy based on fossil fuels to a new, innovative and sustainable economy, based partly on biogenic resources. 'Bioeconomy' goes beyond bioenergy. It strives to increase the use of biomass both for energy and for the production of materials and chemicals. It also includes traditional biobased industries, such as paper and pulp production.

Some of the lessons that were learned from the problems experienced with bioenergy and biofuels have definitely been applied to these bioeconomy strategies:[5] for example, the acknowledgement that bioeconomy projects will only be accepted if stakeholders, such as farmers, industry and citizens in general, are informed and involved. Also, their conception of the bioeconomy envisages the simultaneous production of the four Fs (food, feed, fibre and fuel) and gives priority to food security.

The resource side is more important for the future of sustainable bioeconomy

However, none of these bioeconomy strategies offers concrete steps for simultaneously securing food supply and the provision of biomass for material and energy uses. Instead, they are mainly concerned with the economical uses of biomass, and with biomass conversion technologies. All strategies include the use and development of biotechnology for the purpose of converting biomass. The one-sided focus on technological innovation, which characterised the development of biofuels a decade ago, is now predominant in the broader strategies for a bioeconomy. The lesson is that successful implementation is not only a matter of biomass conversion technology. The resource side is more important for the future of sustainable bioeconomy. It is surprising that bioeconomy programmes invest in research on conversion technology, but provide limited funds for breeding new crops and improving land-use systems.

This is all the more clear in the projected switch on the supply side from sugars and vegetable oils to so-called second-generation biofuels. These fuels will be made out of wood or grass fibres and are considered more sustainable because they do not directly compete with food use. Their high energy yields and low GHG footprint also makes them attractive. However, to make this type of biofuel production economic, production plants need to be large, which does not match with the natural scale for biomass handling. Besides the technology development to convert such 'lignocellulosic' biomass into ethanol or drop-in fuels, the development of a sustainable biomass value chain and a balance between conversion and biomass production scale is needed.

Fundamentals of a sustainable bioeconomy

For any bioeconomy to come into existence, a sustainable biomass supply is the most important consideration. And this is a 'regional game'. To overcome the present bottlenecks of sustainable biomass production, we suggest four aspects need to be addressed.

First, a country must develop a consensus of how theoretical biomass potential translates into realistic, implementable biomass production. There is a huge gap between the studies on biomass, which show that global biomass potential is large enough to fulfil all humanity's needs for food, feed, fuel and fibre production,[3] and the reality on the ground, where there is a heated debate about the limitations of biomass supply and its competing uses. The question has to be asked why this is so.

Part of the answer lies in the so-called 'top-down' approach which is generally taken in these technical potential analyses. These take (quite literally) a satellite view, a global perspective. They generally assume optimal conditions on the ground, for example that all available agricultural land is used intensively and in the most efficient way. They also assume that all available agricultural land is accessible and that there is sufficient infrastructure and logistics to produce and transport all biomass, which is often not the case. Finally, these approaches do not assess the human capital, i.e. the ability and willingness of the people to produce biomass, nor the requirements of good governance.

That geography should be an important consideration in developing a strategy is clear. In contrast to fossil resources, biomass can be produced virtually anywhere, but specific logistical concepts are needed to collect and transport it from larger areas to the point of use. Also local needs should be considered, to determine if various uses for biomass stand in competition with each other and, if so, how this can be avoided.

The need for regional biomass and food production concepts can be seen by the example of the so-called tortilla crisis of 2007. For many years, Mexican farmers had produced enough maize for the total population. But they gave up production when they could no longer compete with the low prices of maize from the USA. When the USA started to increase its production of ethanol from maize, exports to Mexico decreased and consequently prices rose dramatically. The result was that poor people in Mexico could not afford to buy maize for their tortillas.

Farmers were not familiar with switchgrass and its market was underdeveloped

So regional concepts for the planning of biomass production and supply will be based on regional soil, climate and infrastructure conditions. But they also need an assessment of the human capital of a region, which ultimately determines what kind of biomass production is implementable.

For instance, a survey of farmers in part of Virginia showed that less than half of them would be interested in cultivating switchgrass even if the enterprise were profitable. Switchgrass is a perennial non-food grass which at present is being produced in the USA for combustion and which is a promising kind of biomass for second-generation ethanol production. The farmers are reluctant to grow switchgrass both because they are not familiar with its cultivation and because the market for its biomass is underdeveloped.[6]

As another example, a study [7] of a rural community in South Africa revealed an abundance of unused agricultural land. The region therefore had great potential to grow a biomass crop that would not compete with food production. But a survey among community members showed a clear lack of potential: agricultural activity is considered backward and unattractive, especially by young people. In fact, if anything, the local production of vegetables was in need of stimulation to improve the population's diet.[7]

This shows that the potential of biomass production depends both on geography and on the human factor, that is the willingness and ability of the local people, their education and skills and often also their traditions.[8] And it is why a switch is necessary from the top-down question of what share of global energy consumption can be supplied by biomass, to the bottom-up question of what kind of biomass, and how much, a specific region can be expected to produce and use.

Participatory approaches which involve stakeholders in the planning process, for example through surveys or workshops, can help to identify biomass production concepts that are manageable by the local producers and that have a chance of being adopted. To avoid food security problems, the planning process of any biomass project should include an impact assessment that analyses the regional mechanisms for the supply of food and feed, and identifies how biomass production would affect these.

National governments should encourage and support such regional approaches. In developing countries, 'pro-poor' strategies should be linked to programmes for the development of biomass. The negative effects of land grabbing – the takeover of large land areas by outside investors – could be avoided if governments implemented appropriate land-use planning that does not ignore the present uses and ownership of land. Instead, they should allow the involvement of local people in the planning process in such a way that they also profit from land-use activities, and that the local food supply is not jeopardised.

Wise use of biomass

A second consideration for a sustainable bioeconomy is to look for the most sensible way to use biomass. Given that the huge global potential for biomass should be regarded as a theoretical number which in no way reflects the actual production possibilities, we should regard biomass as a renewable but limited resource. Therefore we need to make wise choices for the use of whatever is available.

There is general agreement that energy from biomass should not be in conflict with food security. Next, for energy use, the pathway with the highest potential for reducing greenhouse gas emissions is often recommended as the optimum.

It would seem obvious that one of the main uses for biomass for this purpose is biofuel. In particular, European biofuel policies were initiated with the main aim of greenhouse gas reduction. In the 2009 European Directive on Renewable Energy the target was set to reduce emissions by at least 35% through current biofuel production, gradually rising to 60%.

But there are other applications for biomass that actually reduce carbon emissions by much more. For instance, if maize is grown and subsequently converted into thermoplastic starch, a product used in packaging, this will decrease the use of plastics from oil, preventing four times the level of emissions as when the same plot of land had been used to grow grass for burning or conversion into biofuel.[9] Another example is biochemicals, where the GHG reduction potential per hectare can be seven times that of sugar-based ethanol, provided they are produced from lignocellulose crops.[10]

As the increasing production and use of biofuels in the European Union has been driven by policies using biofuel mandates and taxes as a steering mechanism, these other possibilities have not been taken into account. Meanwhile, agricultural policy experts in particular question whether this political steering is useful or whether it rather forces the inefficient use of high-value food components, like vegetable oils, for low-value biofuels.

But how will we know? Often the criteria for the most efficient biomass use are not the same as the criteria for the most sustainable biomass use, not to mention the different perceptions of what should be considered sustainable. Producers of biomass of course want to generate as high an income as possible and therefore strive to optimise biomass yields and quality. Biomass users are interested in security of supply and optimal biomass quality at low prices. Meanwhile, the public expects biodiverse and attractive, unpolluted landscapes and a secure supply of high-quality food, as well as other biomass products.

Politicians strive to reach political targets such as the reduction of carbon emissions, but also have to answer to their voters on these other topics. Overall, we can observe a whole range of expectations with partly conflicting objectives and possible trade-offs between ecological, economic and social objectives.

Such trade-offs can be seen in biogas production in Germany. Driven by the high prices offered for renewably generated electricity, as mandated by law, the number of biogas plants in Germany has increased to more than 7,900. Most of the biogas plants are on farms and thus create jobs in rural areas. They are heat and power plants; the farmers use the heat and sell the electricity. As much as 7% of electricity generated in Germany now comes from biogas, enabling Germany to meet about 6% of its greenhouse gas reduction target set by the Kyoto Protocol.

It seems quite the success story but, as always, there is a downside, which is the decreasing acceptance of biogas production among the German public. The main reason for this is the increasing production of maize as the biogenic gas source. At present, about 50% of the feedstock fed into biogas plants consists of slurry and waste biomass; the other half is biomass from energy crops. More than three quarters of that biomass stems from maize and in total 800,000 hectares (2 million acres) of maize are now grown for biogas feedstock in Germany. Much of the maize is grown on land which was formerly grassland, a land-use change that is now forbidden, as the public demanded the use of alternatives to maize. Because the plants grow up to several metres in height, a field of maize is considered a deterioration of the landscape compared with the pasture or less imposing crop that was there before.

From an engineering standpoint, this is a step backward. Maize is the most efficient biogas crop for Germany due to its high biogas yield, good storability as silage and low production costs. So far, no crop has been found which can compete with it, if efficiency is the only criterion. Energy crops that appear attractive to the public, such as mixtures of wild species that provide a higher biodiversity and a positive landscape impact, have lower yields and higher biomass production costs, resulting in less efficient land use.

We can see that not all ecological, economic and social targets of sustainable biomass production and utilisation can be perfectly achieved at the same time and that there have to be trade-offs. Natural science approaches are not sufficient to deal with these trade-offs for optimising biomass production and use. One can quantify carbon emission reductions to find the most climate-friendly way of producing and using biomass by carrying out a full life-cycle assessment. But these methods do not provide anything to help decide whether emission reductions or an unchanged landscape should have priority.

Therefore we also need to employ methods from the social sciences and involve stakeholders when it comes to making decisions on biomass production options. This will only work if these stakeholders are educated about the alternatives and consequences, to avoid or at least temper the simple NIMBY (Not In My Back Yard) discussions which we are currently experiencing.

Strategies for land use

As a third consideration, the search for the best use of biomass should also include the question of how the most important resource for its production, namely arable land, should be used.

In Europe, agricultural land is used intensively and there is little potential for further yield increases. On the other hand, there are still large areas of unused or underused land in many African and South American countries that could be used for rain-fed agriculture.[11] What's more, in regions with the largest availability of agricultural land, the efficiency of land use is the lowest, giving a huge combined scope for improvement.

As Figure 2 shows, if only 30% of the attainable yield on a cultivated plot is actually harvested, such as is the case in some African countries, the yield could be more than tripled by more efficient production systems with modern varieties and good fertilisation and crop protection practices. So in countries with large land resources, much of which are unused, improving and extending agricultural production can unlock very large biomass potentials, not only for energy, but also for increased food and feed production.

We can see a practical example of this by looking at three different land-use forms which can be found in the region around Piracicaba in the state of São Paulo, Brazil. The prevailing landscape there is extensive grassland with a few isolated trees.

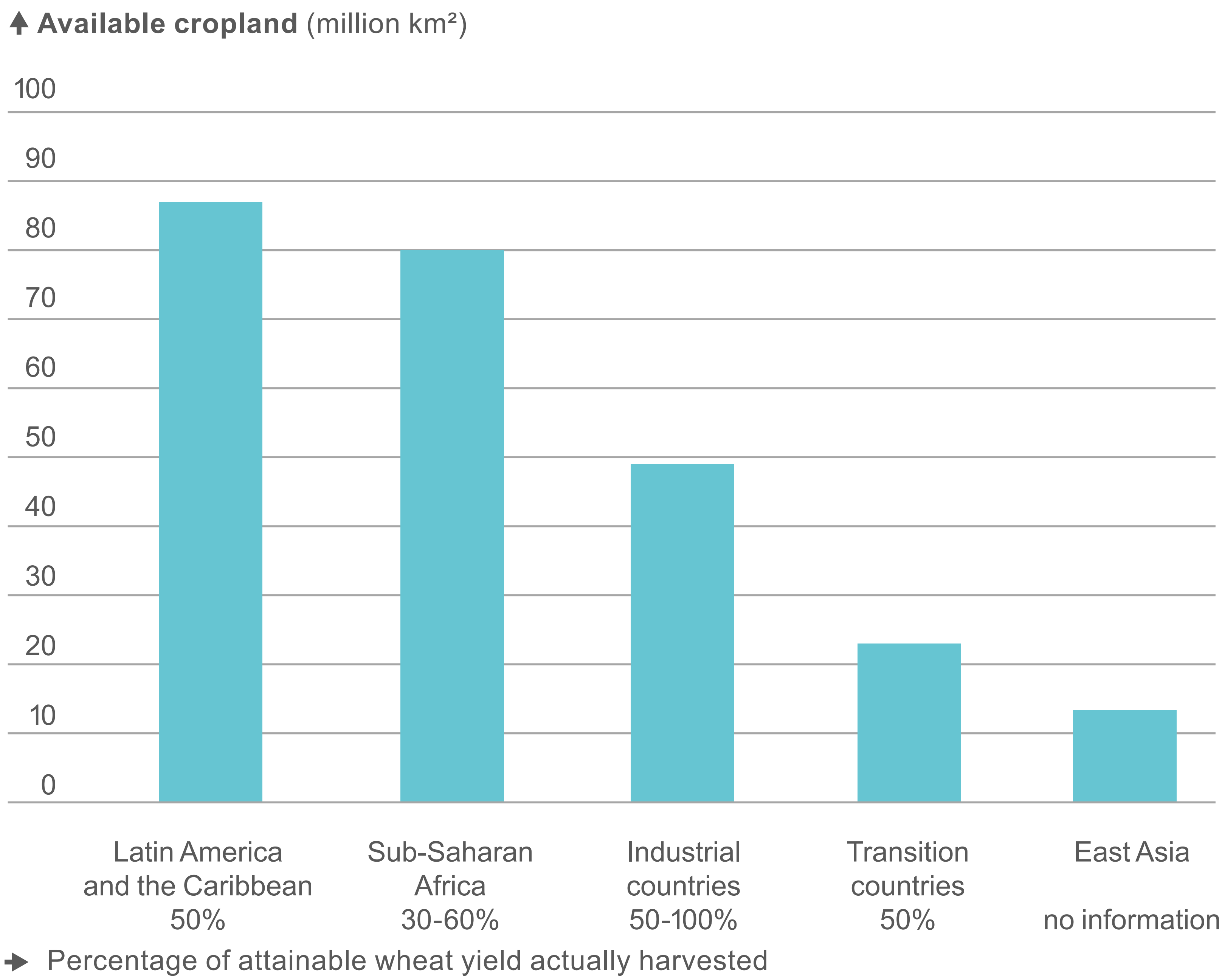


Figure 2: Unused land suitable for rain-fed agriculture in different regions. Also shown are the percentages of maximal attainable wheat yield in these regions.[12]

The productivity of this land-use system is very low. One hectare (2.5 acres) will only sustain one head of cattle for meat production or for the production of 400 litres (100 gallons) of milk per year. However, sugar cane production in the region is expanding. This use of the land leads to a productivity of 7,000 litres (1,900 gallons) of ethanol plus 20 MWh electricity per hectare, which is produced from bagasse, the fibrous residue left over from sugar cane production.

This use of residues and by-products from agricultural production is one approach towards more efficient land use. And from the processing facility's perspective this is the ideal biomass supply scenario: an ethanol plant surrounded by tens of thousands of hectares where nature produces its raw materials. But there are drawbacks, too: crop rotation is not possible and there is no longer any room in this system for smallholder farmers. And local people complain about the 'sugar cane ocean' just as the Germans deplore *Vermaisung*.

For this reason a third, mixed-crop land-use system is being investigated by the University of São Paulo. In this system, cereals, cassava or chilli are grown between fruit, palm or firewood trees, thus combining food and non-food crops.

The productivity of this land-use system and its economical viability are still being explored. The workload in this mixed-culture system is high as a lot of manual work is necessary. But its products are very diverse, supplying higher- as well as lower-value products which include food, feed, fibre and fuel at the same time. And obviously, local people consider the landscape impact of this system far more positive than sugar cane monoculture. But in order to obtain both sustainability and economical efficiency, perhaps a combination of both land-use systems will be necessary.

The competition between biomass uses and the limitation of sustainably produced biomass resources cannot be ignored and these problems will not solve themselves. It is not sufficient to conduct R&D on conversion technologies. We also need to develop sustainable and economical biomass supply systems. These will include the development of more efficient crops, of more efficient biomass production systems for food, feed, fuel and fibre, and of optimal logistic concepts for biomass supply.

Biomass supply strategies

The fourth consideration is the need for a biomass supply strategy. One of the challenges of a future bioeconomy will be that biomass production is often small-scale and localised. This can work well for food and feed, less so for fibre (forestry), but is problematic for fuels and biochemicals because their production requires typically large production plants. If the imperatives of local sustainability are met, as a consequence the logistical efficiency for chemicals and fuels is impaired.

The largest potential for increases in biomass productivity and system optimisation is to be found in developing countries, where the need for increased productivity in food production is also greatest. For this reason, logistical technologies are required that allow decentralised pre-treatment of biomass to turn it into a transportable and tradable product. The first examples of such technologies are mobile pelleting machines and small-scale, mobile pyrolysis plants.

At a governmental level, support for sustainable and efficient land use can be provided through land-use planning and support of the implementation of sustainable land-use systems. The optimal use of land also requires support for the development of agricultural infrastructure and the education of farmers. It is obvious that farmers trained in good agricultural practices are best able to use land and therefore produce biomass efficiently. They will have knowledge, for example, of how to use fertilisers to optimise yields and minimise nutrient losses.

Areas with large amounts of unused arable land often lack the infrastructure for biomass transport. Large investments would be required in these areas and it is not clear who would be willing and able to make them. However, for such areas there is also the option of using biomass for the self-supply of bioenergy and biomaterials. A trend towards the regional use of biomass for bioenergy can currently be observed in Austria, France and Germany, where farmers produce bioenergy for their own or local demand. This is especially the case in areas which are not connected to the natural gas grid.

Zooming in

The major concern with biomass competition scenarios is the reduction in food supply and food security. If biomass potentials are unlocked in a sustainable way it will not only improve biomass supply for material and energy uses, but also create synergies for development in the agricultural sector and for an improved food supply. In order to achieve this, investment in the agricultural sector will be required and the necessary background conditions, e.g. for land-use planning, will have to be set. Where those prerequisites are lacking, activities on a governance level which drive land use away from food production should be carefully considered. To prevent the energy and material use of biomass endangering food security, and to create a useful framework for political decision-making, criteria must be developed to assess what are the most efficient and useful methods of biomass production and use.

In this, too, local stakeholders must be involved and their needs given priority. The promise seen in those satellite images of abundant food and energy for the whole world will probably never be completely realised. But it will only come true even in part if we zoom in until we can distinguish the human beings whose lives and livelihoods will depend on them.

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Iris Lewandowski is Professor of Biobased Products and Energy Crops at the University of Hohenheim, Germany. She has worked as a researcher at the University for over 20 years, researching energy crop production and the sustainability of biofuels. She worked in R&D at Shell for three years and led a global team to manage a global biomass research programme. Since January 2012, she has been associate editor for Global Change Biology (GCB) Bioenergy.

Angelika Voss is Senior Researcher in Shell’s Future Energy team. Her research is in the field of low-carbon future energy systems. She has over 10 years of experience as an R&D project leader and programme manager, mainly in the field of biofuels and bioenergy. Prior to her work with Shell, she worked as a Wood Scientist at the Federal Research Centre for Forestry and Forest Products and as Scientific Project Leader at the TNO Center for Timber Research in Delft, the Netherlands.

Notes and references

1. Biomass is organic material that originates from either plants or animals. Today the term biomass is most frequently used for organic material which is used for energy production and for other non-food purposes such as the production of biogenic materials or chemicals. However, in many cases biomass used for energy or material uses could also be used as food or feedstuff. This is the case, for example, when biodiesel is produced from rapeseed oil or when biogas plants are fed with maize.
2. http://www.iea.org/topics/renewables/subtopics/bioenergy/ (accessed 20 February 2014).
3. V. Dornburg, D. van Vuuren, G. van de Ven, H. Langeveld, M. Meeusen, M. Banse, M. van Oorschot, J. Ros, G.J. van den Born, H. Aiking, M. Londo, H. Mozaffarian, P. Verweij, E. Lyseng & A. Faij (2010). Bioenergy revisited: Key factors in global potentials of bioenergy, *Energy Environ. Sci., 3 (3)*, 258-267.
4. U.S. Department of Energy (2011). *U.S. Billion-ton update: Biomass supply for a bioenergy and bioproducts industry*, R.D. Perlack & B.J. Stokes (Leads), ORNL/TM-2011/224, Oak Ridge National Laboratory, Oak Ridge, TN.
5. L. Staffas, M. Gustavsson & K. McCormick (2013). Strategies and policies for the bioeconomy and bio-based economy: An analysis of official national approaches, *Sustainability*, 5 (6), 2751-2769, doi:10.3390/su5062751.
6. Z. Wen, J. Ignosh, D. Parrish, J. Stoew & B. Jones (2009). Identifying farmers' interest in growing switchgrass for bioenergy in Southern Virginia, *Journal of Extension, 47 (5)*, Research in Brief 5RIB7.
7. B. Winkler (2013). *Monitoring and evaluation of the integrated renewable energy potential assessment: A case study in Mgwenyana, rural Eastern Cape, South Africa*, Master's thesis, University of Hohenheim, Stuttgart.
8. M.-L. Barry, H. Steyn & A. Brent (2011). Selection of renewable energy technologies for Africa: Eight case studies in Rwanda, Tanzania and Malawi, *Renewable Energy, 36 (7)*, 2845-2852.
9. V. Dornburg, I. Lewandowski & M. Patel (2003). Comparing the land requirements, energy savings and greenhouse gas emissions reduction of biobased polymers and bioenergy, *Journal of Industrial Ecology, 7 (3-4)*, 93-116.
10. B.G. Hermann, K. Blok & M. Patel (2007). Producing biobased bulk chemicals using biotechnology saves energy and combats climate change, *Environ. Sci. Technol., 41*, 7915.
11. Food and Agriculture Organization of the United Nations (2002). *World agriculture: towards 2015/2030*, FAO: Rome.
12. Food and Agriculture Organization of the United Nations (2002). *World agriculture: towards 2015/2030*, Summary Report, FAO: Rome.

The artificial leaf
The quest to outsmart nature

An intricate dance of protons and electrons promises to deliver solar hydrogen, thereby outdoing the efficiency of plants. The story of scientists practising the fine art of mimicking photosynthesis.

> *Huub de Groot*

The sun is our only real source of renewable energy. Its potential is huge, but we are not good at tapping it. On the one hand solar energy is plentiful, while on the other hand it is dilute and needs to be concentrated in order to become useful as an energy source. It is true that we can generate electricity with solar cells, or use its energy indirectly through wind turbines or hydropower. But we will need more than just electricity. The transport networks that sustain society are powered with dense fuels that allow for fast ships, trucks and aeroplanes; the world around us is increasingly built with plastics derived from fossil materials. We are not good, however, at doing chemistry with solar energy and using the incoming photons to make fuel and plastics.

Since the Stone Age, agriculture has made it possible to grow produce directly from sunlight using carbon dioxide and water as raw materials. If we succeed in mimicking the primary processes of photosynthesis, we can fabricate molecules as nature does and harvest energy in a fuel that we can store for immediate use when we need it. But for it to become really useful, we need to outsmart nature. Plants throw away most of the energy from the light that they receive. Only a tiny fraction of solar energy can be made available for human use.

Mimicking photosynthesis for efficient and direct photochemical conversion is an old dream. In the 1970s, the US chemist Joseph Katz predicted the development of a chemical cell which would convert sunlight into fuel. He was the first to call it a 'synthetic leaf'. His work on chlorophyll and photosynthetic proteins, and that of subsequent generations of scientists, brought this dream much closer to reality. In 1998, John Turner from the National Renewable Energy Laboratory in Colorado presented the first artificial leaves, which used sunlight to produce hydrogen with 12% efficiency. They were built from very expensive semiconductor solar cells and catalyst materials, with the potential to make them much cheaper with better efficiency.

A green world

Solar energy is dilute, and with optimal photochemical conversion 2-20 kilograms of hydrogen can be produced per square metre per year, depending on the location. At such levels, large-scale production at wholesale energy prices is economically difficult and energetically inefficient. However, consumers don't value economy on the same level as the intimate relation with energy production. When people are asked about future energy, images come to mind of self-sufficiency and local production.[1] Consumers own the surface that may collect the energy. In addition, they like the idea of gaining control and being independent of the institutions around them. They like being involved in the production of what they eat and use. It makes for an orderly world, and may save money as well, since consumers are eager to benefit from supplying their own energy while paying less on excise duties and taxes.

Artificial photosynthesis perfectly blends into this picture. With 'artificial leaves' people could harvest their own fuel on a rooftop and use it for their cars. A little fuel can go a long way, as recent progress in automotive technology shows. Owners of plug-in hybrid cars can recharge their batteries frequently from the electricity grid; they even organise competitions to drive thousands of kilometres without refuelling.

This is comparable to a kitchen garden or having a henhouse. An amateur farmer takes pride in eating his own lettuce, cabbage and eggs and adjusts his lifestyle to the seasons and the pace of his garden. The surplus goes to the neighbours. In the case of hydrogen or natural gas, the surplus could go into the gas grid or be converted into electricity to balance production with demand.

With the help of modern life science and technology, more efficient processes can be developed to make hydrogen and other molecules available by direct conversion of solar energy in pathways that are far more complex than those used in synthesising fuel and without biomass as an intermediate. Harnessing photosynthesis would also open the possibility of closing material cycles on other levels. Hydrogen factories in urban and rural areas could provide the raw materials for plastics or aeroplane fuels, where integration into the existing technological infrastructure and agricultural practices would reduce costs and secure economic viability. Biomass production for food and feed uses less than 1% of the incoming solar flux. For extracting more energy from solar light on the available arable land, scientists are breeding plants that lose less energy and use very little light. Artificial leaves, in contrast, wouldn't need to use arable land. They would provide our fuels directly and deliver the molecules for our material world, mimicking the production of an astonishing diversity of molecules that make up the plant and that may be harvested for food or other purposes.

It is great that we can already mimic plants and that we can breed them for better performance. But for photosynthesis to become really useful for energy, we'll have to outsmart nature. Plants use only a small portion of the light intensity to make the molecules they need. A rooftop with artificial leaves wouldn't fuel your car if we could only mimic nature. The artificial leaf would have to be more productive, and deliver something closer to a fuel than does Mother Nature.

Photosynthesis

Photosynthesis first occurred 3.4 billion years ago in a precursor of cyanobacteria. The chemistry of photosynthesis has remained virtually unchanged since then. Although photosynthesis occurs in different ways, its basic architecture and operational principles have been largely preserved during the diversification into higher organisms and its engineering principles are shared across taxonomic boundaries.

Photosynthesis has proved to be an unbeatable way by which plants and some bacteria use solar energy. It is life's most fundamental lock-in. As with every lock-in, it will be broken when an innovation arrives that is fitter for life. And, in fact, it already has been broken. A photovoltaic cell converts solar light with a much higher energy efficiency than biomass. But it produces electrons, not molecules. The synthesis part is missing: picking carbon dioxide from the air and fixing it as fuel. That is the promise of the artificial leaf.

Photosynthesis is actually an important fuel supply already. Approximately 2.6 billion people cook their food with wood or other fuels made by photosynthesis. Biomass accounts for 10% of global energy use.[2] The modern use for automotive fuel and electricity generation accounts for a much smaller percentage and comes at the cost of massive land use and huge efforts to collect and transform it. The less than 1% efficiency of biomass hits us.

In nature, the poor efficiency of photosynthesis is a result of its optimisation for dealing with all kinds of environmental constraints, such as low carbon dioxide concentration, heat, drought and disease. There is much more light available than plants need. Natural photosynthesis is only light-limited in very exceptional cases, deep in the ocean, in hot springs or in the desert after a rain shower. In order to protect themselves against too much light, plants simply shut off photosynthetic conversion, which limits the overall efficiency in plain sunlight.

Poor efficiency also arises from the internal organisation of the plant. Carbon dioxide fixation in complex biomass involves a large number of metabolic conversions, where every step reduces the available energy (exergy) by generating some heat (entropy). What makes it even worse, natural photosynthesis only uses half of the light spectrum. It doesn't use the lower-energy red photons. That is the reason why leaves are green, not black.

Photosynthesis doesn't pay out when harvesting plants and converting them into biofuels. As a result, maize, soy or rape – which are among the most efficient energy crops – store only around 1% of the available solar energy in hydrocarbons. Algae biomass does slightly better, because micro-organisms need less energy to transport nutrients and build supporting structures. But they still don't surpass 6% efficiency in energy production.

For artificial photosynthesis to become really useful, we need to improve on that. Luckily, there is no reason why we couldn't outdo the overall efficiency of plants. Nature already shows us that it is actually possible to tap a larger fraction of the solar photon flux. The first steps in natural photosynthesis are chemically very productive. The absorbed-light-to-electrical-charge conversion yield – the internal quantum efficiency – exceeds 95%. Much of the inefficiencies in photosynthesis occur in the subsequent reaction steps. While high internal efficiencies are not uncommon in photovoltaics, the critical hurdle for artificial photosynthesis to overcome is to learn how to maintain this high yield over the entire chemical conversion chain, from photons to fuel.

Another reason to free photosynthesis from its biological context is the limited availability of farmland. Wouldn't it be great to have artificial photosynthesis in urban areas, on the roof of a building, or a car, or on a parking structure? Or have it in rural areas where no plants will grow, such as rocks? Only 10% of the earth's land is arable, which leaves large areas for photosynthesis, without competition with food production or other resources. There are many options, which provides the opportunity to choose not only on technological grounds, but also based on other criteria, such as aesthetics.

Artificial photosynthesis could free us from the agrarian context of biofuels and allow us to tap a larger fraction of solar energy and pour it directly into our tanks. But this will only be possible when we manage to outsmart nature at an affordable cost. The quest for solar fuels is primarily a quest for conversion yield with abundant materials. The energy efficiency then follows the yield. With 95% quantum conversion efficiency over the full spectrum, thermodynamics shows that the total energy conversion is better than 40%. This compares favourably with the theoretical limiting efficiency of 30% of crystalline silicon solar cells, which is steadily approached, with energy payback times of 1-2 years.

Harvesting photons

Plants use dyes – chlorophyll molecules – to capture photons and kick out an electron, leaving a hole behind. The electrons are rapidly channelled from molecule to molecule bringing them far enough away from where they originated. The aim is to prevent the electrons from recombining with holes, which would only generate heat. To save energy, the holes are not transported by electric wires but are directly injected across an insulating or tunnelling bridge into a catalyst complex where they are preserved for a millisecond before they go their own way again. They participate in a reaction to split water into oxygen molecules and protons. The resulting protons travel a bit further and meet with the other electrons to form hydrogen molecules. All these reactions take place at different locations, so that they do not interfere with each other. However, they are close enough to use each other's reaction products. This is done

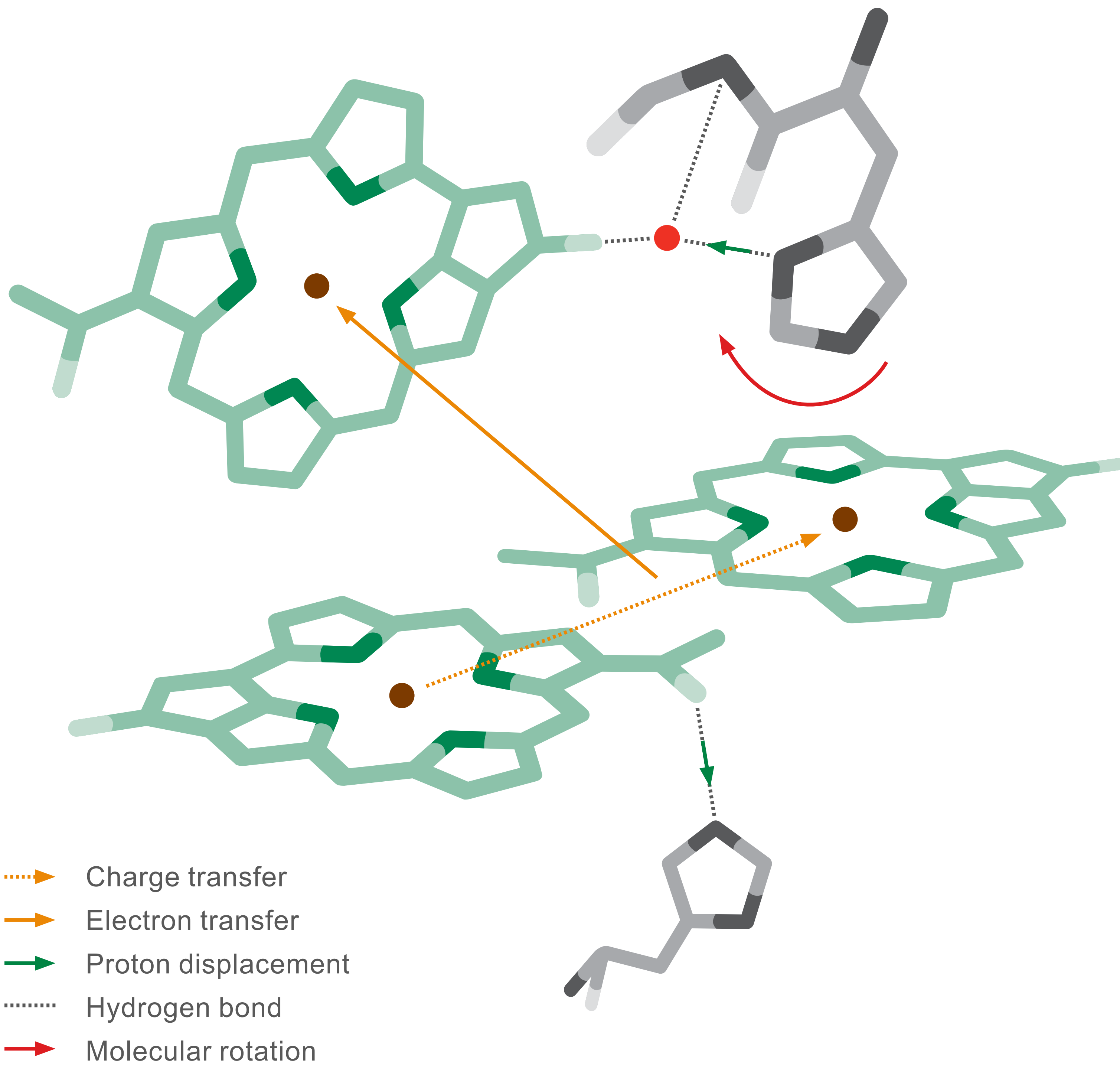


Figure 1: The molecular dance of electrons and protons during photosynthesis.[3] In the first steps of photosynthesis, chlorophyll molecules (green) capture photons and this breaks the symmetry of their motion. They kick out an electron by channelling electrons from molecule to molecule (amber arrows). This is a very productive step, with an absorbed light to electrical charge conversion yield exceeding 95%. Protons and electrons are never far apart, and the electron transfer is accompanied by a proton displacement (the red dot). The proton and electron motions are coupled by the protein structure that contains the chlorophyll molecules. Two histidine protein groups (grey) respond, and one of them rotates away, resulting in the intimate molecular dance, which gives the synergy that enables efficient conversion. Quantum effects probably play a substantial role in this dance by providing a fast channel to the output of electrons. Scientists believe that it will eventually be possible to make artificial systems that incorporate similar functional structures capable to catalyse an efficient multi-step photon-to-fuel process. And then it is let's twist again and again, for multiple electron catalysis.

with the help of catalysts, materials which bring molecules together and act as lubricants that enable the water-splitting and hydrogen-formation steps. The whole process of water splitting is very complex, since it is helped by an intricate dance performed by the catalysts (see Figure 1). The formation of molecular oxygen and the production of heat are delayed to accompany the release of the oxygen at the very end of the conversion.

The production of hydrogen from protons is only the first part of the story. Plants use protons in subsequent steps to extract carbon dioxide from the air and make the hydrocarbons and other molecules that they need. Man is already able to make hydrogen from solar light with a much higher efficiency than nature can make biomass, and without the complex chemistry of photosynthesis. The performance of the best artificial leaves in the lab is already around 20% energy efficiency. There is thus every reason to pursue the path of artificial photosynthesis. Thermodynamics shows us that the maximum efficiency is in principle the same for well-balanced photochemical systems and photovoltaics combined with electrolysis. But the artificial leaf is more direct and bears the promise of a better use of materials. Nature uses abundant materials, readily available in a wide variety of places, with a minimum of special additives. This makes artificial photosynthesis for the production of hydrogen a sensible approach. It may also pave the way for the more complex transformation of carbon dioxide, exactly as plants do.

Although photovoltaics combined with electrolysis is definitely not as indirect as biomass, it does involve transport of electricity over the grid, concentration losses from the separation of the photovoltaics stage and the electrolysis by an electric wire, compression inefficiencies and energy input for transport and transfer of the fuel back to the consumers. Scientists and engineers tend to downplay the indirect character of the technology by loosely multiplying photovoltaic and electrolyser efficiencies, but the potential synergy gains from direct conversion are wasted and the many more potential losses need to be compensated for. It is like the stock market: in order to recover from a percentage loss, a larger gain somewhere else is needed. Often the way out is then to put up more square kilometres of panels to collect more photons. Unexplored as the direct chemical route may be, the artificial leaf holds promises that the electrolyser route cannot fulfil.

Plumbing the artificial leaf

Precisely four photons, brought together in the correct way, are enough to split two water molecules and release four electrons. With another four photons one hydrogen molecule can be produced. This simple chemical perspective follows directly from the conservation of mass and the basics of stoichiometry. That's also how plants do it. To formulate it differently: two photons are needed per freed electron. So a tandem cell is the optimum for the production of hydrogen. By making both halves sensitive to different colours (ideally with cut-off wavelengths of 700 and 1,100 nanometres) the tandem makes optimal use of the solar spectrum. To get even more out of the solar spectrum, the number of incoming photons can be boosted with a photon splitter. For natural photosynthesis, only light with wavelengths up to 700 nanometres is used, which generates a relatively large voltage (3.6 volts) to drive the chemical conversion.

The open voltage input of a two-colour tandem is less, around 2.8 volts. Of this total, 1.23 volts are used for the energy storage by splitting of water. The rest is mostly converted into heat, which is necessary to cover resistance losses and to stabilise the fuel at high pressure, since chemical reactions not only run forward but can also reverse, undoing the effort. Internally, the holes need to be stabilised for a few milliseconds, just like natural photosynthesis does. This requires a little higher potential. Catalysts also require overpotentials to work well, and energy is needed when the oxygen and hydrogen gases are released and the hydrogen is pressurised. The fine art of developing an artificial leaf is to fit all energy requirements into the available budget. Nature has a very clever trick to do this efficiently. It combines the three largest losses: preventing reverse reaction internally, water-splitting potential, and heat at the end, and overcomes them all in one overpotential by controlling the reaction kinetics simultaneously. This feat is pulled off by the complex structure

– a matrix of proteins – that contains all active components. With this integrated triple-play strategy, as little heat as possible is lost.

Researchers believe that they can perform the same trick in an artificial system based on a structure – a 'smart matrix' – with components that exploit this synergy. Among other things, instead of producing useless heat far away from the water splitting, a smart matrix delays the production of heat to the very end of the reaction, the oxygen formation. It is released in the catalyst, at the right time and with atomic precision on the spot where it is needed for a good production yield.

Pushing up against the limits of physics, chemistry and engineering

Developing responsive photocatalytic matrices is an important goal of the research into artificial photosynthesis. A crucial element is the water oxidation catalyst, of which the detailed mechanism is not yet fully understood in natural photosynthesis. Nature uses four manganese ions bridged by oxygen to split water. It is a bad catalyst that is turned into a good one by the action of the matrix around it. To get these details right in artificial photosynthesis requires pushing up against the limits of physics, chemistry, nanotechnology, thermodynamics, engineering and quantum mechanics. Recent measurements of natural photosynthesis have shown that electrons that are freed in the dye form a coherent quantum state. After excitation and charge separation, that correlation doesn't simply disappear. Electrons and holes remain correlated on a distance of 1-2 nanometres and a timescale of 10-100 nanoseconds. That seems like a physical subtlety, but these quantum effects probably play a substantial role in the initial stages of the reaction. In this way, it is possible to understand why the conversion in the first step is so efficient. With control over these quantum coherent processes, both for charge separation and for catalysis, imitating nature may become a reality.[4]

A solar cell

In recent years, various dyes have been developed to capture photons, as well as catalysts for subsequent reaction steps. The challenge is to combine these components effectively into one synthetic leaf. The problem is that individual components perform only one function, while in an artificial leaf they have to operate in concert and participate in each other's functions as well. This is a catch-22. To make it work, the general framework of the artificial leaf first needs to be defined, before materials can be found to make it. Conversely, a framework is hard to imagine, without knowing the materials that will be used for it in the first place. Here again, nature offers inspiration. The biological design of photosynthesis has solved this dilemma by evolution. In every evolutionary step, nature uses what is around and makes only limited modifications. By taking a biological motif and making minor changes, the solutions that biology has selected can serve as starting points for the reverse engineering of an artificial framework. *Chlorobaculum tepidum*, a green bacterium, lives in hot springs where it forms a dense mat, with hardly any light penetrating it.

To survive under such harsh conditions, green bacteria evolved chlorosomes, highly ordered structures where chlorophyll molecules have found their place in such a way that they capture almost all incoming photons and communicate very efficiently with the reaction centres involved. Every bit of energy is precious when often less than one photon per hour reaches a chlorophyll molecule. Under these circumstances, you also need to be extremely economical with materials. The framework is remarkably robust and accommodates a large chemical variety. These chlorosomes may thus provide clues about how to build an efficient and robust artificial leaf. But the structure is difficult to determine, because of its heterogeneity. Together with colleagues in the Netherlands, Germany and the USA, we have been working on it since the early 1990s. We have built an entirely new generation of solid-state nuclear magnetic resonance (NMR) equipment working at an ultra-high magnetic field, and recently managed to map the structure of the chlorosomes.

We now use them as a source of inspiration for artificial systems.

The structure is forbiddingly complex, so it is impossible to copy it. The way to go is to focus on the competing processes in the chlorosome. There is a jumble of ferroelectric effects, molecular vibrations, bi-stability, steric hindrance and many other features that are in competition. It's actually a bit of a mess, but it works out fine. With chemical intuition and a broad knowledge of chemical synthesis, analogues with a similar competition may be designed. They have an excellent chance of exhibiting the desired properties, often in a manner slightly different from nature's example. That's the beauty of chemistry, because you can add something which nature has not yet devised.

In a team effort, we managed to design molecular analogues of the chlorophylls of *C. tepidum*, together with colleagues in the Netherlands, Germany and Poland. In our labs, these chlorins self-assemble in a different structure as in nature. Taking the evolution of chlorosomes into account, we were led to think that the typical parallel stacking of chlorophyll molecules found in nature is essential for charge transfer. The trick seemed to be to reproduce this. One possibility is to build it in so-called metal-organic frameworks (MOFs). They offer excellent opportunities to combine the different steps into one overall structure. These porous solids are built up from organic and inorganic building blocks. MOFs are relatively easy to prepare and have a large structural uniformity. MOFs are often surprisingly stable at high temperatures or in adverse chemical conditions. One variety, which is now being tested for its charge-separating properties, can survive a bath in sulphuric acid. The system can take a beating, which is important when you want to install it on a rooftop. The next step is to build water oxidation and hydrogen production into it. This will then be integrated in a programmable scaffold to catch photons and trade reaction time for better efficiency.

There are many other promising proposals to integrate photosynthetic processes. We are still at the beginning of their development, with many available alternatives. This is another clear reason not to bet only on the electrolyser route to produce hydrogen. There are many possibilities for reinventing photosynthesis.

A historical approach

The differences between the electrical and natural approaches also lie deeper. The electrolyser route is modular, based on a reductionist approach, dissecting each step and linking different unrelated parts together. The artificial leaf is synergistic and requires a much more integrative view where protons and electrons are separated in a smart matrix, but are never far apart. The fine art of getting it to work is in piecing the parts together in an interrelated system to forge the efficient triple-play conversion approach instead of a wasteful sequence of detached steps that require extra energy for concentrating protons and electrons.

This is what we should learn from biology. It is not enough to unravel nature's mechanisms. The physicists' and chemists' way of looking at it only teaches us part of the story. It shows us how certain proteins interact to produce electrons and store them. This is an important first step. But the goal is not to make an exact copy of nature, which in most cases is impossible. To mimic nature, we should penetrate to its core. This means that we shouldn't approach photosynthesis as a chemist or a physicist by trying to catch it in formulas. Neither should we approach photosynthesis as a biologist, who categorises the diversity of the phenomenon and tries to systematise it.

Mimicking nature should start from the notion that biology is a historical science. Biological systems are the result of the path that evolution has taken. Photosynthesis has been engineered by an array of events, forcing it to adapt to changing environments. If a new context emerges, a conflict with previous developments can arise. From these contradictions, new functionalities are formed.

In order to understand this, you need to be able to deal with these contradictions. Biophysicists have a special mindset to enable them to see order in the complexity of life and to capture its essence. Often there is more information in the differences than in the similarities between biological systems. The challenge is to recognise the important information when it comes along. We were puzzled by some common characteristics of organisms with chlorosomes, although they were only very distant evolutionary relatives. That led us to the conclusion that chlorosomes are a much earlier phenomenon in evolution than previously assumed. Conversely, that realisation gave us a different view of the mechanism of light harvesting in chlorosomes. It led us to see chlorosomes as a precursor to other mechanisms of photosynthesis. In this more primitive form, several features interlock that were later developed separately. It made us appreciate the biological engineering of fast charge transfer.

When you take a step back and see how nature has dealt with historical changes, you see patterns that allow the identification of mechanisms that survived the events of life.

Heading for the unknown

This approach to science does justice to the complexity of life. But it cannot be planned in the way that we look for elementary particles or engineer a new satellite. Instead of dissecting a process, one encounters crossroads which need to be explored. That makes the roadmap for artificial leaves different from that for building the Large Hadron Collider. The latter was designed with a known goal, and identified the barriers that had to be addressed. On the road along these ‘known unknowns’, many disappointments and delays had to be taken into account. But it was a road along the unknowns that could be identified from the outset. The road led inevitably to the discovery of the Higgs particle. By contrast, the development of the computer or the human genome project, sketchy as they were at their outset, were full of crossroads and pleasant surprises that changed their direction. For the human genome, the complex nature of the genetic systems blurred the horizon. It was unknown what the unknowns were. Nobody expected that a technology like high-throughput sequencing would come out of this project, which caused a revolution in genetic research. That development was possible because of the open attitude of the programme. It built on the added value in swarm intelligence, unleashing the power of as many scientific minds as possible. It was highly successful in mapping the human genome, but it also opened up a new territory, by providing for the first time a comprehensive view on biology as an information science.

Similarly, we know that the road towards artificial photosynthesis is full of unknown unknowns. We don't have a complete picture of how to make our own leaves, let alone how they could reshape society. In the end, the energy problem is a materials problem, and the next eight to ten years will be crucial in shaping our imagination of how to resolve the paradox of a material that can perform a subtle catalytic dance in response to the arrival of a photon while being at the same time a robust coating that can sustain exposure to light for several decades. We have little experience on how abundant materials can be chemically transformed to suit our purpose, and strategies to minimise conversion losses are not yet converging. Fossil fuel will probably be the single largest market for decades to come. But even beyond that, liquid fuels will always be sought after because of their density and ease of use. The ancient biological success of photosynthesis gives us a glimpse of how organic chemistry can produce fuel from sunlight, water and carbon dioxide. It is up to this century's scientists to see if they can improve on it.

Related essay

The multi-terawatt challenge
Preparing photovoltaics for global impact
> *Wim Sinke*

Huub de Groot is professor of Biophysical Organic Chemistry at Leiden University in the Netherlands. His research is on solid-state nuclear magnetic resonance of membrane proteins. He participates in the BioSolar Cells project, in which Dutch universities and industry collaborate to produce sustainable energy from photosynthesis. In 1995 he received the Royal Dutch/Shell Prize for sustainable development for his NMR research on photosynthesis and artificial photosynthesis.

References

1. L. Hanssen & H. de Vriend (2013). *Toekomstbeelden van een duurzame energievoorziening in Nederland: Rol en positie van het onderzoeksprogramma BioSolar Cells in de energietransitie*, report on www.biosolarcells.nl.

2. IEA (2013). *World energy outlook*, IEA: Paris.
3. T.J. Eisenmayer, J.A. Lasave, A. Monti, H.J.M. de Groot & F. Buda (2013). Proton displacements coupled to primary electron transfer in the *Rhodobacter sphaeroides* reaction center, *Journal of physical chemistry B*, *117 (38)*, 11162-11168, doi:10.1021/jp401195t.
4. R.L. Purchase, H.J.M. de Groot (2015). Biosolar cells: global artificial photosynthesis needs responsive matrices with quantum coherent kinetic control for high yield. *Interface Focus 5*, 20150014, doi:10.1098/rsfs.2015.0014.

Changing patterns of use

Households and companies can tap into the huge potential of energy efficiency and even become net energy producers. The new citizen rediscovers proximity – or drives a hydrogen car.

Energy efficiency
The rest of the iceberg

Efficiency is the energy user's most abundant resource, with expanding returns from radical redesign. It is a disruptive technology in its own right.

> *Amory B. Lovins*

I live on, or more precisely in, a passive solar banana farm. Banana crops numbers 48-54 are currently ripening in the 85 square metre semitropical jungle in the middle of my house. Last year, crops 46 and 47 harvested themselves when their 30 kilogram weight pulled down the tree.

Yet this house is 2,200 metres high in the Colorado Rockies near Aspen, where temperatures have dipped as low as –44 degrees Celsius, continuous midwinter cloud has lasted up to 39 days, and the growing season between hard frosts used to be six weeks. Locals joked about having two seasons, winter and July, until what Hunter Lovins calls 'global weirding' added August.

My house also has no conventional heating system. It's roughly 99% passively heated by more than doubled thermal insulation, airtight construction, heat-recovery ventilation, and superwindows that insulate like 14 (or even 22) sheets of glass, look like two, and cost less than three. Until 2009, the remaining 1% of the space heating came from two stoves occasionally burning wood or obsolete energy studies, but five winters ago we decommissioned those woodstoves – combustion is so 20th-century – and replaced them with surplus active-solar heat.

Saving 99% of this house's space-heating energy lowered its 1982-84 construction costs by about $1,100 (€1,000), because the eliminated conventional space-heating system would have cost more up front than the heat-saving technologies that displaced it. Reinvesting that saved capital cost, plus $6,000 (€5,000) more, in water- and electricity-saving technologies then saved 99% of the water-heating energy, half the water, and 90% of the household electricity. All the savings recovered their total 1% extra capital cost in the first 10 months, and in the next decade will have paid for the entire building. They also made all-solar power supply affordable.

This is the kind of project we at Rocky Mountain Institute (RMI) find instructive. RMI is an independent, non-partisan, non-profit think-and-do-tank that drives the efficient and restorative use of resources. We employ rigorous research to develop breakthrough insights. We then convene and collaborate with diverse partners, chiefly large firms, to speed and scale solutions for a clean, prosperous, and secure energy future. Thus we create abundance by design.

This superefficient building, which was also RMI's initial headquarters during 1982-2000, illustrates highly integrative design, getting multiple benefits from single expenditures: its central arch, for example, has 12 functions but only one cost. The building helped to inspire more than 32,000 passive buildings in Europe which, like ours, have no conventional heating system but roughly normal construction cost, since experience shrank their premium from an initial 10-15% to zero, plus or minus a few per cent. Similarly integrative design has eliminated homes' air-conditioning needs and reduced construction cost at up to 46 degrees Celsius in California (not an upper limit), and saved 90% of air-conditioning energy in steamy Bangkok at normal construction cost, both achieving better comfort. Almost everyone in the world lives in a climate somewhere between Bangkok's and mine.

Big buildings have surprising efficiency potential too. The 2010 retrofit design I co-led at the Empire State Building is saving two-fifths of its energy with a three-year payback. That's the same payback offered by a major energy service company, but with six times its savings, because that firm optimised individual components in isolation, while we optimised the entire building as one system. Remanufacturing all 6,514 double-glazed windows onsite into superwindows that would insulate four times better and be nearly perfect in admitting light without unwanted heat, plus more conventional improvements, together cut peak cooling loads by one-third. Renovating smaller chillers rather than adding bigger ones then saved enough capital cost to pay for most of the improvements. Three years later, an RMI retrofit of a large Federal building in Denver saved 70% of its energy, again with good economics. Similarly, Peter Rumsey's and Rohan Parikh's new office designs for Infosys in Bangalore and Hyderabad cut energy use by 80% with lower capital cost and higher occupant satisfaction and productivity.

Such results stem less from technology than a new design mentality – asking different questions in a different order. If you asked an engineer how much insulation my cold-climate house should have, you'd probably be told, "Just the amount that will repay its extra cost from the heating fuel it saves over the years." The engineering textbooks all agree.

But they're wrong, because this methodology omits the immediate, and avoidable, capital cost of the heating equipment. Most engineers make the same mistake (and others) when designing buildings, vehicles and factories. In our latest $40+ billion worth of new and existing industrial redesigns, including seven for Shell, my RMI colleagues and I found practical energy-saving potentials typically around 30-60% with retrofit paybacks of a few years, or in new construction, about 40-90% with nearly always lower capital cost. This wouldn't be possible if they'd been optimally designed from the start.

Continuous change

Such examples of today's energy-efficiency potential[1] are actually just a few frames in a very long movie. Ever-improving technologies, design methods, financing and marketing channels, business models and public policies now make potential energy savings ever cheaper. Saving electricity today costs about two-thirds less than it cost in 1980. Costs continue to drop with no end in sight and new vistas continually unfolding. As Dow found by saving $9 billion (€8 billion) so far on a $1 billion (€0.9 billion) efficiency investment, enculturating and cultivating energy efficiency often reveals new opportunities faster than engineers use up the old ones.

Efficiency then becomes an expanding and renewable resource with returns that, far from relentlessly diminishing, often expand, so bigger savings cost less, not more – a design innovation more disruptive than any technology.[2] RMI's practice has demonstrated this potential not just in big industrial projects but also in more than 1,000 buildings and in various automotive and ship designs. The methodology can be taught.[3] We're starting to spread it and overhaul design pedagogy and practice. Our modest goal is the non-violent overthrow of bad engineering.

Efficiency is not a binary attribute you have or lack; its goalposts move continuously. In the late 1990s, my house was turning into a museum of 1983 technologies, so we updated them, not because there was a business case – hardly any energy was left to save – but to check how much better they've become. From initial monitoring of several hundred data streams, we've found so far that the monitoring system is probably using more energy than the lights and appliances.

Today's technologies and design methods can do almost everything with far less energy, and ultimately with almost none. Yet they're not yet widely taught, used, or even considered. This book contains 14 essays on energy supply but just this one on efficiency. Even firms as aware as Shell typically devote a similarly lopsided ratio of analytic and strategic attention to energy supply versus efficient use.

Many are leapfrogging from kerosene to LEDs

Yet the 118% rise in US energy productivity since 1975 (mostly from technical improvements, some from compositional change, a little from behaviour) was equivalent by 2012 to a 'resource' 1.85 times that year's US oil and gas consumption. The USA and several EU countries, notably Germany and Denmark, now have growing economies but shrinking electricity use. US weather-adjusted electricity use per dollar of real GDP fell by 3.4% in 2012 alone. US electricity and petrol use both peaked in 2007.

Perhaps developing economies will grow faster than they become efficient. But that's a bet, not a given. Already, many are leapfrogging from kerosene and incandescent lamps to LEDs, just as their televisions leapt from vacuum tubes to modern microelectronics and their telecommunications skipped over wireline phones. If developing countries exploit the advantage that building things right is easier, faster and cheaper than fixing them later, they could shake off the prediction of their slow slog akin to rich countries' historic development patterns and refute the forecasted high energy demand that suppliers are investing to meet.

Something similar is happening in China, which during 1976-2001 cut its energy intensity (primary energy used per unit of real GDP) by more than 5% per year, a feat probably unrivalled in world history. After a five-year hiatus, savings nearly as brisk have resumed. In 2012, China's efficiency and renewables displaced so much electricity that coal plants were run much less frequently, adding more new electricity from non-hydro renewables than from all fossil-fuelled and nuclear plants combined. (China made more electricity from wind than from nuclear power, and in 2013, added more solar capacity than the US has.) Similarly, US 2012 energy savings were nearly twice as important as natural gas in displacing coal-fired electricity.

Bloomberg New Energy Finance and ren21.net track the global progress of modern renewable energy in admirably granular detail, finding that renewables other than big hydro dams added more than 80 billion watts and received a quarter-trillion-dollar investment in each of the past three years. But annual global investment in saving energy (about $150-300 billion or €135-270 billion in 2011) was first credibly estimated only in 2013, when the International Energy Agency (IEA) found that 1974-2010 energy savings in 11 IEA countries totalled 1.5 times their oil use.[4]

Statistical experts track energy's volumes and prices in exquisite detail, yet devote dramatically less effort to tracking savings. Nobody knows how much energy the world is saving. Being less visible than the submerged part of an iceberg, efficiency poses a hidden peril to navigators of supply-side waters, because when supply outruns demand, prices crash as they did in the mid 1980s, and overinvested suppliers can sink without even knowing what they ran into.

In short, efficiency is "generally the largest, least expensive, most benign, most quickly deployable, least visible, least understood, and most neglected way to provide energy services".[5] It is the energy area ripest in risks for suppliers – and nowhere more strikingly and unexpectedly than in motor vehicles, the world's biggest user of oil.

The missing automotive story

Demand for motor fuels could shrink or even disappear in the next few decades as radical design and business innovations transform the manufacture of cars and light commercial vehicles – driven not by regulation but by customer demand, powerful competitive forces, and emergent realignment of energy strategy in China, where RMI's *Reinventing fire* synthesis of advanced efficiency and modern renewables[6] is informing the 13th Five-Year Plan. China's polluted air is strongly reinforcing the drivers of oil risk and cost, climate change, and a rapidly growing but not yet globally competitive automotive industry.

The opportunity is rooted in vehicle physics. A typical US car uses roughly 100 times its own weight every day in ancient plants, very inefficiently converted from primeval swamp goo into trapped, discovered and extracted oil. Yet only about 0.3-0.5% of the fuel used by the car ends up moving its driver; about 87% is lost in the powertrain (and minor accessory loads) before reaching the wheels. Of the 13% delivered to the wheels, 7% heats the air that the car pushes aside or heats the tyres and road, and only 6% accelerates the car. That two-tonne steel vehicle weighs more than 20 times as much as its driver, and for the past quarter-century has gained weight twice as fast in an epidemic of automotive obesity.

Manufacturers of cars and light commercial vehicles have traditionally focused on wringing slightly more work from the powertrain (the engine plus the driveline that delivers its torque to the wheels) because that's where most of the losses occur. But two-thirds of the energy needed to move a typical US car (its 'tractive load') is actually caused by its weight, so ultralighting – using far lighter but stronger materials and smarter designs that sustain or improve crash safety – is the most effective way to save fuel. Combined with better aerodynamics and tyres, it can cut tractive load by half to two-thirds. Each unit of energy thereby saved at the wheels subsequently saves six more units previously lost delivering that energy to the wheels, generating seven units of total fuel savings at the tank. Thus 'vehicle fitness', and capturing its snowballing weight savings with 'mass decompounding' and radical simplifications, can cut fuel needs by roughly half to two-thirds. This then makes electric propulsion affordable, displacing the remaining motor fuel while capturing electric traction's inherent advantages – it is efficient, powerful, modular, reliable, compact, quiet, controllable, clean and fairly cheap. Furthermore, electric traction offers far richer design flexibility and rapid evolutionary potential than the mature Victorian mechanical arts.

Accelerating a lighter vehicle needs less force. Shrinking its powertrain (especially if electric and hence high-torque) saves capital cost that then helps pay for the lightweighting and streamlining – just as eliminating my house's furnace helped pay for the efficiency that displaced it. Needing severalfold fewer batteries or fuel cells for the same driving range can speed, by a decade or two, the adoption of electric propulsion (plug-in hybrid, battery-electric, or fuel-cell). Lithium-ion battery packs became 43% cheaper from 2010 to early 2014, another 30% or more drop is on the way, and other promising battery chemistries are emerging. The car- and truck-building industry's two hottest trends for the past five years – lightweighting and electrification – both compete and co-operate. Electrification might even become inexpensive before ultralighting, but regardless of their sequence, combining both captures strong synergies.

This idea is so simple that it was slow to take hold

The traditional strategy of first making batteries and fuel cells cheaper through better technology proved difficult without high sales volumes driven by a compelling value proposition. But using vehicle fitness instead to make batteries and fuel cells fewer reduces their cost equivalently. This then builds sales volumes that make the components cheaper, achieving the same ultimate goal with less time, cost and risk. This idea, so simple that it was slow to take hold, entered the US Department of Energy's policy in 2013 and is now in various stages of adoption by four to seven automobile manufacturers on several continents, sped by such agile and uninhibited competitors as Tesla Motors.

Limited foresight

Nonetheless, most industry and government analysts continue to assume only slow and incremental lightweighting, efficiency gains and electrification. In 2009, the US National Research Council again declined to examine ultralighting and its enabling of affordable electrification via whole-vehicle design optimisation.[7] In 1991, GM had built the sporty 100 miles per US gallon (2.3 litres per 100 kilometres) Ultralite carbon-fibre concept car. In 2000, a complete virtual design of a luxury midsize SUV (by RMI's Hypercar spinoff with two European Tier One engineering firms) had startled manufacturers with 3.6-6.3-fold higher efficiency (using petrol or hydrogen respectively) and a calculated one-to-two-year retail payback.[8] Repeating a long history of being rapidly outpaced by market developments,[9] the 2009 NRC report was followed within two years by BMW and VW announcements that in 2013 they would begin series production of cars integrating ultralight carbon-fibre bodies with electric drives. Those vehicles were entering the market in 2014. Their carbon-fibre-body manufacturing methods now face competition from 16 other commercialised processes.[10]

In 2011, RMI published a rigorous and independent zero-US-oil-demand-in-2050 scenario with forewords by the President of Shell Oil and the then Chairman of Exelon.[11] Yet a year later, the US National Petroleum Council's (NPC's) transportation-fuels study[12] forecast only medium or high automotive fuel demand, because its integration model, ignoring expert peer-reviewers' objections, limited 2050 weight reductions to just 30%. More than a dozen vehicles had already demonstrated greater weight reductions by 1988, and another 19 – including five in production and four in pre-production prototypes – by 2010.[13] In 2007, Toyota's 420-kilogram carbon-fibre 1/X plug-in-hybrid concept car – not built for amusement – had reduced weight by 69% with the interior volume of a Prius but half its fuel use – and the world's largest maker of carbon fibre had announced a ¥30 billion (€220 million or $240 million) factory to "mass-produce carbon-fibre car parts for Toyota".

The NPC study's leaders ignored the transformational potential revealed by these more than 30 examples. Their innovation-resistant analysis tacitly assumed the global automotive industry won't continue to develop very lightweight cars and light trucks that not only save most of their fuel but also make electrification rapidly affordable, displacing the rest of their fuel. Yet probably every significant manufacturer has such efforts under way. Such vehicles could beat legally mandated efficiencies by 2-4-fold, achieving 1-2 litres per 100 kilometres rather than 4-8, and better meet both makers' and customers' requirements without compromise. Retail customers could see payback times below three years at low US fuel prices (or immediate paybacks using temporary size- and revenue-neutral 'feebates' that let car buyers value life-cycle fuel savings as society does). Manufacturers could achieve 80% lower capital intensity, systematic de-risking, and far greater manufacturer and dealer margins. Other players in this intensely competitive global industry would have to follow suit or lose share. Why wouldn't developing countries, the only source of forecast growth in world oil demand, want to leapfrog to such advantageous vehicles too? What would this mean for fuel suppliers?

Drilling under Detroit

In the USA alone, RMI's *Reinventing fire* synthesis showed that such superefficient electrified vehicles could realistically eliminate automotive motor-fuel demand by 2050, saving about 1.5 Saudis' or 0.5 OPEC's worth of oil at an average cost of $18 per barrel (in dollars of 2009). How many oil companies' investment plans include this contingency?

If you went to the ends of the earth to drill for very expensive oil that might not even be there, while someone else brought in more than 8 million barrels per day of $18 per barrel 'negabarrels' from the 'Detroit Formation', wouldn't you feel embarrassed or perhaps broke? Shouldn't we drill the most prospective plays first? And might you want to invest in the automotive revolution, making less money on oil but more on vehicle sales – a hedge we call the 'negabarrel straddle'?

Even without the accelerating carbon-fibre revolution, familiar light-metal structures offer impressive gains. Ford's 2015 all-aluminium F150 pickup truck (America's best-selling vehicle) shrank its engine displacement by 31-57% helping to pay for the aluminium. A 1997 proprietary study by RMI and a major manufacturer found this approach could make a high-volume aluminium-intensive production car more efficient than a Prius hybrid but with a conventional non-hybrid powertrain, three-fifths higher fuel economy, higher manufacturer and dealer profits, and a two-year retail payback. Similarly, RMI spinoff Bright Automotive's aluminium-intensive 2009 IDEA commercial fleet van's plug-in-hybrid driving prototype saved nearly a tonne of weight, considerable drag, and hence half its batteries. Its fuel-efficiency gain from 17-19 to 1.5-3.4 litres per 100 kilometres offered fleet buyers a compelling business case with no subsidy.

Carbon-fibre and other advanced polymer composite structures are less familiar and commercially mature than metal ones, but offer higher performance and crashworthiness, far simpler manufacturing and, with astute design and manufacturing choices, comparable or lower total manufacturing cost at scale. The resulting two- to threefold smaller tractive load could enable all kinds of advanced powertrain.

For example, the fuel-cell midsize-SUV virtual design from 2000 mentioned above needed only 3.4 kilograms of 345-bar hydrogen, in 137 litres of safe off-the-shelf 1990s-vintage carbon-fibre tanks, to drive 530 kilometres. These two-thirds-smaller tanks could be easily packaged, leaving plenty of space for people and cargo, without needing a break-through in storage (such as the difficult 700-bar tanks now being introduced by several makers of heavy steel vehicles). The fuel cell too would become two-thirds smaller, justifying three times higher cost per kilowatt. A typical 80% experience curve – so a doubling of cumulative production volume cuts the real cost by 20% – would then need some 32 times less production to reach a competitive price point, cutting a decade or two off deployment times. The key was a 53% lighter carbon-fibre vehicle so efficient that its motorway cruise speed needs less energy delivered to the wheels than today's heavy steel SUVs use on a hot afternoon just to run the air conditioner. That 14-year-old design could be much better done today. Hydrogen economics (using forecourt reformers except where wind power is cheap enough for electrolysis) also look sound, and practical, profitable hydrogen infrastructure solutions were worked out in 1999.[14]

In short, a disruptive design and manufacturing strategy integrating ultralighting, excellent aerodynamics and tyres, superefficient accessories and electric traction could improve automotive efficiency by an order of magnitude without compromising safety, handling, acoustics, acceleration, cost, styling or other customer attributes. Twenty-three years into this revolution, its technical basis is now looking clearly feasible, its competitive advantage enticing, and its market success plausible. By 2014, RMI and trade allies had boosted its prospects by catalysing two potential game changers: a new supply chain for volume-produced carbon-fibre automotive structures, and Chinese strategic exploration of an automotive leapfrog initiative that, if adopted, could transform the global competitive landscape.

Wider implications

Such affordable electric vehicles' distributed storage, intelligently linked to electric grids, could help integrate variable renewable generators, making the automotive and electricity problems much easier to solve together than separately. And we don't need a smart grid to use a dumb grid in smarter ways. My battery-electric car (whose registration plate, OFF OIL, is not aspirational but factual – perhaps unique among NPC members) is solar-recharged by a circuit that adjusts its charge rate every second between 0 and 7 kilowatts according to real-time grid frequency. This dispatches to the US Western Interconnect a valuable ancillary service called 'fast regulation'. If my utility paid me properly for this service, I'd make several dollars' profit every night just by recharging my car.

Such technological and design innovations can also inspire new business models. For example, David Moskovitz of the Regulatory Assistance Project notes that vehicle manufacturers could sell electrified vehicles at a deep discount – boosting sales – if the buyer agreed that when each vehicle is plugged in and parked, the manufacturer could control it and conduct profitable electrical transactions with the grid, providing invisible settlements and using its aggregation volume to negotiate a good sales price while guaranteeing the owner uncompromised driving capability and experience.

Even more disruptive emergent business models are leading some manufacturers to consider a shift from selling cars and trucks to leasing mobility and access services. Cars, typically the second-biggest US household asset, sit idle about 96% of the time, inviting shared transport or electrical transactions. The winners may well be firms that shift vehicles from a revenue source to a cost of delivering desired access and mobility. Like the classic ‘solutions economy’ approach,[15] this could align provider with customer interests, rewarding both for doing more and better with less for longer. Providers – of vehicles, finance, fuel or information services – that seriously adopt this approach could put intolerable market pressure on laggards.

Even if this didn’t occur, the USA could provide the same access with 46-84% less driving just by combining proven methods for IT/transport integration, charging drivers for road infrastructure by the kilometre not the litre and encouraging smart spatial planning so more customers are already where they want to be and needn’t go somewhere else. Any savings from videoconferencing, virtual presence and other ways to move only electrons and leave the heavy nuclei at home, or from better freight logistics, more-localised manufacturing, and dematerialisation, would displace even more fuel. During 2005-2013, Walmart’s giant truck fleet cut its fuel use per case by 46% without yet using many available options. Some jurisdictions are also moving toward making markets in ‘negatrips’ and ‘negamiles’, so all ways to travel, or not need to, can compete fairly. This could permit dramatically reduced physical mobility with fuller and fairer access, and enable a potential shift of drivers’ largely socialised costs from the whole population (about a third of which, in the USA, is too old, young, poor or infirm to drive) to drivers themselves, so they get what they pay for and pay for what they get.

Other transport

Heavy trucks, the second-biggest oil user, can double their efficiency at a very attractive cost by improving aerodynamics, tyres, weight and powertrain.[16] That doubling becomes a tripling with ‘turnpike doubles’ – two trailers per tractor – linked in proven ways that improve safety and stability and reduce road wear.[17] These shifts are straightforward technologically but not institutionally, especially because tractors and trailers are typically made by different firms whose business models don't consistently reward efficiency or integration. Today's typical US Class 8 truck efficiencies of roughly 50 tonne-kilometres per litre could thereby rise to about 129 tonne-kilometres per litre or 2.6 times the initial value. That factor could reach or exceed 3.0 with better auxiliaries, accessories and refrigeration where present; hybrid drive and regenerative braking; idle elimination by using an auxiliary power unit when parked rather than idling the big diesel engine; and optimising driver training and driving speed. Beyond that tripled efficiency, if lighter, smaller, cheaper, fully digital diesel engines fulfil their initial lab- and road-test promise,[18] it may also become possible to make today's truck diesels dramatically more efficient, clean, small, light, cheap and fuel-flexible.

The number three oil-burner, aeroplanes, already saved 82% of their fuel per seat-kilometre during 1958-2010, but comparable or larger gains still lie ahead. A Lockheed-Martin Skunk Works tactical-fighter airframe designed in the mid 1990s – 95% carbon-fibre composite, one-third lighter, two-thirds cheaper – illustrates lightweighting potential in commercial jets, where removing 1 kilogram is worth about $2,000 (€1,800) present value. Boeing, NASA and MIT have designed tube-and-wing and blended-wing-body aeroplanes 3-5 times more efficient than today's jet fleet, still burning kerosene or equivalent drop-in-replacement advanced biofuels (slated for US Navy delivery at oil-competitive prices starting in 2015). Ultimately, with new airport fuel infrastructure, 'cryoplanes' exploiting liquid hydrogen's very light weight (more important than its greater bulk – that's why it's the best rocket fuel) may raise that saving to six- or seven-fold, with kerosene-like economics but better safety.

From motorcycles to trains and buses to ships, similar integration of advanced materials, powertrains, hydrodynamic surfaces and controls, other components, and system operations can dramatically reduce energy use and improve safety and performance. For example, RMI has co-led three analyses finding an economically attractive potential to save about half the 'hotel load' and a third of the total energy use of diverse bluewater ships. As with aeroplanes, further savings may emerge from promising innovations in hydrodynamics – notably laminar vortex flow[19] – often inspired by imitating nature's design (the science and art of 'biomimicry'[20]). And new micromodular structures could offer order-of-magnitude weight savings beyond today's ultralighting, without even invoking more-exotic materials.[21]

Overall implications for transport

Reinventing fire found that just the straightforward and currently feasible gains in vehicle technology and design mentioned above, modestly reinforced by more productive use of vehicles, could enable a 2050 US economy with 158% higher GDP than in 2010, 90% more automobility, 118% more trucking and 61% more flying – without using any oil. The 1-2 litre-equivalent per 100 kilometres electrified ultralight cars could use any mixture of hydrogen fuel cells, electricity and advanced biofuels. Heavy trucks and aeroplanes could realistically use advanced biofuels or hydrogen. Trucks could even burn natural gas. But no vehicles will need oil. Any biofuels the USA might need, at most 3 million barrels per day, could be made two-thirds from wastes, without displacing cropland or harming climate or soil. The land-use and other problems of large-scale biofuel feedstock would be avoided by superefficient use, leaving a very diverse portfolio of competitive options – a long-term mix that cannot but need not be known in advance.

Reinventing fire found a 17% internal rate of return for moving US mobility completely off oil by 2050, assuming that carbon emissions and all other hidden or external costs are worth zero – a conservatively low estimate. The required technologies all provide a more than 15% per year real return in trucking or a less than three-year simple payback to the car buyer. The average cost of saving or displacing oil for US mobility would be roughly $25 per barrel (in 2009 US dollars levelised at a 3% per year real discount rate) – a small fraction of today's fuel price. This implies a $4 trillion (€3.5 trillion) net-present-value US saving potential – or about $12 trillion (€11 trillion) if we added just the economic and military costs of US oil dependence, excluding any harm to health, safety, environment, climate, global stability and development, or national independence and reputation.

Since burning oil, three-fifths for transport, releases two-fifths of global fossil-fuel carbon emissions, this implies that a similar fraction of those emissions can be abated not at a cost but at a profit, because efficiency costs less than fuel. The same turns out to be true for virtually all other carbon emissions too.

For example – and importantly for natural gas's prospects in electricity generation, since buildings use nearly three-quarters of US electricity – *Reinventing fire* showed how integrative design, modern technologies and proven financing and delivery methods applied at historically reasonable rates could triple to quadruple the energy productivity of US buildings by 2050 with a 33% internal rate of return (IRR). Industrial energy productivity could double with a 21% IRR. All analysed improvements meet normal commercial hurdle rates for the respective sectors.

The energy productivity of US buildings could be tripled to quadrupled by 2050

The policy innovations needed to enable and speed these developments can all be done in the USA administratively or at a subnational level (where most energy policy has long been made anyway). The only policy needing an Act of Congress – harmonising federal highway standards to modernise heavy trucks' size, weight and multi-trailer rules – could be omitted with only a 0.26 million barrel per day foregone saving.

The electricity industry faces even greater institutional challenges as 21st-century technology and speed collide with 20th- and 19th-century rules, institutions and cultures. Some devotees of central thermal power stations don't yet even consider the rapidly emerging distributed renewables a competitive threat, even though they've taken about half of the US, two-thirds of the European Union, and one-third of the Chinese market (with big hydro another third). Many still claim that renewables can do little without a breakthrough in cheap bulk electrical storage; yet without adding bulk storage, four European Union countries with modest or no hydropower generated about half their 2013 electricity consumption from renewables (Spain 45%, Scotland 46%, Denmark more than 47%, Portugal 58%). Denmark and Germany (25% renewable) have Europe's most reliable electricity, about tenfold better than America's.

The big picture

Quadrupling US electrical productivity using the best technologies from around 2010 and moderately integrative design has an average levelised technical cost of about $6.40 (€5.70) per megawatt-hour – far below the short-run marginal cost for any non-renewable generator. Even with suboptimal design and implementation, which raise many utilities' efficiency costs to about $20-30 (€18-27) per megawatt-hour, few supply-side projects can withstand such competition.

Reinventing fire found that running a 2050 US economy 2.58 times bigger than that of 2010 with no oil, coal or nuclear energy and one-third less natural gas could cost $5 trillion (€4.5 trillion) less in net present value than business as usual, emit 82-86% less carbon, require no new inventions or Acts of Congress and be led by business for profit – including making its electricity system 80% renewable, half distributed and highly resilient. This entire bundle yields a 14% IRR based on private internal cost alone, and could be enormously higher when counting even a shortlist of its vast external benefits. Yet few hydrocarbon or electricity firms are preparing for such a future.

Around 1999, using a variety of logics, some far-sighted analysts began forecasting 'peak oil' – not in supply but in demand, with global oil demand peaking as early as this decade, and then declining. Like whale oil in the 1850s, oil is becoming uncompetitive even at low prices before it becomes unavailable even at high prices. The whalers were astounded to run out of customers before they ran out of whales. But in the nine years before Drake struck oil in Pennsylvania, at least five-sixths of the lighting market long dominated by whale oil went to coal-oil and coal-gas competitors, and 20 years after Drake, Edison's electric light began to displace those too. Thus were the remnant whale populations saved by technological innovators and profit-maximising capitalists.

As demand-side innovation threatens oil sales, and as new US gas-combined-cycle power plants become ever costlier than new wind and solar power, the oil and gas industries are coming under the stress of upside-down marginal economics. In the past decade, while oil prices nearly tripled from $40 to $110 per barrel, oil majors' return on capital employed fell by one-third, and for over half of them in 2013, it fell to or below 10% due mainly to higher cost, risk and complexity.[22] In 2013 alone, ExxonMobil, Chevron and Shell invested more than $120 billion (€100 billion) upstream, more than the cost of putting a man on the moon, bringing their five-year total above a half-trillion dollars; yet their output and profits declined.[23]

Oil exploration and production's capital intensity is spiralling beyond the ability to sustain it; the revenue model is broken. Elephant projects are less profitable and more risky than legacy output, together depressing risk-adjusted returns. Fragile and utterly unforgiving megaprojects, each risking tens of billions of dollars with no revenue for many years, can hazard the reputation if not the stability of some of the world's largest firms.

Furthermore, the industry's fundamentals are discouraging and deteriorating. International oil companies have extremely high capital intensity, decadal lead times, and high technological, geological and political risks. Parastatals own about 94% of global reserves and can take or tax away the companies' remaining 6% at any time. Resource owners also force the majors into riskier and costlier plays even as investors demand lower risks and higher returns. The industry is politically fraught, unpopular, interfered with, and reputationally damaged by its worst actors. Its service companies are becoming formidable competitors. Its permanent subsidies are coming under greater scrutiny. It's a price-taker in a volatile market. Much of the reserve base underlying its valuation may be unburnable, potentially wiping trillions off balance sheets. The costly frontier reserves that get half the supermajors' marginal investments are also economically stranded assets – at least four times costlier than demand-side competitors, and increasingly challenged even by some supply-side competitors. Thus the business model's prime imperative –

value must exceed price must exceed cost – is being remorselessly squeezed at both ends.

What a recipe for headaches! Why would anyone want to stay in such an enterprise? Isn't oil – like airlines – a great industry but a bad business? No wonder some savvy investors are starting to shift their money into assets with rapid growth, wide benefit, solid consensus, modest risk and durable value. Energy efficiency and renewable energy lead the pack. Increasingly they poach investment, momentum and people from the deep talent pools of major oil companies. Even RMI's CEO is a 10-year Shell veteran.

Natural gas differs from oil, but not much, with high capital intensity, price and counterparty risk, and geological risk. After the Henry Hub gas price dipped below $2 (€1.80) per gigajoule in 2012, many pundits insisted US gas price volatility was history. Less than two years later, the price was steadily over $4 (€3.5) and had spiked to nearly $8 (€7). Moreover, 'cheap' gas actually costs $1-3 (€0.9-2.7) more than its spot price on a risk-adjusted basis.[24] That is, a fair comparison with stably priced alternatives, efficiency and renewables, must add to gas's commodity spot price the market value of its price *volatility*, which is discoverable from the straddle in the options market and likely to increase if wellhead gas becomes cheap and stably priced (because that drives liquefied natural gas exports, petrochemical pivot to gas, and exploitation of downstream-bottleneck rents). The result – not $3-4 but $6-8 gas – is consistent with futures markets. It's logical because markets equilibrate: if you want $6-8 gas, assume $3-4 gas and use it accordingly. And it's reasonable because fracking's eight main kinds of risk and uncertainty, which will take perhaps a decade to resolve, are fairly unlikely all to come right. So fracking creates an important story about affordable and abundant energy for the long term – but that story is less about gas than about its physical hedges, efficiency and renewables, which are outpacing and increasingly outcompeting it.

Whither hydrocarbons?

Any durable way forward for applying the hydrocarbon industry's unique and remarkable capabilities must begin with a mature assessment of these conditions. It must soberly compare competitive prospects and risks on a timescale commensurate with the lives of proposed supply-side investments. And it must seek ways to redeploy assets and skills to thrive in and help to shape the emerging new world of radical efficiency and diverse, distributed, renewable, resilient supply.

International oil companies have unusual, if not unique, skills in organising very large, complex projects. How far can those skills be turned to a mix of medium-sized, moderately complex projects (such as offshore wind power complexes) while morphing increasingly into the financing of many smaller projects with short lead times, low risks, and fairly fast paybacks (such as efficiency, combined heat and power, and many modern renewables)?

What if extremely capital-intensive, risky, long-lead-time upstream investments were diverted to a far less capital-intensive, low-risk, short-lead-time portfolio of non-hydrocarbon energy investments? Mightn't one expect a rather quick turnaround in risk-adjusted returns? And mightn't oil companies with the courage to undertake this wrenching change gradually evolve toward becoming normal companies, valued not materially on the questionable book value of their hydrocarbon reserves (which they could deplete or sell) but just on their free cash flow, their net earnings, and their leadership, management, technical, marketing and financial skills? This is not to say that hydrocarbons lack substantial future value; it is rather to question whether that value will rise or fall under the twin assault of carbon concerns and of cheaper, better ways to do the same tasks. This uncertainty creates such an existential question that avoiding it, by strategies offering low cost and risk, would seem prudent.

A saving grace could also be that the hydrogen in hydrocarbons is generally worth more without than with the carbon, even if nobody pays to keep carbon out of the air. Because hydrogen can be used so much more efficiently than hydrocarbons one will generally make more money extracting hydrogen in a reformer than adding hydrogen in a refinery. Thus hydrocarbons in the ground could remain, as Mendeleev foresaw, precious as a feedstock (competing with biofeedstock and more productive use of molecules) but far too valuable to burn. That is, their highest and best use is as feedstock and as a hydrogen source; their lowest-value use is as fuel – the market most suppliers emphasise today.

The accelerating efficiency revolution challenges many fundamental assumptions that underlie oil-industry strategy. Many in the industry do not yet understand that their competitors are not other upstream players but rather thermal insulation, ultralight electrified cars and integrative design. But it’s clear that customers will increasingly realise they’ll get better service at lower cost by buying less energy and using it far more productively. It’s generally a smart strategy to sell customers what they want before someone else does. All the rest is detail.

Amory B. Lovins, an American physicist, is co-founder and Chief Scientist of Rocky Mountain Institute (RMI). He is an ex-Oxford don, honorary US architect, and Swedish engineering academician. He has written 500+ papers and 31 books, taught at 10 universities, redesigned numerous buildings, vehicles and factories, and advised major firms for 40+ years in 60+ countries. A member of the National Petroleum Council (NPC), he advises the US Chief of Naval Operations.
He received the ‘Alternative Nobel’, Blue Planet, Volvo, Zayed, Onassis, Nissan, Shingo and Mitchell Prizes, MacArthur and Ashoka Fellowships, 12 honorary doctorates, and the Heinz, Lindbergh, National Design and World Technology Awards. In 2009, *Time* named him one of the world’s 100 most influential people, and *Foreign Policy*, one of the 100 top global thinkers. He has had a loose advisory association with Shell since 1973.

Notes and references

1. Actually, the ‘end-use efficiency’ described here – wringing more desired service from each unit of delivered energy consumed – is only one of five classes of energy efficiency. The others are in capturing or extracting primary energy, converting it to secondary forms like petrol or electricity, and transporting them to the user, as well as in translating delivered services like hot showers and cold beer into human happiness and satisfaction. For this and much else complementary to this essay, please see A.B. Lovins (2005), *Energy end-use efficiency* (commissioned by S. Chu for the study Transitions to sustainable energy systems), InterAcademy Council (a consortium of ~90 national academies of science): Amsterdam, RMI Publ. #E05-16, www.rmi.org/images/other/Energy/E05-16_EnergyEndUseEff.pdf.

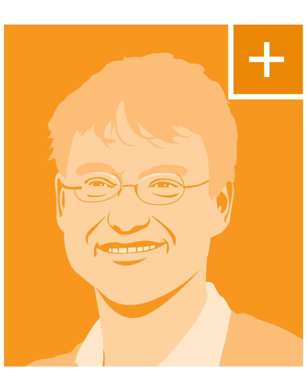
2. A.B. Lovins (2010a). *Integrative design: A disruptive source of expanding returns to investments in energy efficiency*, RMI Publ. #X10-09, www.rmi.org/rmi/Library/2010-09_IntegrativeDesign; (2010b), *Factor ten engineering design principles,* RMI Publ. #X10-10, www.rmi.org/rmi/Library/2010-10_10xEPrinciples.
3. A.B. Lovins (2007). *Advanced energy efficiency*, five public lectures at Stanford Engineering School, www.rmi.org/rmi/Stanford+Energy+Lectures (also in Chinese).
4. *Energy Efficiency Market Report* (2013). International Energy Agency: Paris.
5. Ref. 2 *supra*.
6. A.B. Lovins et al. (2011). *Reinventing fire*, Chelsea Green: White River Junction, VT, and its backup materials at www.rmi.org/reinventingfire. Nearly all the details in this section are documented there or in its predecessor, A.B. Lovins et al. (2004), *Winning the oil endgame*, Snowmass, CO: Rocky Mountain Institute, www.oilendgame.com.
7. National Academy of Sciences / National Research Council (2012). *America's energy future*, Washington, DC: National Academies Press. The efficiency chapter devotes five pages to improved powertrain, three vague sentences to lightweighting, and not a word to their synergies.
8. A.B. Lovins & D.R. Cramer (2004). 'Hypercars®, hydrogen, and the automotive transition', *Intl. J. Veh. Design, 35 (1/2)*, 50-85, Publ. #T04-01, www.rmi.org /rmi/Library/T04-01-HypercarsHydrogenAutomotiveTransition.
9. J.G. Koomey, D.E. Schechter, and D. Gordon (1993). *Cost-effectiveness of fuel economy improvements in 1992 Honda Civic hatchbacks*, LBL-32683, http://enduse.lbl.gov/Info/Honda.pdf; A.B. Lovins et al., *Winning the oil endgame* (ref. 6 *supra*), p. 51.
10. One of these, the Fiberforge process – developed by an RMI spinoff I used to chair, sold in 2013 to Tier One pressmaker Dieffenbacher – appears able to make complex 2 × 2 metre parts in one minute.
11. Ref. 6 *supra*.
12. National Petroleum Council (2012). *Advancing technology for America's transportation future*, http://npc.org.
13. A.B. Lovins (2012). *Mass-market adoption of ultralightweight automobiles*, Topic Paper #7, Working document of the NPC future transportation fuels study, Washington, DC: National Petroleum Council, http://npc.org/FTF_Topic_papers/7-Mass-Market_Adoption.pdf.
14. A.B. Lovins & B.D. Williams (1999). A strategy for the hydrogen transition, *Procs. 10th Ann. US Hydrogen Mtg. Natl. Hydr. Assn.*, RMI Publ. #T99-7, www.rmi.org/rmi/Library/T99-07_StrategyHydrogenTransition; A.B. Lovins (2003). *Twenty hydrogen myths*, www.rmi.org/rmi/Library/E03-05_TwentyHydrogenMyths.

15. P.G. Hawken, A.B. Lovins & L.H. Lovins (1999). *Natural capitalism*, Little Brown: Boston, www.natcap.org.
16. National Academy of Sciences (2010). *Technologies and approaches to reducing the fuel consumption of medium- and heavy-duty vehicles*, National Academies Press: Washington, DC.
17. M. Ogburn et al (2008). *Transformational trucks: Determining the energy efficiency limits of a class-8 tractor-trailer*, RMI Publ. #T08-08, 2008, www.rmi.org/rmi/Library/T08-08_TransformationalTrucksEnergyEfficiency.
18. Sturman Industries, Woodland Park, Colorado.
19. J. Harman (2013). *The shark's paintbrush*, White Cloud Press: Ashland, OR.
20. J. Benyus (1997). *Biomimicry*, Harper Collins Perennial: New York.
21. K.C. Cheung & N. Gershenfeld (2013). *Science, 341*, 1219-1221.
22. H. Lund (CEO, Statoil) (2014). Keynote, Spring 2014 Energy Policy Conference, Center on Global Energy Policy, Columbia University, 8 May, http://energypolicy.columbia.edu/events-calendar/spring-2014-energy-policy-conference.
23. D. Gilbert & G. Scheck (2014). Big oil companies struggle to justify soaring project costs, *Wall St. J.,* 28 Jan.
24. As anticipated in A.B. Lovins & J. Creyts (2012), Hot air about cheap natural gas, http://blog.rmi.org/blog_hot_air_about_cheap_natural_gas.

Consumers at the gate

How energy comes closer

We may have reached ‘peak centralisation’. Decentralisation of energy production will increasingly empower customers to opt out of the electricity grid’s central supply.



> *Jurriaan Ruys and Michael Hogan*

Throughout history, societies have relied on a mix of distributed and centralised organisations. And technology in its modern form has often favoured the centralising tendencies in any society.

Before modernity, many people lived mostly rural lives, protected (if at all) by a local potentate, a landlord in the literal sense of the word. Cities mostly governed themselves, whether or not they had pledged allegiance to some distant ruler. Transport by foot or horse, communication by horse or pigeon, energy from wood, dung or peat, and education through local guilds and father-to-son and mother-to-daughter teaching: none of the major determinants of how societies worked was especially amenable to directives or influence from a powerful centre.

But with modernity, centralisation became the rule rather than the exception. Countries became able to combine strength and size. Governments commissioned the exploration of the world, distant territories were colonised. The wealth from these conquests, and from early technological innovation, allowed further development of science and technology. Weapons, printing presses, water mills, better roads and bridges, larger and faster ships were the result. And these in turn further contributed to the centralisation of capital and power.

It isn’t always obvious what is centralised and what is not. Surely, transport itself is a local phenomenon whatever the technology, whether bicycle or car. One person, or a family, decides where to go. On the other hand, many people rely on centralised forms of transport, such as trains, trams, buses and aeroplanes, that adhere to rigid schedules. And even cars rely on central infrastructure such as petrol refineries and distribution systems, highways and bridges.

The same might be said of what we now call snail mail and the almost as outmoded fixed-line telephone: they are services that are used by individuals, but depend on centralised networks. At the same time, until very recently a large part of communication was very centralised in the form of mass media: print, radio and television.

Centralisation has also taken place in manufacturing, education, health care, and in government itself. Larger factories, schools, hospitals and administrative units have become the norm. And even those that managed to remain small must dance to the tune of increased standardisation.

And, of course, energy has become highly centralised, in the way electricity, natural gas and petrol are produced and distributed.

There are signs that suggest that this tide of centralisation may be turning, that we may have reached ‘peak centralisation’. Several thinkers have suggested trends that fit well with the concept of decentralisation. Jeremy Rifkin describes a connected world, designed to be open, distributive and collaborative, allowing anyone, anywhere and at any time, the opportunity to access it and use it. Thomas Friedman describes a hybrid system in a flat world in which, even with the world globalising, decisions are shifted back to local communities, or even individual people.

We may have reached ‘peak centralisation’

Mobility is an interesting example of a sector where not only technology but the entire business model may change as a result of decentralisation. As driverless cars become a reality, for instance, people will have the possibility to travel fast, flexibly and conveniently, without having the work of driving. Kent Larson of MIT Media Lab describes a modern transport and city design that is compact and flexible. Facilities are close to where people live, like in the old European cities. Inflexible modes of transport (most public transport) are slowly being replaced by automated cars that can drive long distances in chains, like a train.

The death of public transport wouldn’t necessarily mean an expansion of the road system because its capacity will be used vastly more efficiently. Cars will be able to travel much closer together when not driven by a person. They will be less held up by traffic lights. Charging stations will disappear from the public space as cars can find their own way to the socket. If ownership is not individualised, there will also be a need for fewer cars than people, and fewer parking spaces than cars: people may still own or share a 'traditional' car for fun or function, but the majority of transport will be a service.

In this vision, we won't just change our modes of transport, we will completely change the way we work and live. But this change will come gradually, if only for economic reasons. Huge investments have been made based on earlier concepts. Even now, new cities in China and Brazil are still being built based on the surely obsolete urban planning model of the USA from the 1960s, where cars move people between houses and facilities, with lots of parking spaces on either side. A lot of investment is still going into slow and centralised public transport such as light rail, metro and trams.

Struggling centralised systems

In the same way, a decentralising trend in the energy sector will have to overcome tremendous inertia, but that doesn't mean it won't happen. What would the consequences be?

Right now, incumbent energy producers are already under pressure. Large central utilities, once the safe haven of dependable returns stemming from a stable, well-protected, capital-intensive business model, are losing public support, regulatory support, money and talent.

The cause is a change in the economics of the conventional energy business. Demand has actually fallen, due to the recent recession and increasingly efficient energy use. Because this was not anticipated, and because strong investment in renewables in many markets has been promoted by policy, investment in production capacity has been too large.

As a result, the business has become more marginal. Incumbents are losing customers to attackers with lower costs and more appealing propositions or brands. The retail margins on the remaining customers have eroded and sometimes disappeared. Finally, forced decommissioning of profitable older thermal generation is threatening to take away the remaining profit cushion.

It is no surprise that there have recently been some big write-offs by European energy giants such as RWE. And the end is not yet in sight. Of course, this could be just a temporary crisis. After all, demand may pick up again and surplus capacity may eventually be retired, removing the cause of today's thin margins. On the other hand, renewables will keep developing technologically and growing in scale.

Rattling at the gate

But whatever happens, all this may pale before the general trend towards decentralisation, if it comes to pass. In that case, consumers will shift away from central production and large organisations. To understand how that transition will occur, it's important to keep in mind that consumers don't really consume electricity, gas or oil. They consume hot water, warm air, cool air, illumination, entertainment, information, transportation, chilled or frozen food, heat for cooking. They consume energy services, and what they know is when, where and how they want them.

The slate of energy-related services people desire may change. But what is changing perhaps more rapidly than anyone could have imagined even a few years ago is the nature of the relationship between these energy services and the primary energy upon which they rely.

The reason for this change is that the conveniences made possible in the past 200 years by the extraction, processing and storage of fossil fuels come at an environmental price greater than anyone realised. Concern about climate change has led to the development of alternative sources of energy.

The nature of these alternative sources is forcing a change in the nature of the complete energy system. For although there is enough, for now even excess generation capacity, the variability of some of the key sources of renewable generation compared to traditional sources will drive a need for new system architectures to ensure security of supply at a reasonable cost.

One solution is to move to a more flexible mix of generating resources. Regulators are considering incentive schemes (such as capacity markets) and strategic generating reserves. But as 'smart appliances' are rolled out and new and unconventional players get in the game, consumers themselves may become key players in allowing demand to track varying supply based on the rapidly evolving 'internet of things'. It may turn out that the old paradigm of a centralised power grid able to slavishly follow demand for energy services will no longer be much of a barrier.

Who will fund the necessary investments in these innovative grids and appliances, in transforming the generation mix and in renewables? Many of the traditional utilities have retreated from investments in conventional power generation, while they are also seen to be cutting back investments in renewable generation. Traditional retail suppliers have demonstrated limited capacity to revolutionise their relationship with their customers. Will new players step in? What will be their business models?

In many countries, energy costs are increasing. There are many reasons for this: the cost of replacing ageing infrastructure (in developed markets) or building new infrastructure (in developing markets), rising fuel costs, taxes, subsidies and environmental regulation being some examples. The end result is that the shrinking cost of self-supply options such as photovoltaics is on a collision course with the rising cost of continued reliance on centralised power networks.

At the same time, consumers are already investing for a range of different reasons. About 20% of the large power users in Germany have made investments in photovoltaics, combined heat and power or energy storage to meet their energy needs. Use of the centralised network is slowly eroding and some customers have even moved to ‘cut the cord’ altogether by adding local storage systems to their own renewable energy sources. This is already beginning to happen, for instance, in Hawaii, where the combination of an already high cost of grid-provided electricity and a very good solar resource have combined to make going off-grid an attractive alternative for consumers.

When customers decide to go completely off-grid, a fascinating effect takes place: for the remaining customers, costs to use the central system increase, triggering even more customers to go off-grid. So the adoption of self-supply, for instance from photovoltaic systems, sets in motion a virtuous circle in which the presumption of round-the-clock, unfettered access to centralised production and delivery systems will become ever more costly – or less true.

But a complete ‘death spiral’ leading to the abandonment of all central power generation seems unlikely for the foreseeable future, as there will remain a large core of customers for whom going off the grid is not very easy: city dwellers. As a result, changes in consumer preferences and differences in consumer circumstances will be met by be a steady stream of new entrants offering innovative services – often with business models very different from those of the incumbents. In energy, these services range from lowest cost offerings to premium green products. But new entrants are also emerging in the area of power equipment. Photovoltaics manufacturers and installers, financing companies, energy installation companies – each of them is trying to get close to the consumer.

This trend is getting help from regulators interested in giving consumers options for controlling their costs and sources of energy. For instance, in California not only do users have the right to feed energy they generate themselves back into the grid, but also a new law has created ‘community choice aggregation’ (CCA). This means that counties can wrest control of power procurement from their monopoly utility. Marin County (population: 265,000) created Marin Clean Energy, and Sonoma County (population: 491,000) created Sonoma Clean Power. The city of Boulder (Colorado, USA) has recently voted to secede from the local monopoly provider in order to control its own energy choices, with the approval of state regulators. These are local power agencies that procure cheaper and cleaner power than they were getting through their old utility.

Gates wide open

What would a completely decentralised energy sector look like? What lies beyond the obvious trends of more efficiency and more renewables?

In, say, 2025 you might hand-pick your energy source in your neighbourhood. Already, for instance, a Dutch company called ‘Van de bron’ (‘From the source’) allows Dutch consumers to see which solar, wind, combined heat and power or other energy source exists in their vicinity and buy their energy there. Balancing services are provided by the network operator. No traditional retailer sits between the consumer and the producer. Energy generation becomes as sharable as lodging through Airbnb or cars through Lyft. And like these peer-to-peer platforms, it seems almost inevitable that some new entrant will seek to offer a 'concierge' service at a price that will make this sort of option attractive to a large and expanding consumer segment.

Helping this along will be an increasing value in the participation of demand in the balancing of energy consumption with variable renewable supply. This will be made possible by a steady decoupling of the use of energy services from energy delivery. For some applications, such as refrigeration and water heating, this is already the case: they involve the storage of heat, so their supply of energy isn't very time sensitive, and it is surprisingly easy and cheap to expand that functionality. There is vast potential to extend that to other energy services which traditionally required the immediate delivery of energy.

For instance, gathering at a preordained time in front of a television tethered to a wall outlet is already becoming a quaint tradition from a different time. And even when it does happen – Naples will continue to come to a complete standstill during live broadcasts of Italy's World Cup matches – the screens on which people are watching will increasingly be battery-powered, so they will be using electricity produced and delivered hours or even days earlier.

So let them in?

As a result of these developments, the consumer won't be interested in how much energy he uses and what the cost per kilowatt-hour is. Rather, he will concentrate on the services he gets, and what these will cost him per month or per year. Thanks to the 'internet of things', he can share with an 'efficiency provider' what equipment and devices he uses and receive targeted proposals for the delivery of their services.

Amid all those changes, the concept of a utility will become lost. To stay in the race, companies need to invent, develop and market exciting, decentralised energy products. As these are skills that current energy companies don't have, and the privileged regulated access to customers disappears, new companies will take over – companies with more positive and exciting brand identification for consumers than the utilities they have been forced to rely upon for so many years.

But won't the big centralised energy companies simply be supplanted by big centralised information companies? Possibly, but the battle over control of information has raged for some time and will be decided on a broader stage. What is new for the energy industry is that, for the first time in many decades, consumers may have a prominent voice in deciding who wins.

And what remains for the incumbents? In the spirit of decentralisation, they may break down the functional silos and cut off parts of the company that can survive on their own in the global network. Complexity, cost and lack of ownership will outweigh the synergies on which they used to rely.

The winners will be those players, whether new entrants or hived-off components of incumbents, that can empower customers to decouple their enjoyment of energy services from an increasingly unresponsive portfolio of primary energy sources.

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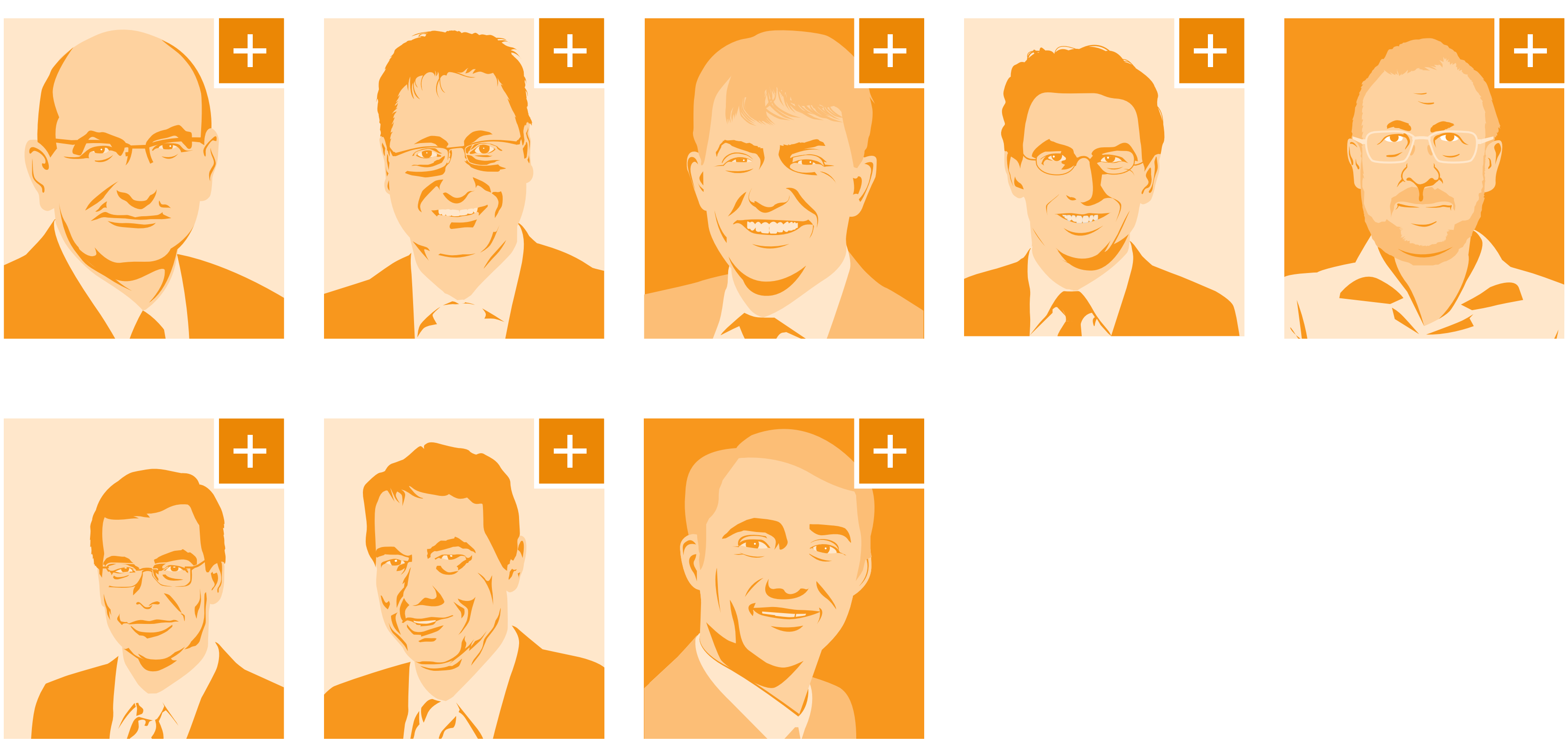
An intergenerational perspective on the energy challenge
> *Herman van der Meyden and Maaike Witteveen*

Jurriaan Ruys is CEO of the Land Life Company, active in sustainable agriculture and nature restoration. Prior to the Land Life Company, he was a partner with McKinsey & Company, COO at Eneco (a Dutch utility) and a chemical engineer at Shell. Jurriaan holds a Master's degree in Chemical Engineering from Delft University of Technology, the Netherlands.

Michael Hogan works on electricity decarbonisation policy with the Regulatory Assistance Project. He previously led the European Climate Foundation's Power Programme. Over the 25 years prior to that he helped build and lead three independent power businesses with over 13,000 megawatts on four continents. He earned an MBA from Harvard, an MSc from MIT, and BA (Philosophy) and BS (Aerospace Engineering) degrees from the University of Notre Dame, Indiana, USA.

Hydrogen
Getting the fuel of the future on the road at last

The development of hydrogen cars is a boulevard of broken dreams. Yet technology has matured, uniting industry in forcing a breakthrough by building a large infrastructure serving hundreds of thousands of cars.



> *Walter Böhme, Klaus Bonhoff, Gijs van Breda Vriesman, Peter Froeschle, Philippe Mulard, Andreas Opfermann, Oliver Weinmann and Jörg Wind*

Jules Verne dreamed about a future where hydrogen would furnish an inexhaustible source of heat and light. “It will be the coal of the future,” he believed.[1] Hydrogen has remained promising ever since.

The idea of using hydrogen for a really clean fuel motivated engineers to develop better solutions to store and use hydrogen. The first hydrogen car, called the Chevrolet Electrovan, was introduced in 1966. Its entire rear section was filled with hydrogen tanks and fuel cells to convert the gas into electricity. Yet industry has announced time and again that technology would improve and that the commercial introduction of hydrogen cars was 10 years away.

The promised hydrogen future never seemed to come any closer, but promises were renewed with unflagging enthusiasm. A study by a Canadian supplier of fuel cells – the power source of a hydrogen car – predicted in 1995 that under mass production and continued technical advancement assumptions its costs would drop by two thirds within five years.[2] This would make hydrogen a €7-11 billion ($8-12 billion) market by 2010. Another study promised that 100,000 cars would be on the road by 2010, with two thirds of all car manufacturers selling at least one hydrogen model. Governments and hydrogen suppliers have both made bold statements about future hydrogen infrastructure. In 2004, former California Governor Arnold Schwarzenegger promised to build a ‘hydrogen highway’ with 250 filling stations for the 20,000 hydrogen vehicles that would travel on California’s roads by 2010. In 2015, California had only a two dozen stations, serving only a few hundred cars.

In spite of these false starts, Europe is now on the verge of an exciting new development. New promises are being made, this time not about technological progress, but about co-operation and scale. Car manufacturers, hydrogen providers, public stakeholders and others involved have joined forces to bring hydrogen on the road. For the first time, a transition to a new infrastructure, serving real customers, is coming within reach.

There has always been talk about the ‘problem of the chicken and the egg’. Who would buy a hydrogen car without a hydrogen infrastructure, and who would build a refuelling infrastructure without enough hydrogen vehicles on the road? Yet, until recently, a hydrogen filling station cost many millions of euros – some 10 times the cost of a regular station.

Hydrogen cars were also an order of magnitude more expensive than a regular car.

This has now changed. The long and troubled history of hydrogen as a future fuel has obscured the progress that has already been made, especially over the last decade. Ten years ago, the three must-do's for hydrogen were cost, lifetime and reliability. On all of them significant, order-of-magnitude improvements had to be made. But by 2011, Daimler managed to drive around the world with three hydrogen cars, over the dusty roads of China, through the heat of Australia and the cold of Scandinavia. Linde delivered the hydrogen across four continents reliably with a mobile fuelling solution. From a customer's perspective, the hydrogen car has almost become a normal car.

The long and troubled history of hydrogen as a fuel has obscured its progress

The long path of technology now allows for a large rollout, and is trying to find a way to get around the chicken-and-egg problem of new vehicles and a new fuel. This is the story of how H2Mobility came together – a coalition of 14 industrial parties, including the organisations of the authors of this essay. Their aim is to build a large fuel infrastructure in Germany for hydrogen filling stations and the cars that will be served by them.

Improving hydrogen cars

The promise of hydrogen has endured because of its unique potential to fully decarbonise road transportation. There are only a few other technologies that hold this promise. The other main options are battery electric cars and biofuels, provided they are produced responsibly and don't conflict with the need for food, feed and other alternative uses. None of these options have displaced more than a few per cent of fuel up to now. The jury is still out, but we would argue that all three technologies will be needed to meet the aspirations of motorists and their governments to make personal mobility truly sustainable. This includes battery electrics for smaller vehicles and short distances; hydrogen for larger vehicles that drive longer distances, for smaller trucks and for buses; and biofuels where high energy density is required, such as in heavy-duty trucks and aeroplanes.

Publicly funded large-scale research, development and demonstration programmes such as the National Innovation Programme for Hydrogen and Fuel Cell Technologies (NIP) in Germany have helped to improve the technology via a stable public-private-partnership approach. Also, the development of hydrogen cars has profited from the recognition of battery electric cars. For half of its technologies, a hydrogen car piggybacks on technological developments of the battery electric car.[3] The hydrogen car actually is also an electric car, carrying its own power plant in the form of a fuel cell. It has the same battery technology, power electronics and motors as pure battery electric cars and there are many synergies in the technical components. The rising acceptance of electric cars is clearly a leverage for the development of hydrogen electric cars.

However, a hydrogen car is different in its energy source. The fuel cell that is at its heart converts hydrogen into electricity. Within the cell, hydrogen ions are forced through a membrane covered by a catalytic layer mainly containing platinum. During this process electrons are released, which can then be used as electricity. The only emissions of fuel-cell electric vehicles are water and heat.

Although the principle of how a fuel cell works dates back to as early as 1839, it was only thanks to material development at NASA in the 1980s that a proton exchange membrane (PEM) fuel cell could fulfil the performance requirements for its use in cars. These cells have an operating temperature of 80 degrees Celsius and a rapid start-up time, which makes them suitable for cars. PEMs are 50-60% efficient, but they tend to have a short life. Ten years ago, they could only operate without degradation for around 1,500 hours. Yet in road experiments, fuel cells have now demonstrated more than 2,500 hours (125,000 kilometres) of durability, with less than 10%

degradation. Around 5,000 hours is required for cars and car manufacturers have achieved this on stack level in the lab for the next generation of hydrogen cars, which will hit the road between 2015 and 2017.

PEMs have also become more compact. The fuel cell, which in the Mercedes-Benz NECAR 1 had also occupied the larger part of the back of a van in 1994, now easily fits under the bonnet of a standard car, taking almost no more space than a standard internal combustion engine. This size reduction is due to a dramatic increase in the power density based on an improved membrane- and catalyst performance as well as a massive reduction in the overall system complexity.

A better understanding of the mechanisms affecting durability has made it possible to counteract degradation. This can be done by nano-scale structuring of the platinum support and by better cell voltage management. Also excess water inside the fuel cell used to make a cold start at freezing temperatures impossible, but now the cell may be ignited at minus 25 degrees Celsius (minus 13 degrees Fahrenheit), or even lower, thanks to water purging at shutdown and the use of new materials such as metallic bipolar plates.

Fuel cells still contain platinum, a rare and costly metal. Recent advances, however, make it possible to pattern fuel cells on a nano-scale, so that it may be used far more effectively. This reduces the need for platinum by a factor of 10 compared to a decade ago. Fuel cells used in the cars that are currently on the road in fact still need about four times the amount of platinum of standard exhaust catalytic systems. Car makers are confident that the use of platinum can be further reduced by at least a factor of two in 2020.[3] Even more importantly, platinum is easy to recycle from the fuel cells at the end of its lifetime. Recycling companies say that they can recycle more than 90% of the platinum from a fuel cell, compared to less than 50% from a catalytic system.

Daimler’s AG B-class F-Cell has already been produced in a small series. The company has produced about 200 fuel-cell cars of this type so far. It is still a small series, but a big step up from the handmade vehicles of the 1990s. In 2014, Hyundai’s Tucson sport utility vehicle hit the road in California – customers can already sign up for a $499

(€450) monthly lease including the fuel. The company has deployed about 1,000 hydrogen cars in 2015 globally. Toyota has released its Toyota FCV for the USA in 2015, and says it has reduced production costs by 95% in seven years. Around the same time, Honda's FCX Clarity has appeared on Californian roads. It is a complete reworking of the version that was introduced five years ago. Its fuel-cell stack is 35% smaller and its energy density has increased by 60%. This makes it generate more power at a lower price. All this marks the first larger-scale introduction of fuel-cell cars, with fuel cells comparable to the normal life of a car.

Agreeing on an infrastructure

In order to build up a hydrogen infrastructure, agreement about the fuelling process and the form of onboard storage is required. Three possibilities exist to store enough hydrogen – a light gas – to give cars a 400-600 kilometre range: as high-pressure gas, as ultra-cold cryogenic liquid (or a combination of the two), or chemically absorbed in, for instance, lightweight metals. All three routes were extensively explored in the early 2000s, and it was an important milestone when the industry settled for high-pressure gas storage.

However, this still left open the question of whether 200, 350, 500, or 700 bar should be the standard filling pressure. Negotiations about the refuelling details were a difficult give and take, lasting for a decade. Increasing the pressure of hydrogen, for example, would increase the capacity of a tank and shorten the refuelling time but also make the tank and the refuelling infrastructure more expensive. The challenge was to find a technically optimum solution that would share the burden evenly among all parties involved.

This exercise could not be done on paper only. It had to be shown in practice that the proposed solutions were feasible. Non-public trials began around 2000, as a joint effort of industrial gas distributors, car manufacturers and oil and gas companies. In the end the industry settled for the higher pressure of 700 bar. While high, this is still in the range for the use of common materials such as aluminium and carbon fibre for tanks and it allows for refuelling within three minutes and a driving range of 400-600 kilometres (250-375 miles).

With agreement on 700 bar, the details of nozzles, pressures, temperatures and many other specifications could be set in a refuelling protocol for hydrogen cars. The agreement reached in H2Mobility is becoming a de facto standard for the global rollout of cars and filling stations.

Hydrogen is abundant, but not simply available

Almost as popular in this field as the Jules Verne quote at the beginning is the observation that hydrogen is the most abundant element in the universe. While true, it could lead one to infer that it is simply ‘available’. This – unfortunately – is not the case. On earth, hydrogen is found chemically bonded to, for instance, carbon, in hydrocarbons, or to oxygen in water. From this pure hydrogen can be produced in the form of a molecule connecting two hydrogen atoms. The most common route is to produce it from natural gas. This has been practised by the chemical industry, which produces hydrogen as a commodity chemical, for over 100 years. Based on existing sources for so-called by-product there is sufficient hydrogen available in the German market for the fuelling of the first few 100,000 fuel-cell cars. Beyond that, when hydrogen grows to scale, it offers the prospect of a low-carbon or renewable fuel, as we will discuss later.

Bringing hydrogen to the cars is less straightforward. Trailers for hydrogen transport to filling stations have the same drawbacks as tanks in cars. The density of the gas needs to be increased either by compressing or liquefaction. Trailers can currently store around 6,000 cubic metres (400 kilograms) of hydrogen at 200 bar, which carries 15 times less energy than a petrol trailer with the same volume. However, new technology is closing the gap. Linde has developed the first new trailer that can be pressurised up to 500 bar, increasing the payload and hence the distribution effectiveness to more than 1,100 kilograms of hydrogen.

In the long term, storage of hydrogen at this high pressure at a filling station is not economically viable. Hydrogen is therefore decompressed to around 45-200 bar for large storage tanks, and compressed again when it is pumped into small buffer tanks that service the cars.

This interaction of compression and buffer is the heart of the filling station. It uses a compressor and a cooling system to condition the hydrogen for the refuelling of the car. Alternatively the hydrogen is transported and stored at the fuelling site in liquid form, that is, as a cryogenic liquid at minus 253 degrees Celsius. The liquid hydrogen is then efficiently pumped to 700 bar leveraging the high density of the fluid. The cold stored in the cryogenic liquid can be used for the conditioning of the hydrogen at the station.

Over the last 15-20 years, development was aimed at increasing the performance of the compressor and cooling system, while reducing energy demand and space requirements. This has led to the development of an ionic compression system and a 700 bar cryogenic pump, in line with the development of the hydrogen tanks in the fuel-cell cars.

Today a hydrogen filling station uses proven and well-known technology, but it requires sensitive equipment that is not particularly suitable for outposts along a motorway. Demonstration activities have shown the need for maintenance, which may make it costly and could cause interruptions. Improving reliability was therefore another crucial element in the development of the last decade. Standardisation will bring availability to levels that consumers accept. It has already reduced costs. Its price of €2 million ($2.2 million) was brought down by one third, and further upscaling will shrink costs even further.

Breaking the circle

Road testing in large-scale demonstration projects, such as the Clean Energy Partnership in Germany, with globally more than 500 cars covering over 15 million kilometres and 90,000 refuellings, has clearly demonstrated the potential of the technology. It's now all about cost and customer acceptance. Lifetime and reliability – the buzzwords of the last 10 years – are almost where they need to be, namely taken for granted.

Through hard engineering work and technical development, costs have come down dramatically during the last decade, but they still have some way to go to be fully commercially viable. Hydrogen cars, like all technologies, will benefit from mass production and economies of scale. The cars may not be cheap enough for mass markets today, but prices will further sink as manufacturers start to produce them in larger series. Likewise, the price of the infrastructure will get lower. The focus is shifting from technological issues to logistics and scale.

All these developments will come to fruition at the moment when the customer faces the choice of vehicles in the showroom. That will be the moment of truth for all who have been working intensively together for more than two decades.

However, the broken promises of earlier, and the history of ever-receding targets, has made everybody involved cautious of announcing a new imminent breakthrough. If one thing is needed to bring a new car and a new fuel to the market, it is trust. Trust between industries that the fuel companies will deliver as they promise, at the time when cars are to come on the market as promised, under the aegis of a supportive government that is in it for the long term. That is why over 30 major companies and organisations came together in 2009 to exchange data and expectations. This included all major car manufacturers, oil and gas companies, utilities, industrial gas companies, car equipment suppliers, and others including the organisations of this essay's authors.

This was the beginning of an evaluation of the economics, sustainability and performance of the full range of alternative power trains: hydrogen fuel cells, battery electric, and conventional petrol- and diesel-engine cars and the outlook of how both types of combustion engine are likely to improve over time. The study required that the best company data be used across rival technologies, and between rival companies. This is not a natural thing to do, but it was vital to create the required cross-industry trust. For this reason an independent consultant was hired who pulled the confidential data of all companies together and published anonymised numbers. Following this principle, data was pooled about the costs of the vehicles, of various fuels, and of the fuelling infrastructure, as well as the best available evidence on performance, efficiency and emissions. Such data was used for formulating three future images for automotive transport in 2050: one with a large share of battery-powered cars, another with significant penetration of hydrogen cars, and a third one largely based on improved conventional cars using increasing amounts of second-generation biofuels. The pathways towards these futures were based on this unique set of confidential industry data.

The results became available in 2010. The study concluded first that all electric vehicles will by 2025 be viable economic alternatives to conventional cars with internal combustion engines. Hydrogen cars are especially suitable for medium and larger cars and longer trips, the study concluded. In Europe, these segments account for almost 70% of the total carbon dioxide emissions of passenger cars. Second, installing a dedicated hydrogen infrastructure over the course of the next decades is ‘justified and doable’. Up to 2050, the infrastructure costs are only 5% of the total costs of the hydrogen cars themselves. These costs are comparable to rolling out a charging infrastructure for battery electric cars and hybrid cars (excluding potential upgrades in power distribution networks). The attractiveness of the hydrogen business case is therefore hardly affected by the additional costs required for distributing and retailing hydrogen: if hydrogen cars make commercial sense in 2025 – as demonstrated by the study – building a dedicated hydrogen infrastructure can be justified.

The study was less confident about the development of cars. Although hydrogen cars could be in the same price range as battery-powered and improved conventional cars by 2020, the development risks were marked as ‘high’ in all three of the categories analysed in the report: performance, economics and environment.

Breaking the chicken-and-egg stalemate would require a reduction of these risks. The study concluded that higher-risk investments by first-movers could be greatly reduced when several companies invest, with government co-ordination, and with dedicated funding and legislative support.

At the time of the study, the world had plummeted into a severe economic crisis. In the aftermath of the collapse of Lehman Brothers and, later, General Motors' bankruptcy filing, both the USA and the European Union were busy saving their banking system. Even as Germany, the USA and other countries had begun to actively support their car industries they could not also take on the burden of responsibility for new mobility and refuelling infrastructure. The Fuel Cell and Hydrogen Joint Undertaking, the European technology programme, almost collapsed under the pressure. At its start in May 2008, enthusiasm was still high. All 27 member states of the European Union had supported its funding, making available €940 million ($1,050 million) over six years, half of which was supplied by the 60 participating industrial companies and 60 research institutions.

And it was not just governments who struggled. Companies were also forced to focus on their core business. As a consequence in 2009 more than a few of the participants resigned from the Joint Undertaking, including some large manufacturers such as Siemens, Rolls-Royce, BMW and VW, although a few years later many of them returned. Of the remaining companies, many scaled back their budgets and reduced their staff dedicated to the development of hydrogen cars. This meant that the industrial contribution to the programme (mostly in kind) had to be carried by an ever smaller group in very uncertain times. The remaining faithful needed to be motivated to spend more and sustain that spending over 10 years.

Projections of lower costs and rising production numbers were not realised and the spectre of broken promises and receding targets was once again back. The fuel cell was apparently not yet ready for commercialisation. Fuel cells had lost their credibility.

Starting to build it

At that moment of crisis and in this complex landscape, the Power Train study became available, with its broad, fact-based approach and robust projections. This boosted confidence. The study effectively silenced doubts and it did create the confidence it had set out to. Five days after its publication in November 2010, the remaining participants voted on a €20 million refinancing package for the salaries and the administrative costs of the Joint Undertaking, assuming a larger share of its costs per individual company and research institute. Negotiations took months as companies had to commit individually to the funding over a period of 10 years, whilst getting no company-specific guarantees on potential subsidies for their projects. The European Commission granted official autonomy (it became an independent legal body of the European Union) to the programme, which up to then had come under the Directorate RTD, the European Ministry of Research and Innovation. This allowed the Joint Undertaking to determine its own direction towards a breakthrough. Seed funding for similar market development efforts as the Power Train study could now be financed by the Joint Undertaking. This has been a huge breakthrough and since 2010, two more large global coalitions have been formed to de-risk fuel-cell buses for public transport and fuel cells for distributed power generation. The former is aiming to put 1,000 fuel-cell electric buses on the streets of Europe before 2020.

A fuel-cell vehicle coalition was also forged to provide a market breakthrough by rolling out a national network of hydrogen filling stations and to produce the cars that would use them.

In 2009, seven major global car makers had joined to publish an open letter, in which they pledged that they would mass-produce hydrogen cars starting in 2015 by the hundred thousands, provided that there were enough filling stations.

This brought together a European coalition to provide this infrastructure for Germany and get enough cars on the road. This 'H2Mobility' coalition included, several months after its inception, Daimler as a car manufacturer; Linde, Air Liquide and Air Products as industrial gas companies; Shell, Total and OMV as oil and gas companies; Vattenfall and EnBW as utilities; and NOW as a neutral chair of the group, which would also provide advocacy. When the outcome of the Power Train study became available, those parties decided to engage in more advanced business planning and develop a variety of scenarios for a rollout. These scenarios could only be made when BMW, Hyundai, Nissan, Toyota, GM/Opel, VW, and later Honda informally joined the table. The Power Train study had convinced them that a rollout was worthwhile.

Eventually, H2Mobility decided to extend the German network of 15 filling stations to about 400 by 2023. This would provide a station at least every 90 kilometres along the motorway between densely populated areas and at least 10 stations in each metropolitan region of the country. Calculations had shown that this infrastructure could be profitable with 350,000 cars.

Germany was chosen for this first rollout. It is a large European car market, where many different car makers have production facilities. The German government is actively trying to achieve climate targets and via NOW did support hydrogen innovations over a longer period. Moreover, because of the country's geography, Germans are used to driving large distances, which is where hydrogen cars would excel and electric cars have their limitations.

A network of 400 filling stations serving hundreds of thousands of hydrogen cars could provide the springboard for a full-scale introduction – first in Germany and then across Europe. This positive outcome was much to the surprise of some of the participants. It turned into enthusiasm when the scenarios were stress tested with taxes, rebates and other sensitivities, and still presented a positive albeit very-long-term business case. It turned out to be the perfect chicken-and-egg dilemma. Changing the system would require investments for a difficult transition, which wouldn't be economical for the first 10 years. Normally such investment decisions would not be considered. However, a transition seemed commercially viable because many of the parties were willing to share the risk or collaborate to reduce the risk. The breakthrough was the joint analysis that operating a hydrogen infrastructure can be a long-term profitable business.

It is not unusual in the energy business for it to take a long time to achieve profitability. In the early-stage business cases payback times can be 20 years or more. Incentive schemes may shorten this time period, but business cases often still remain too risky for a single company. In order to get public and private parties on board, full transparency is needed about the status and prospects. Without this transparency, there will always be someone saying that it is too early, that the analysis is not profound enough, and that the technology is not mature. Sharing the detailed analysis in the confidentiality of the H2Mobility consortium was therefore the key to this breakthrough.

Details about the rollout were negotiated over one year. Air Liquide, Daimler, Linde, OMV, Shell, Total and NOW reached an agreement in September 2013 to set up a joint venture that would be responsible for buying hydrogen as well as the procurement and operation of the 400 hydrogen stations. The overall investment for the 400 stations would be €350 million, shared by public and private shareholders and stakeholders. The first step would be the development of 100 stations by 2017 based on the 50-Station Programme in the framework of the NIP.

On a global scale, the crisis caused the hydrogen vehicle programmes to be delayed for two to five years. However, something more significant happened. Car manufacturers started to expand their existing R&D collaborations into fuel-cell vehicle production. Toyota and BMW joined forces, and so did Daimler, Nissan and Ford; GM and Honda formed another coalition. They came to the same conclusion as the European parties who joined forces in H2Mobility. Partners are required in order to get the necessary numbers which would motivate the automotive suppliers to scale up their production.

Early commercialisation of hydrogen cars is about to start. The broad adoption of the mass market is still about 5-10 years away. This seems to be a time constant inherent in the introduction of hydrogen. It is reminiscent of the bold statements in the late 1990s and late 2000s, which failed to materialise. Yet this time the promises are not about technological progress, but about scale and costs. It involves scaling up a hydrogen station network fast enough, so that consumers start perceiving hydrogen as an alternative fuel with affordable cars.

New sources of hydrogen

Hydrogen cars offer the promise of sustainable mobility. And this in turn depends on the sustainability of the hydrogen fuel – just as electric cars are no more sustainable than the electricity they use. Most hydrogen today is made from fossil fuels – in Europe mostly from natural gas. Even with these fuels, hydrogen cars are by nature not only clean at the end of the exhaust pipe but also relatively clean along the entire fuel production and consumption chain. In fact they emit 30% less carbon than conventional petrol-powered cars and about the same as electric cars, when the grid-average European electricity is used as a basis for comparison.

But there are even better ways to produce hydrogen. First, the carbon dioxide emissions from the existing production method from natural gas can be captured and sequestered, leading to an 85-90% reduction in emissions. Second, hydrogen can be made from all types of primary energy from natural gas to coal from biomass to (renewable) electricity. In the latter case hydrogen is generated by electrolysis of water using electricity. If that electricity is renewable, so is the hydrogen. In fact, using hydrogen as a storage medium for the excess renewable power generated during windy or sunny periods is a promising option especially when it comes to balancing seasonal supply and demand. In contrast to electricity, hydrogen is relatively easy to store (in tanks or caverns). This kind of buffering is necessary to stabilise the electricity grid when intermittent sources such as wind and sun have a large share of the supply.

One of the few installations already in operation – at Berlin's new airport – is a hydrogen filling station operated by Total, in collaboration with Linde, McPhy Energy, Enertrag, 2G Engines and the NOW, where wind power from a nearby wind farm is first converted to hydrogen and then conditioned for use as a car fuel. This is a world first.

The production of hydrogen is a realistic option to help decrease the carbon emissions from cars, while at the same time levelling out the fluctuating yield from renewables. This relieves some of the constraints in the power sector in order to increase the share of renewables and at the same time offers a viable way to use renewable energy in the transportation sector.

Selling the cars

Improving the environmental profile of hydrogen would also make cars more interesting for customers. It is a matter of speculation on what exactly they are willing to pay, but the popularity of electric cars shows that environmental benefits in combination with the driving experience of the electric drive train justify a premium price.

The average consumer tends not to decide on the basis of the total cost of ownership (as fleet owners do), but by considering the purchase costs and the price of fuel at the pump separately. Hence both must be attractive to have mass-market appeal, and much of the effort within H2Mobility is directed towards this goal.

How fast consumers will accept and buy hydrogen cars will also depend on the range of models that are available. When Fiat introduced compressed natural gas as a fuel in Italy, it offered the option in many different models, thereby addressing multiple consumer segments at once. This resulted in a rapid growth of the refuelling infrastructure. Acceptance in Germany, where the large car manufacturers each had only one model on offer, was much slower. Building on this awareness the hydrogen car manufacturers are now co-operating to get a wide range of models on the road.

Following the initiative for Germany, an H2Mobility programme was also initiated in other countries. In Mobility Hydrogen France, 20 partners joined forces to plan the deployment of a private and public hydrogen refuelling infrastructure in France between 2015 and 2030. H2Mobility has already finished a robust fact-based analysis of the potential in the UK, based on an exchange of data by its 15 partners.

The Californian approach is different. They have imposed a top-down hydrogen infrastructure, with the government investing $20 million (€18 million) a year to finance the construction of 100 filling stations. This will result in the 'hydrogen highway' that former Governor Arnold Schwarzenegger announced in the 1990s, while at the same time mandating the production of zero-emission cars.

The progress in hydrogen technology has been one where the pushing and pulling of stakeholders was different every time. On a global scale, it proved to be important that different regions and governments proactively supported research, development and demonstration at different times during the last decade. When the USA started its technology validation programme in the early 2000s, Japan and Europe soon followed this example. Long-term stable public-private partnerships such as the Fuel Cell and Hydrogen Joint Undertaking within the European Union or the NIP in Germany, which provide funding but also networking structures, have proved to be a stabilising factor regarding the continuous development of hydrogen as a fuel and of hydrogen vehicles.

By breaking the chicken-and-egg problem for hydrogen, another breakthrough has been reached at the same time. The weight of public debt stemming from the financial crisis has diminished the policy-guided long-term investment of major public works and development programmes, such as transport infrastructure, energy, aeronautics and space. Businesses are also investing less in the future, as low growth creates the pressure to be cost-competitive. Meanwhile, the economic crisis continues to play out against the still greater long-term crisis of climate change.

Escaping from these multiple crises is only possible by joining forces, as H2Mobility shows. We need a long-term driven co-operation scheme to move into energy transition.

"Water as fuel for steamers and engines. Water to heat water. Water decomposed into its primitive elements by electricity, which will then have become a powerful and manageable force. I should like to see that," Jules Verne wrote. "You were born too soon," the protagonist in his story replied.

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Walter Böhme is Head of Innovation at OMV. His work focuses on the contrast between rising energy demand and the necessity of reducing greenhouse gas emissions. The OMV Future Energy Fund GmbH, founded in June 2006, identifies and sponsors renewable energy projects. OMV is a signatory to the UN Global Compact and an active supporter of its values.

Since 2008, **Klaus Bonhoff** has been Managing Director of NOW, Germany's National Organisation of Hydrogen and Fuel Cell Technology. He has extensive experience in the fuel-cell industry. He has headed development projects at Ballard Power Systems and DaimlerChrysler. Among his responsibilities are the subjects of strategy, communication, worldwide demonstration projects, government programmes and market development. In addition, he is an honorary member of the board of trustees of the Fraunhofer Institute for Solar Energy Systems (Freiburg), the Centre for Solar Energy and Hydrogen Research Baden-Württemberg (Stuttgart), the NextEnergy Institute (Oldenburg) and Erdgas mobil (Berlin) (all Germany).

Gijs van Breda Vriesman was until recently Commercial Manager Europe of Shell Alternative Energy and is currently working for Shell Shipping & Maritime. He has a Master's degree in Chemistry from the University of Utrecht, the Netherlands, and a Master's in Business Administration from INSEAD, France. In addition to Shell, he was worked for Bain & Company as a consultant in their Benelux office, working for clients in the chemicals, financial services, and construction industries. Vriesman was Chairman of the Governing Board of the public-private partnership Fuel Cells and Hydrogen Joint Undertaking from 2007 to 2011. He was the 2013 recipient of the Erik Middelman Innovation Award.

Peter Froeschle is the Managing Director of Arena2036. This organisation brings together researchers and engineers from institutes and companies relating to production and lightweight materials. They explore and develop competitive production models for the flexible automotive factory of the future in 2036, the 150th anniversary of the motor car. Before, he was head of the department Strategic Energy Projects & Market Development Fuel Cell / EV. During this period he was elected as a vice chairman of the Board of the New Energy World Industrial Grouping and subsequently as a member of the governing board of the Joint Undertaking for Fuel Cells and Hydrogen. He is also a member of several executive committees which accelerate the development of new energy technologies. In his position as a programme manager between 2000 and 2004 he was responsible for Daimler's worldwide F-CELL fuel-cell vehicle fleet programme.

Philippe Mulard is Directeur Mobilité Hydrogène at Air Liquide Advanced Business. Within Air Liquide Advanced Business, he is responsible for developing Hydrogen Mobility solutions integrating the supply of Hydrogen Refuelling Stations equipment & Hydrogen Fuel. Prior to his work at Air Liquide, he was Hydrogen Programme Manager at TOTAL Marketing & Services from 2004 to 2012. He graduated as a Chemical Engineer in Lille, France and completed postgraduate studies at the French Institute of Petroleum.

Andreas Opfermann is Head of Clean Energy and Innovation Management at Linde. He studied Physics and Mathematics in Heidelberg, Germany and at St John's College, Cambridge, UK, where he graduated with an MA degree and a PhD in Physics and Mathematics. For six years Opfermann worked at McKinsey & Company. In 2005 he joined The Linde Group. He is responsible for technology and business development in clean energy markets, and for the development of innovative technologies and business models for The Linde Group.

Oliver Weinmann is Managing Director of Vattenfall Europe Innovation. As a subsidiary of Vattenfall GmbH, the enterprise focuses on strategic business development and directing activities in the field of product and technology development for Vattenfall in continental Europe. In 1992 he started his career at HEW in Hamburg and moved to Vattenfall in 2003 as Head of Innovation Management. In 2010 he was appointed as Managing Director of Vattenfall Europe Innovation. The core projects deal with topics such as smart systems, demand response, energy storage, hydrogen and e-mobility.

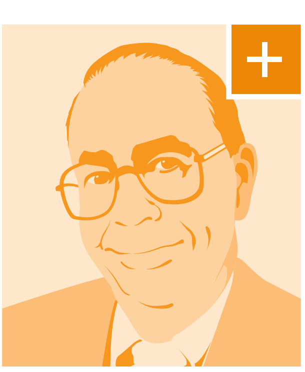
Jörg Wind is Manager Energy Systems Analyses and EU-projects at Daimler AG. He also leads the NEW-IG transportation committee as vice chair. After doing his PhD in the field of semiconductor physics and sensor technology at the TUM in 1992, he started working in the field of fuel cells and hydrogen. He was responsible for high-temperature fuel cells and exhaust after-treatment, and later for PEM stack development at Daimler. Since 2002, he has been responsible for strategic energy projects, comprising projects in the field of fuel-cell vehicles and battery electric vehicles.

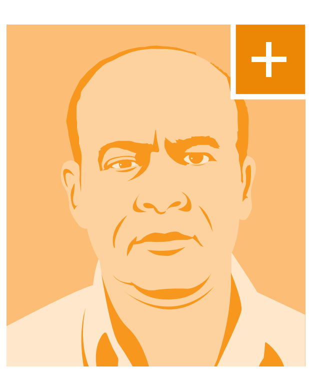
References

1. Jules Verne, *L'île mystérieuse* (1874-75).
2. McKinsey & Company (2010). *A portfolio of power trains for Europe: A fact based analysis*, p. 55.
3. *Ibidem,* p. 36.

Entangled circles
Energy and its resource connections

The production of energy is closely linked to the use of water, metals and land. It is important that these are recognised in energy outlooks, lest we blindside ourselves to the very real constraints they impose.





> *Tom Graedel, Ayman Elshkaki and Ester van der Voet*

Energy production is tied to the production of other resources. As a consequence, the future of energy will depend on its links with the production of water and metals and with agriculture. These ties will strengthen, as it becomes progressively more difficult to produce enough energy, food and metals.

There is a myriad of links between energy and other resources. Water is needed as a coolant for fossil fuel and nuclear power plants. Energy is needed to extract, purify and move water from its sources to its uses. All power facilities need metals in their construction or operation. If the metals that are now used became scarcer, it would be almost impossible to find substitutes, at least for nuclear, solar and wind power. Conversely, extracting and processing metals from their ores, or through recycling, requires huge supplies of energy. Biofuels are producing more and more energy worldwide, and the harvesting and processing of agricultural products depends on various forms of energy. Other examples could be given, but the point is obvious: energy itself is only part of the story.

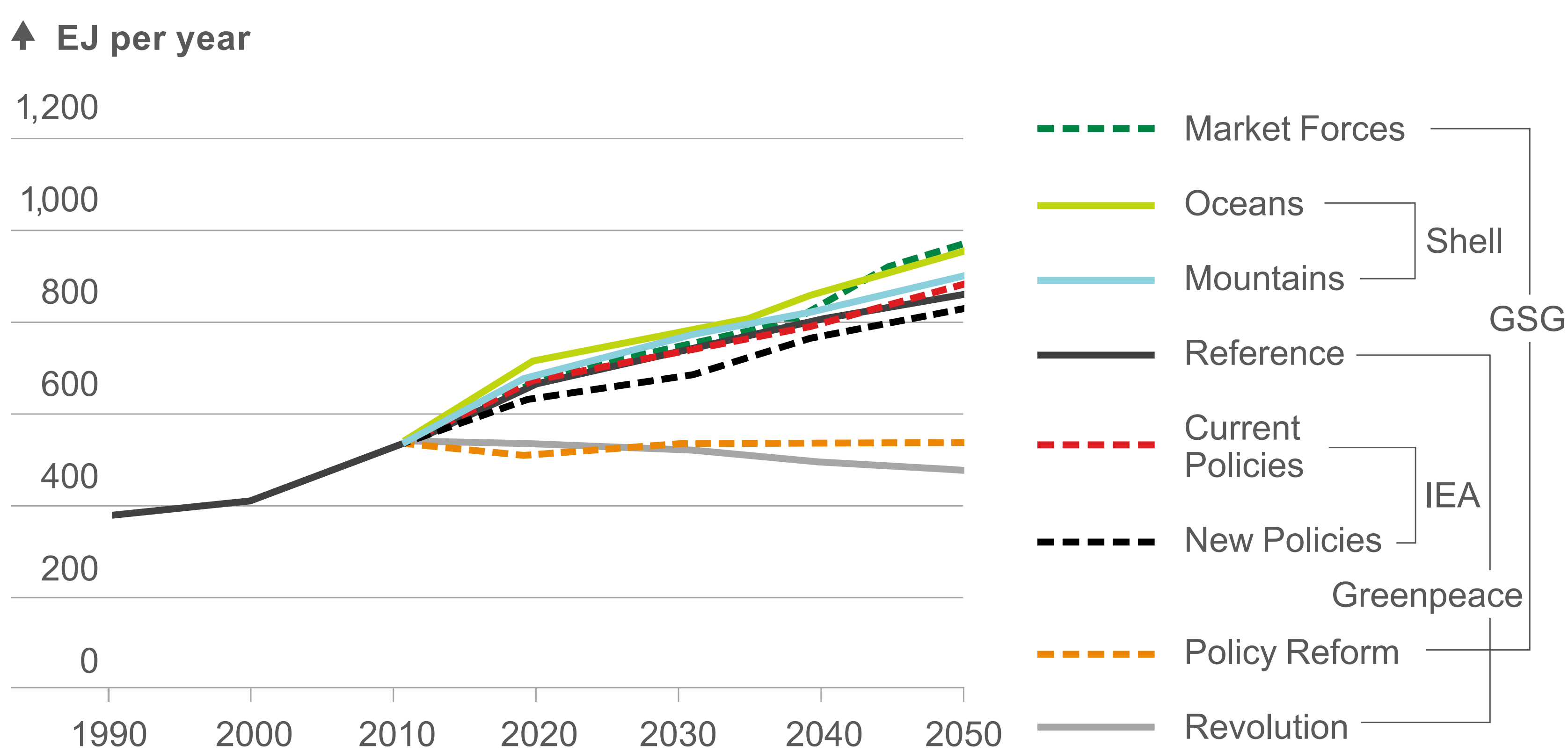


Figure 1: Global primary energy demand under different scenarios, 1990-2050. Note: IEA is International Energy Agency; GSG is Global Scenario Group.

Future energy mix

Several organisations have developed scenarios for the future demand of energy and the energy mix globally and regionally (Figure 1). Broadly speaking, they include business-as-usual scenarios, capturing an energy system that is shaped by market forces – systems that are evolutionary rather than transformative. By contrast, in green policy scenarios governments devise strong policies and plans to change the energy system in order to reach specific social and environmental goals. And there are disruptive scenarios, with a more revolutionary transition to a new energy system.

The International Energy Agency foresees growth of energy demand from 550 exajoules per year today to 750 exajoules by 2035 under 'current policies' or just over 600 exajoules in the aspirational '450 scenario'. In all scenarios the relative share of electricity in the consumption mix increases, so that electricity production is expected to almost double by the same date.

The market shares of the 'new' electric renewable energy technologies – photovoltaic solar, concentrated solar power, and wind – are expected to increase strongly in all scenarios, and dramatically so in the scenarios that assume strong policy action. By 2050 their combined share in electricity is expected to reach from anywhere between 13% in the IEA's New Policy scenario to almost 50% in Shell's Ocean and Greenpeace's Energy Revolution scenarios. On the other hand coal will be the big loser in all policy-driven scenarios, with a share of 30% or below by 2050. Nuclear is more or less constant around 15% by 2050, and is only expected to be phased out in revolutionary scenarios.

Yet will there be enough water, metals and agricultural production to make these scenarios come true? All scenarios assume that the necessary resources will be available for use by the planet's energy technologies. They also assume that no competing activity, such as agriculture or mining, will take the lion's share of the energy and water, leaving energy technologies without the required resources. In the discussion that follows we explore whether these assumptions are reasonable.

Water for energy

It takes water to produce energy, as we see with hydro-power and biofuels. Other types of energy generation also use water, although usually less. The literature about the water–energy nexus distinguishes between water withdrawal and water consumption. Most of the water *withdrawn* for fossil and nuclear energy is used for cooling, so it is returned to the water cycle almost immediately. The water *consumed* (a much smaller amount) refers to the amount of water that is actually dissipated from the freshwater cycle. The cradle-to-gate water withdrawal, which at the present global level is around 4,000 cubic kilometres,[1] is less than 10% of global available water, but the geographical distribution of that water is far from uniform.[2] Of the water withdrawn, roughly 5% (or about 200 cubic kilometres) goes to energy generation in our current system, which is primarily fossil-based.[3]

To mitigate climate change, we need to move from a fossil-based energy system to one that is based on renewables, a move that may have consequences for the system's water requirements. Renewables generally use less water than fossil fuels, with two exceptions: hydro-power and (especially) bio-based energy. This means that in a future scenario where the share of these two sources of energy is high, we are going to need much more water.

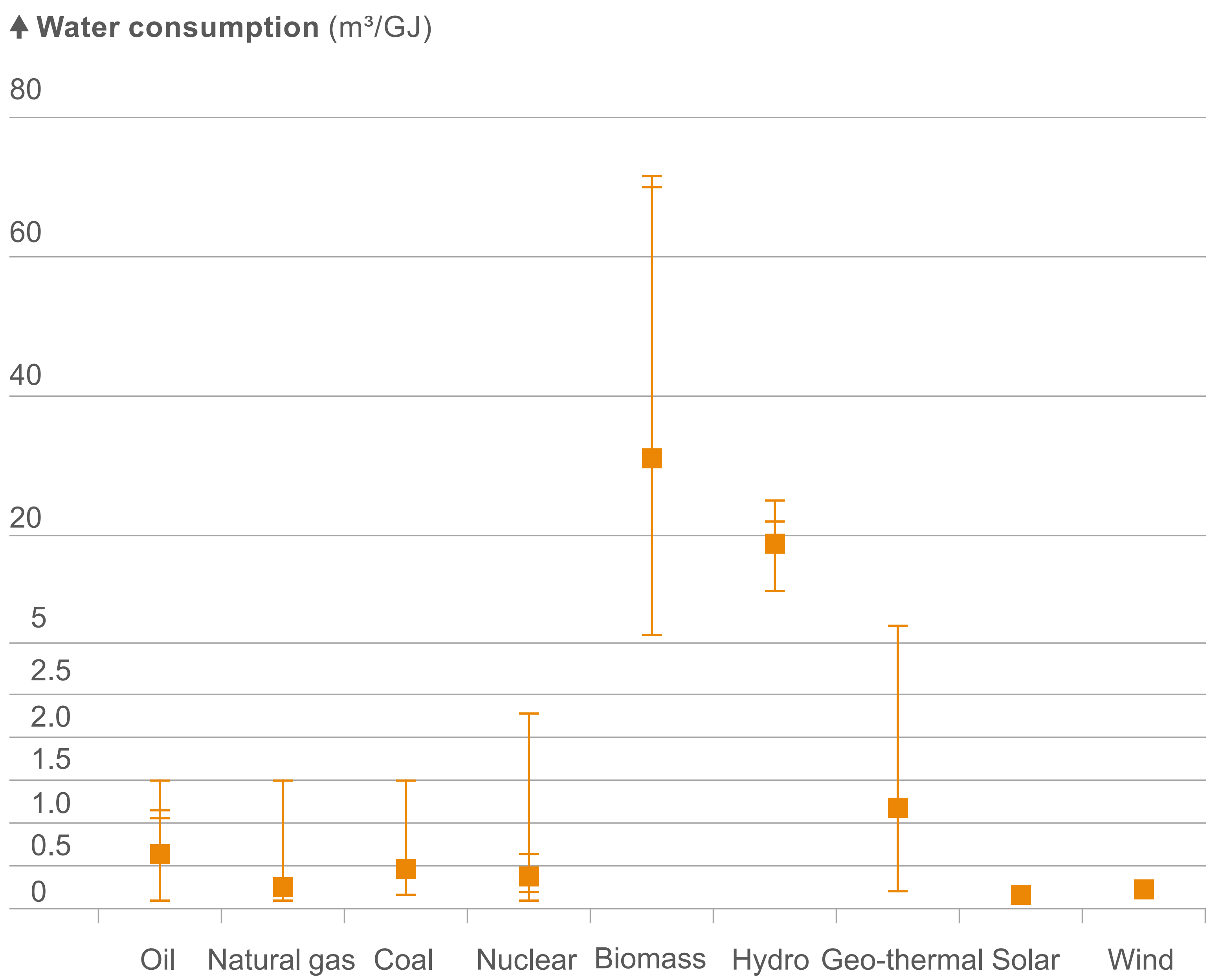


Figure 2: Estimates for water consumption for electricity production using the data from references 3, 4, 5 and 6.

So how will these assumptions affect water footprints? For our calculations we use data on water requirements per energy source (Figure 2). There are very large differences between the estimates in the scientific literature.[4-6] This depends, among others, on whether or not rainfall is included in the footprints. For biomass, allocation may be one of the variables. For example, when we use agricultural waste, the water extraction for this biomass may be allocated to food production instead. So there is a bias in favour of biomass energy, especially when the amount of biomass used becomes substantial compared to food production. In terms of water consumption, however, such an allocation might not make sense, since water that would otherwise remain in the agricultural system is extracted regardless of any economic value.

But irrespective of such academic squabbles, a clear picture emerges: that as we look out to a century in which fossil-based power increasingly gives way to renewable power generation, the 'old renewables', hydro and biomass, are an order of magnitude more water-intensive, while the 'new renewables' of wind and solar tend to diminish the extraction of water for power.

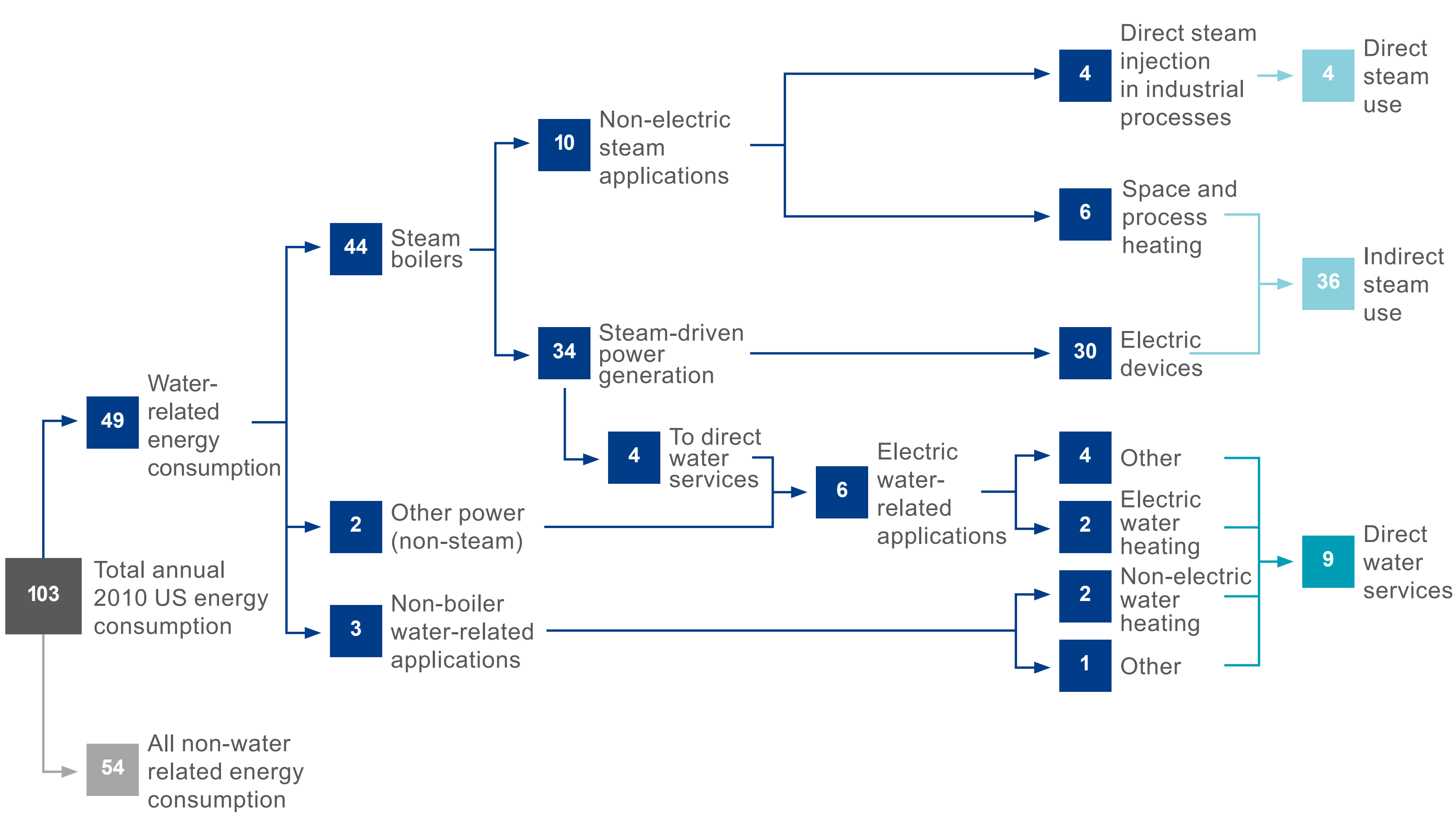


Figure 3: Water-related energy use in the USA (in EJ/year), according to K.T. Sanders & M.E. Webber (2012), Evaluating the energy consumed for water use in the United States, *Environmental Research Letters, 7*, 034034).

To summarise: the water required for global energy production is presently estimated as roughly 5% of all global water use, with about half of that for electricity. In the future, these numbers are likely to be higher in both absolute and relative terms. Because the total water use around the globe is expected to triple in 2050 compared to 2000, the percentage of water needs for energy production rises to 10% for electricity only, and more if fuels are included as well. These are large numbers. It is doubtful whether water scientists include a shift in energy carriers when they predict future water use. Whatever the uncertainties, scientists should reflect the water requirements of new energy technologies more explicitly in their scenario assessment than they seem to do. Shell, for one, has recognised the issue in its work on the water–food–energy nexus.

Energy for water

In some parts of the world, nearly half of all energy consumption is water-related. Most of this energy is used to make steam for electricity, space heating and industrial processes. Smaller but still significant amounts are needed for heating, chilling, treating, pressurising and pumping water. Figure 3 illustrates the water-related energy flows for the USA in 2010.

Taking water from freshwater sources uses relatively little energy, but distributing it also takes energy – and large amounts of it if transport is needed over long distances. Parts of the world where there are not enough freshwater resources have to use salt-water desalination, a process that uses a great deal of energy, typically 3-4 kilowatt-hours per cubic metre.[7]

It also takes energy to clean water. We need to do this in two places in the anthropogenic water chain: we must clean raw water to make it fit for drinking, and clean waste water so it can be returned to the environment. Desalination processes require much more energy than freshwater treatments. In view of the growing population, a greater proportion of drinking water in the future will probably need to be produced from salt water, as freshwater sources become insufficient. This means the production of drinking water will consume more energy too.

Some 380 cubic kilometres of water per year is presently extracted worldwide for domestic use.[8] How much of this is treated before entering homes is unclear. We assume it will be about 150 cubic kilometres, since about half of the world's population lives in urban environments. Assuming an electricity requirement of 0.4 kilowatt-hours per cubic metre, equalling 1.4 megajoules per cubic metre, we can calculate the global energy input for domestic water use as being about 270 petajoules per year, proportionately quite a small amount.

The present domestic water supply relies mostly on freshwater sources. At present desalination constitutes only 0.34% of the total.[9] In the future this will certainly change. If all of the water required domestically were produced via desalination, the upper limit would be 20 times higher, that is, in the order of 5 exajoules per year, or about 1% of present global energy use. This excludes the expected increase in global domestic water demand.

Each year some 1,500 cubic kilometres of waste water is produced globally.[10] Of this, about 10% is currently treated – 150 cubic kilometres per year. To obtain an order-of-magnitude estimate for the amount of energy involved in cleaning up this waste water, we assume an energy requirement of 0.5 kilowatt-hours per cubic metre, or 1.8 megajoules per cubic metre. Total global energy use for the treatment of waste water would then be 0.27 exajoules per year. In the future, with urbanisation, this will certainly grow. With the same assumptions of energy requirements and a total amount of 1,000 cubic kilometres of waste water to be treated each year, the electricity requirement would equal 1.8 exajoules.

Of course, these numbers are highly uncertain, but they do provide an order-of-magnitude insight into energy requirements for domestic water consumption. The numbers do not include either industrial or agricultural water use. Generally, less cleaning is needed in those cases. But if the share of salt water also goes up for these uses desalination may be needed, which would mean a considerable increase in the energy requirement.

To sum up: water and energy are both vital resources, and they are coupled to a significant degree. One cannot do without the other. But the linkage is asymmetric: about 1% of energy is needed for water, whereas tens of percents of water use are involved in energy production. Both percentages are likely to increase over the next decades, enhancing the ‘nexus’ between water and energy.

Metals for energy

Metals are used in most modern technologies either as necessary components or to enhance efficiency. For the energy system, metals enable virtually all energy-generation technologies, and the number of metals required is quite large. Some metals are used in just one technology, while others are used in almost all of them (see Figure 4).

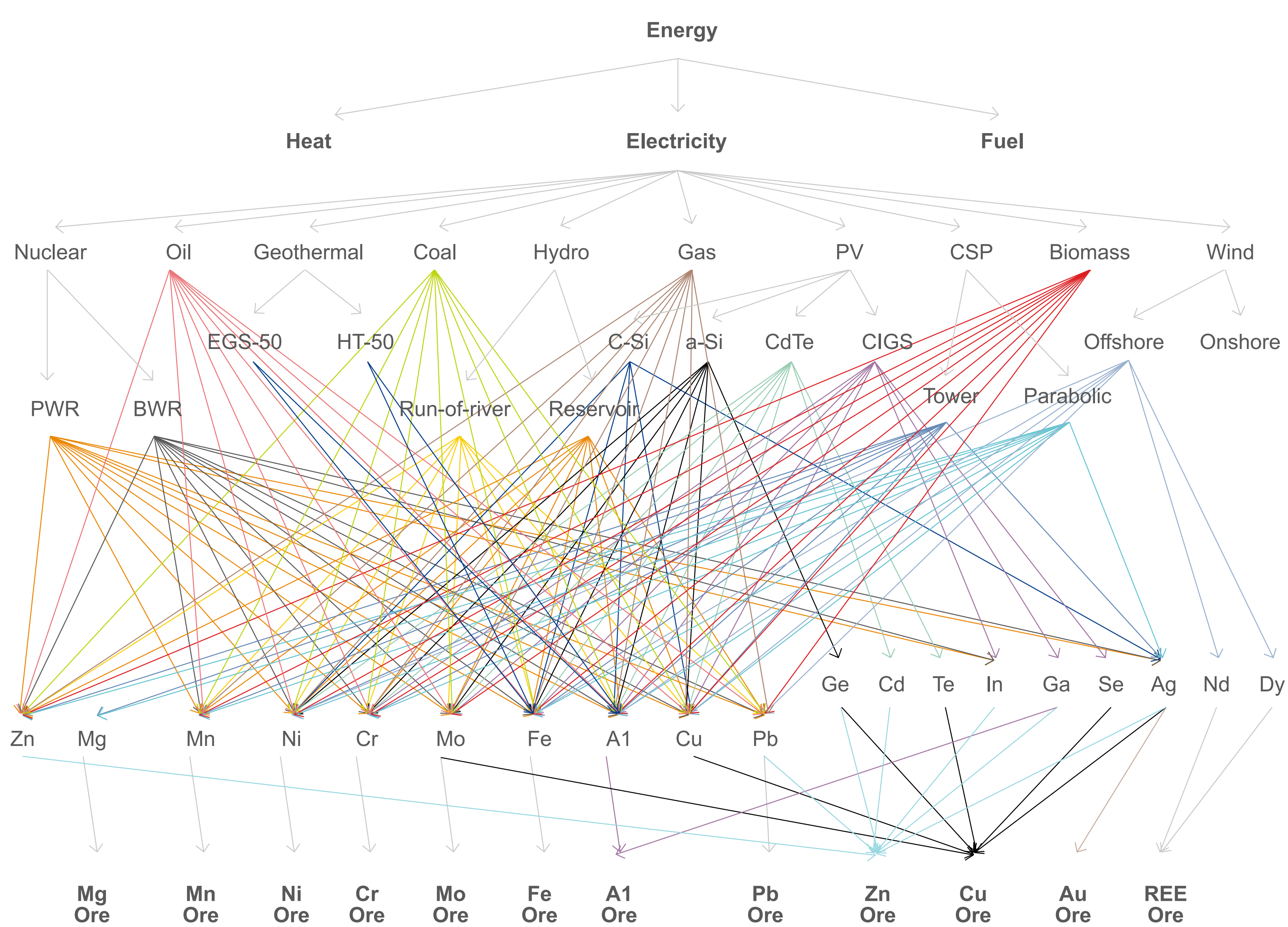


Figure 4: The network of metals used for providing energy.[11]

How much and which metals are required for electricity generation is primarily determined by several factors, the major ones being the total demand for electricity, the market share of electricity-generation technologies, the geographical location of the installation, its efficiency, its performance ratio, the metal's content and utilisation rates, and the possibility for substitutions. The supply of metals from primary resources is determined by the total demand for the metals and the supply from secondary resources. The latter is determined by the total demand for the metals, the lifetime of the technology, and the recycling rate.

Several recent studies have measured how much metal will be needed for electricity-generation technologies in the future and have gauged whether it will be available. The amount of metal required for a specific technology is determined by the scenarios and assumptions mentioned above.

Photovoltaic solar technologies require silver, indium and tellurium. If it is assumed that the four photovoltaics technologies – silicon-based, amorphous silicon, cadmium telluride, and copper-indium-gallium-diselenide (CIGS) – get an equal share and generate 10,000 terawatt-hours of electricity by 2040, the amounts needed of these three metals are estimated to exceed their current reserves by at least a factor of two for indium and tellurium. Of silver we 'only' need a third or half of current reserves.[12] Or viewed in another way, when we use up all known reserves of these metals, we could reach a 50% market share of silicon-based technologies by 2050, assuming an equal share of the three thin-film technologies, and 4,300 terawatt-hours of photovoltaic electricity.[13] Several studies have concluded that there is enough dysprosium (Dy) and neodymium (Nd) to meet the cumulative demand for the two metals by 2050.[14,15] In terms of annual production capacity, however, it has been estimated that the demand for dysprosium for wind turbines by 2050 will be between 450 and 4,200 tonnes (30% to 280% of the 2010 dysprosium production).[16] By 2050 the annual demand for neodymium and dysprosium is expected to be more than 60% and 140% respectively of the 2010 production levels.[17]

Most of the metals that are essential for modern electricity generation, especially for the renewable technologies, are co-produced with other metals, for example: indium, germanium and cadmium with zinc; tellurium and selenium with copper; and neodymium and dysprosium with other rare earth metals, mainly from iron deposits. If the demand for these metals grows faster than the rate for the host metals, we will need to recycle the energy-related metals more, increase the rate of recovery of metals from ores, or increase the production of the host metals. The third option is perhaps the easiest, but it would affect the supply of host metals from secondary resources.[18] Although we expect the recycling rates for most of these metals to be moderate to high, several studies have shown that secondary resources are likely to cover only a fraction of the rapidly increasing total demand, because of the long lifetime of the technologies.[19,20] Except for indium, the current ratio of production of companion metals compared with that of their host metals is low. One option would be to increase the recovery rate of companion metals from ores, but the prices of companion metals would need to go up to cover the cost of building the necessary infrastructure. Substituting one electricity-generation technology for another would merely transfer the pressure from one metal to another, rather than removing it.

The mining industry is one of the largest contributors to carbon dioxide emissions

Energy for metals

The mining industry is one of the most energy-intensive sectors, and thus one of the largest contributors to global carbon dioxide emissions. This is mainly because of the amount of metals produced and the low concentration of most metals in ore deposits, which means we need to mine large quantities of ore to produce one tonne of metal. The global energy consumption for the main primary metals is estimated to be about 32 exajoules annually.[21] That is about 18% of the world's total electricity consumption every year.

The energy required for the production of metals is consumed mainly at the extraction and refining stage. This accounts for about 90% of the total energy required, with the mining and mineral processing stage accounting for the remaining 10%.[22] Although, compared with other metals, iron and steel have low energy requirements per tonne, the energy required to produce iron and steel each year is by far the largest simply because of the amount produced. In the future, the total amount of energy required to produce the metals, and the associated carbon dioxide emissions, will be determined by the ore grade of the metals, the efficiency of the energy, the demand for the metals, and the source of the energy. Since the grade of ore is decreasing over time, the energy required to extract and purify it will correspondingly increase.[23,24] So the decline in ore grade will lead to an increase in the energy required per tonne of metal produced, mainly at the mining and mineral processing stage.[25] Conversely, as we increase energy efficiency, the energy required per tonne of metal produced will no doubt decrease.

It has been shown that the actual energy currently used for metals is several times more than they theoretically require.[26, 27] Therefore, it should be possible to reduce the amount of energy required per tonne of metal produced. Demand for the metals is expected to increase, although at different rates. Based on the likely growth rate in the demand for metals,[28] and the energy required for the production of each metal, the total amount of energy required for all metals is expected to reach 80,000 petajoules by 2035 and 134,000 petajoules by 2050. This is, respectively, about 15.6%, 16.5%, and 18.4% of the total final energy demand in 2035 and 19.8%, 21.5%, and 24.1% of the total electricity production in 2035 according to the Current Policy, New Policy and 450 scenarios. The high values for the 450 scenario are due to the low global final energy demand and electricity demand compared with the other two scenarios. The share of iron and steel is about 66.4% of the total energy required, and for aluminium, copper, zinc, nickel and lead, the shares are 29.2, 1.9, 1.4, 0.9, and 0.25% respectively.

The emissions of carbon dioxide will depend on the total energy required and the sources of electricity supply, especially for metals that require a high component of electrical energy, such as aluminium. The change in the electricity mix will have a huge impact on these carbon dioxide emissions. Although the ratio of the total energy required for all metals to the total electricity demand is highest in the 450 scenario, the carbon dioxide emissions will probably be lower than the emissions in the other IEA scenarios. This is because of the high market share of renewable technologies and nuclear power.

Energy and agriculture

At present agriculture is only a modest source of energy. Some crop residues and some crops are used to produce biofuels and bio-electricity, but the use of 'traditional' biomass (mainly wood) is minor in the total global energy supply, with a share of around 10%. In the future, however, this may change. The share of biofuels and bio-electricity in the global energy supply is likely to grow. In the two Shell scenarios, Mountains and Oceans, the share of biofuels is modest. But their implications for land use are considerable (see Figure 5). The yield of bio-energy for a wide variety of feedstock, including fuels and electricity, ranges between 26 and 225 gigajoules per hectare per year, the average being 214 gigajoules per hectare.[29] Using this number, the land use Shell Mountains scenario, growing from practically zero at present to 29 exajoules per year in 2060, can be calculated and compared to available land. The Shell Oceans scenario has a somewhat lower score.

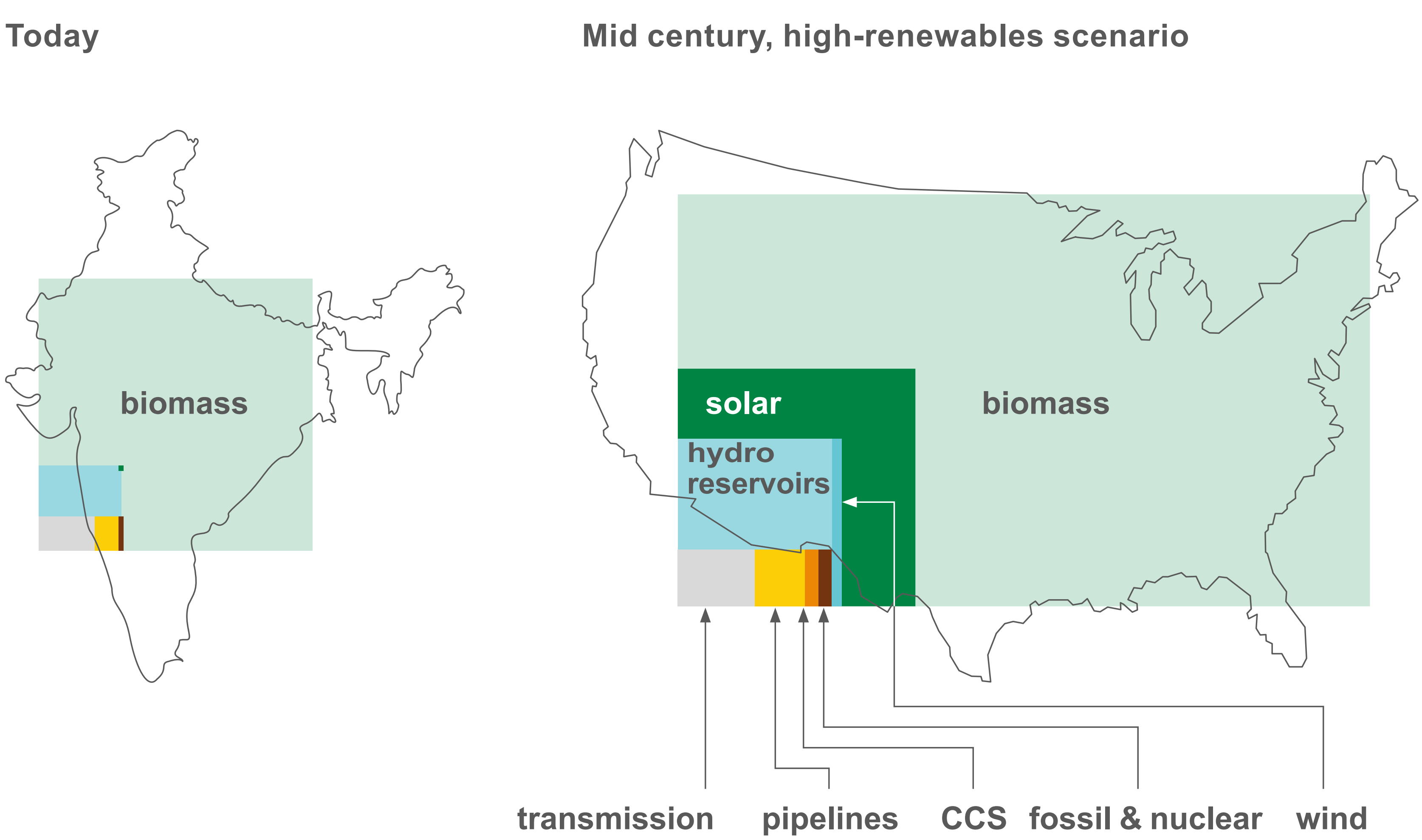


Figure 5: Land use for different energy sources, projected on India (left) and the USA (for details about the calculations, see the essay 'The energy density conundrum').

This suggests that even a modest share of biomass in the total energy feedstock has significant implications for land use. If productivity were increased the area could be reduced, but it is still a considerable amount of land.

As with water, it could be argued that since the main source of biomass for energy could be agricultural waste streams, no extra land is needed. This means, however, that those waste streams are removed from the purpose they are currently used for – as fodder, or to improve the soil – and that additional fodder needs to be grown or the soil is degraded. So one way or the other, the pressure on land use will grow significantly through the use of bio-energy.

Agriculture is an activity that is 'powered' mainly by solar energy. However, the amount of fossil energy that is used for present-day agriculture should not be underestimated. The fossil input in agriculture has two main sources: the use of fuels (mainly diesel) in equipment such as tractors, lorries and harvesting machines, and the use of energy for the production of agrochemicals, especially fertilisers. The intricacies of energy use in agriculture are seen most clearly with bio-energy.

The most problematic issue is possibly maize-based ethanol. A widely cited study[30] found that for this particular biofuel, more energy is actually required as input than is delivered in the fuel. At the time this was a significant finding, as previous studies had painted a more optimistic picture of the energy balance of biofuels by ignoring agricultural production altogether. This led to a host of new biofuel studies, in which a variety of assumptions on energy inputs were tested.[31] The conclusion was that the energy balance of maize-based bio-ethanol was not good, but when co- and by-products were used to generate electricity, thus increasing the overall efficiency of the process, the score improved. It was also found that allocation choices affected the outcomes of such studies, sometimes even reversing the results.[32] In the case of waste streams from agriculture, the energy was sometimes discounted altogether, being allocated away to the main product.

In general, then, biomass electricity reduces greenhouse gas emissions compared to the fossil alternative. Greenhouse gas emissions can be reduced by up to 90% for electricity. For biofuels a 30% improvement for so-called first generation biofuels is considered a good score. The earlier biofuel studies included only energy and greenhouse gas emissions in their assessments. Lately, studies appear with a wider scope. It appears that biofuels are worse than fossil fuels for most impact categories, as well as for land and water use. This leads to the conclusion that reduction of greenhouse gas emissions comes at an expense: another linkage.

The ongoing support for biofuels and the persistent interest in making them better can be explained by the fact that so long as hydrogen and batteries cannot replace liquid hydrocarbon fuels, biofuels have the potential to play a major role.

Currently, agriculture does not use as much fossil energy as other sectors. The cradle-to-gate input of fossil energy for a crop such as maize, grown in the USA, is about 15-30 gigajoules per hectare.[33] Animal systems are more energy-intensive, but the total global energy use for agriculture is still probably less than 1% of the total. Looking at it from the other end, food consumption, an energy input of 7-21 gigajoules per person per year for the Swedish population is estimated.[34] If the whole world's population were to eat a Swedish diet, the energy input would be around 50 exajoules per year, which is about 10% of the world's energy consumption. This includes not just agriculture but also transport and food processing. The Swedish diet is quite energy-intensive, however, and so the actual global number would be significantly lower.

As the world's population continues to grow, food production must grow as well, and as standards of living improve, the global diet might shift towards the Swedish energy input level. Since we are reaching the limits of available land, the only way forward is to increase productivity. That means the energy input per kilogram of agricultural product can also be expected to rise. In the future, then, energy requirements for agricultural production should rise considerably, leading to another entangled cycle.

The system of resources

It is clear from the above that the world of energy is a world of systems within systems. Energy, water, metals and agriculture are indisputably systems in their own right, but together these systems form a linked resource system at a higher level. In turn, this higher-level system has the potential to be influenced in varying ways by changes and perhaps transformative shocks involving climate change and geopolitics.

The entangled circles of resources demand integrated assessments that are broad and of a high calibre. Scenarios targeting the future of energy, water, metals or agriculture are not complete without this kind of integration, and any guidance obtained from incomplete studies has limited value. Addressing the full scope of the resource systems will be challenging, but it is a task we need to undertake if we as a society are to properly understand and anticipate our future.

Related essay

Earth sciences for the Anthropocene
An emerging discipline
> *Dirk Smit*

Tom Graedel is Clifton R. Musser Professor of Industrial Ecology, Professor of Chemical Engineering, Professor of Geology and Geophysics, and Director of the Center for Industrial Ecology at Yale University, USA. Professor Graedel was elected to the US National Academy of Engineering for “outstanding contributions to the theory and practice of industrial ecology”. He is a member of UNEP’s International Resource Panel, where he chairs the Working Group on Global Metal Flows.

Ayman Elshkaki is an Associate Research Scientist at the Center for Industrial Ecology at Yale University, USA. Prior to Yale he worked as a Research Associate at Imperial College London, UK and as a Research Assistant at Leiden University, the Netherlands.

Ester van der Voet is an Associate Professor and senior researcher and project leader at the Institute of Environmental Sciences (CML) at Leiden University, the Netherlands. In a previous position with the Centre of Energy Conservation, she evaluated the consequences of energy scenarios on the natural environment. She is active in the International Society for Industrial Ecology, presently as Associate Editor of the Journal of Industrial Ecology. She is a member of UNEP's International Resource Panel.

References

1. S. Kanae (2010). 'Measuring and modeling the sustainability of global water resources', in: *Linkages of Sustainability*, T.E. Graedel and E. van der Voet (Eds.), MIT Press: Cambridge, MA, pp. 291-306.
2. Ref. 1 *supra*.
3. S. Pfister, D. Saner & A. Koehler (2011). The environmental relevance of freshwater consumption in global power production, *International Journal of Life Cycle Assessment*, *16*, 580-591.
4. J. Schornagel, F. Niele, E. Worrell & M. Böggemann (2012). Water accounting for (agro)industrial operations and its application to energy pathways, *Resources, Conservation and Recycling, 61*, 1-15.
5. H. de Wever (2010). 'Interactions of the water cycle with energy, material resources, greenhouse gas production, and land use', in: *Linkages of Sustainability*, T.E. Graedel & E. van der Voet (Eds.), MIT Press: Cambridge, MA, pp. 243-265.
6. P.W. Gerbens-Leenes et al. (2008). *The water footprint of bio-energy and other primary energy carriers*, UNESCO-IHE: Delft, the Netherlands.
7. M. Elimelech & W.A. Phillip (2011). The future of seawater desalination: Energy, technology, and the environment, *Science, 333*, 712-717.
8. Ref. 1 *supra*.
9. UN Water (2003). *The United Nations world water development report 2003: Water for people, water for life,* UNESCO [s.l.].
10. Ref. 9 *supra*.
11. A. Elshkaki, unpublished.
12. A. Zuser & H. Rechberger (2011). Considerations of resource availability in technology development strategies: the case study of photovoltaics, *Resources, Conservation and Recycling*, *56*, 56-65.
13. A. Elshkaki & T.E. Graedel (2013). Dynamic analysis of the global metals flows and stocks in electricity generation technologies, *Journal of Cleaner Production, 59*, 260-273.
14. Ref. 12 *supra*.

15. S. Hoenderdaal, L. Tercero Espinoza, F. Marscheider-Weidemann & Wina Graus (2013). Can a dysprosium shortage threaten green energy technologies?, *Energy, 49*, 344-355.
16. Ref. 14 *supra*.
17. Ref. 12 *supra*.
18. A. Elshkaki & E. van der Voet (2006). 'The consequences of the use of platinum in new technologies on its availability and on other metals cycle', in: *Conservation and Recycling of Resources: New Research*, C.V. Loeffe (Ed.), Nova Science Publishers, Inc.: New York.
19. Ref. 12 *supra*.
20. J.H. Rademaker, R. Kleijn & Y. Yang (2013). Recycling as a strategy against rare earth element criticality: A systemic evaluation of the potential yield of NdFeB magnet recycling, *Environmental Science and Technology, 47*, 10129-10136.
21. T. Norgate & S. Jahanshahi (2011). Reducing the greenhouse gas footprint of primary metal production: Where should the focus be?, *Minerals Engineering, 24*, 1563-1570.
22. Ref. 20 *supra*.
23. G.M. Mudd (2007). An analysis of historic production trends in Australian base metal mining, *Ore Geology Reviews, 32*, 227-261.
24. G.M. Mudd (2010). The environmental sustainability of mining in Australia: key mega-trends and looming constraints, *Resources Policy, 35*, 98-115.
25. Ref. 20 *supra*.
26. S. Alvarado, P. Maldonado & I. Jaques (1999). Energy and environmental implications of copper production, *Energy, 24*, 307-316.
27. Ref. 20 *supra*.
28. Ref. 20 *supra*.
29. UK Biomass Energy Centre, Roslin, UK, http://www.biomassenergycentre.org.uk/. Accessed April 2, 2014.
30. D. Pimentel & T.W. Patzek (2005). Ethanol production using corn, switchgrass and wood; biodiesel production using soybean and sunflower, *Natural Resources Research, 14*, 65-76.
31. L. Luo, E. van der Voet & G. Huppes (2009). An energy analysis of ethanol from cellulosic feedstock – Corn stover, *Renewable and Sustainable Energy Reviews, 13*, 2003-2011.
32. E.R. van der Voet, R.J. Lifset & L. Luo (2010). Life-cycle assessment of biofuels, convergence and divergence, *Biofuels, 1*, 435-449.
33. Ref. 30 *supra*.
34. A. Carlsson-Kanyama, M.P. Ekström & H. Shanahan (2003). Food and life cycle energy inputs: consequences of diet and ways to increase efficiency, *Ecological Economics, 44*, 293-307.

The second death of distance
Hidden drivers of mobility and energy

We often see travel and distance as identical. Tali Trigg suggests mobility is more than just getting from A to point B. It is the key to thriving cities and a sustainable energy future.

> Tali Trigg

We often think that we are exempt from the rules of predictability. However, human beings travel in patterns and in extremely predictable ways. Our cars are parked 95% of the time and we prefer to travel no more than one hour per day. This is remarkable, as it has been true since the dawn of civilisation. We overestimate how far we travel – only 12% of Americans drive over 100 kilometres (60 miles) each day, but 48% think that they do. We irrationally place an intrinsic value on cars even when other modes of travel are faster, cheaper and safer.[1] Travelling is much more intricate and interesting than simply getting from point A to point B. However, it is no less predictable.

The notion that human beings travel in patterns has some interesting consequences. It is, for example, detrimental to bike- and car-sharing. An anarchistic system [2] where everyone can pick up a bike or car and drop it off wherever it is convenient quickly leads to bunching. It ends up with all bikes at the bottom of a hill and all cars at peripheral metro stations. Yet the predictability of human behaviour is also the solution. To keep the system viable, the Paris bike-sharing system Vélib' introduced a differential pricing system, incentivising users to leave their bikes at less popular locations. The bike fleet is now better distributed, with higher system efficiency and an increased availability of bikes. The system has become more robust, and the journeys travelled more predictable.

Two futures

In the decades to come, the predictability of human mobility in cities will increase. There will be more grids, less off-roading, and more readily available options such as metro and bus lines. They all provide regularity for the traveller.

Since 70% of the global population will live in cities by 2050, the regularity in mobility and energy is a guide to the future. This means that we may not only need models and projections to predict what shape transportation will take in future decades. By using common sense we can improve numbers-driven scenario-building. In the mid 21st century people will travel in predictable patterns, using the modes supplied, in ways that integrate well into the primarily urban and – especially in affluent countries – older lives of the mid 21st century.

Yet that doesn't mean that all cities will be identical in future. Mobility depends on the available transport modes, which depends on the decisions that are made by urban and transport planners. There are many resulting implications. We will examine two possibilities for future mobility, not only for cities, but at the global level. The left graph in Figure 1 shows the current car-dependent world and the business-as-usual tomorrow. This is a world in which personal cars account for almost all mid-distance travel, and a large share of the short- and long-distance travel. Driving down the block to buy milk is considered to be normal behaviour. It is a place where the bicycle plays a minor role, and the aeroplane rules supreme for long-distance travel.

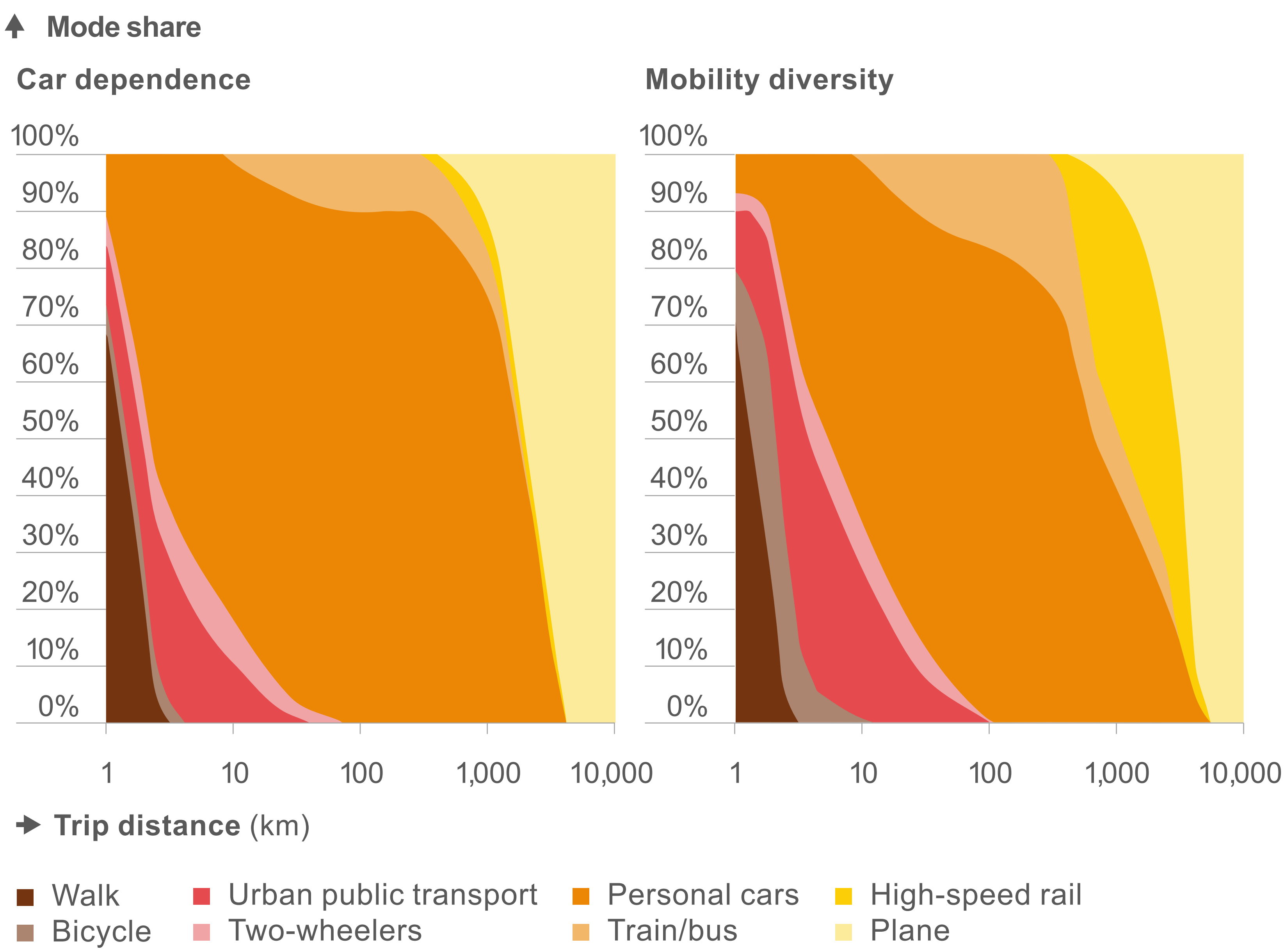


Figure 1: Two possibilities of how the transport modality distribution might develop (adapted from: IEA (2009). *Transport, energy and CO_2: Moving towards sustainability.* IEA: Paris).

The right graph depicts the world in 2050 with a wide variety of travel modes with all of their respective pros and cons. Walking, cycling and public transport have become part of the city's fabric and have increased urban efficiency and the city's liveability. Trains would serve popular corridors and replace driving and even flying. The success of a future low-carbon and efficient mobility system depends on how well it is integrated into the urban and national transportation grids. This will determine how well it connects people to people. Trains need to conveniently link one central urban location to another, as well as to a city's entire transport system. As an example, China built more high-speed rail between 2005 and 2013 than the world has built to date. This construction activity has facilitated urban efficiency at the national level, and has made sure that people are increasingly connected. It has also allowed connections to other countries, as is often done with train lines in Europe. This improves the prospects for what are predominantly our future habitations: cities.

Urbanites have a hard time imagining owning a car

Within cities themselves, what role will, for example, electric cars play in future mobility? It is often thought that they would only be useful within cities because of their limited range. Others think that they will only serve inter-city travel with improved batteries, because most people wouldn't want to have a car in the city. These two incompatible thoughts reflect the two views of the future outlined above. It is true that electric cars still have a limited range, but that might change. In addition, since the average travel distance is 12 kilometres per day, the average daily range requirements are already adequately met. However, if the existing population has a hard time imagining owning a car in the city due to pollution, noise, congestion or inadequate parking, what will the future be like with increasing urbanisation? The car in the inner city faces an uphill challenge.

The city of proximate liveability

What will the two views on mobility hold for the future of the city? William Gibson, famed science-fiction writer, once noted that the future had already arrived, it was just unevenly distributed. Following that logic, certain locations already reveal what is to come for the world in the future. Current urban success stories foreshadow the future; not for niche applications, but for the fabric of the system as a whole. This is because it appears to be what people demand and will spread to other areas over time.

When people are asked why their city is successful, people never say that it is due to transit-oriented development, mobility options or rapid bus transit. They usually talk about the places to live, the ease of commuting, the breathable places, parks, water bodies, good lighting and the clean and safe streets and neighbourhoods. Although they may not call it that, people basically want convenience and places to hang out.

This is now happening in cities like Pittsburgh, Tallinn and Melbourne where the so-called creatives of the world are flocking to. They are not drawn there by the high salaries. They are attracted to these cities because they are very liveable. They have walkable, mixed-use neighbourhoods with short commutes,[3] as well as the environment needed to incubate the types of services, online ideas, products and projects that are the economy of the future.

This has always been true. The very first towns were created by putting a wall around them. Once the citizens' safety was guaranteed, it enabled them to interact with each other. They traded, conversed, married, learned, exchanged ideas, and started businesses. It is the city as 'social reactor' that attracts activity and prosperity. The mathematician Luís Bettencourt of the Santa Fe Institute has studied cities as connections that link people with people.[4] He relates the success of a city with the intensity of its internal links. He found that the efficiency of these connections increases with urban size. As a city grows, the intensity of the interactions grows with it. In other words, cities that intensify their synergistic human connectivity attract more people and manage to grow. Interactions catalyse activities that bring prosperity.

The true sea-change of this insight is the decoupling of economic activity from mobility. It is well established that gross domestic product (GDP) per capita is correlated with passenger kilometres and GDP growth with freight activity. But in the statistics of successful cities that relation is tenuous if not redefined. When they increase economic activity, the transport per dollar earned decreases, and with it the associated energy use.

The energy intensity of Indonesia, for example, decreased 23% between 2000 and 2011 due to urbanisation (measured by how much energy is used to produce a unit of GDP). And according to the World Bank, if China were to focus on increasing the density of its cities rather than building new ones, it would save $1.4 trillion in infrastructure spending alone.[5]

This is the logical consequence of travel as a derived demand. Transport is a go-between; an unseen broker. Done well, transportation can accelerate the efficiency of cities, as density is a prerequisite for successful public transport. It is a shadow currency, adding cents and dollars to every transaction by the very fact that it made the transaction possible in the first place. This also implies that cities that disperse in never-ending sprawl face demise and eventually collapse.

The death of cities and distances

Cities where it takes hours to get around are not optimally using their chief resource: the population. When master planner Robert Moses ruled New York City from the 1920s to the 1960s, he tried to make people believe that cities are made for traffic. However, cities that adhere to this doctrine don’t attract the global herd of creatives. They are destined for irrelevance. For this reason, emerging economies will regret copying the car dependence with its detrimental urban design from the developed world. They will find themselves forced to reurbanise their amorphous urban sprawl.

I am often baffled at San Francisco and Silicon Valley, two places 70 kilometres apart that should be one, where the latter should be part of the former. Just imagine a place as dynamic and economically vibrant as Silicon Valley, but where its creative workers actually run into each other continuously rather than working in isolated communes outside the real liveable space, which is San Francisco.

What if these companies were to relocate back to the city, paying the higher rents but reaping the added benefits? The workers would be able to live healthier, happier and more economically connected lives where programmers and scientists run into each other at the cafés, museums, parks and other creative spaces inherent to cities (similar to main streets in villages and towns, on a smaller scale). This trend is becoming more common as companies actually are relocating back to the city. While Google fights with the residents of San Francisco about its many shuttle buses, Twitter has taken offices in the city centre. This is especially appealing in a post-housing-crisis world with high petrol prices. No one should be surprised when the benefits start accumulating.

To achieve a high urban efficiency, be it in terms of energy efficiency or time budgets, the cities that achieve what we can call 'proximate liveability' are the ones that will succeed. A high level of urban interactivity fosters the spark of creativity and spontaneity that makes cities attractive. It is not how much you travel, but rather what you achieve by travelling.

Transport as an enabler for urban efficiency should be the goal of any transportation system. Transport in 2050 should be like the smooth flow of a city's lifeblood. It brings the 'death of distance'. This is not because the need for mobility vanishes in the Internet age, as argued by some geographers. In fact, city life thrives because of mobility and accessibility. They are necessary for the continued survival and success of a city. But it is the notion of distance which needs to disappear. This includes the effort and fatigue that is associated with travel. We need to abandon the overly simplistic point-A-to-point-B approach, which made a mess of so many cities. Distance itself is no longer a fixed given, with more people living closer together. The city of the future decreases distances, thereby increasing its attractiveness and efficiency. We can call this vision 'the second death of distance'. When distance is slain in this new way, a new city will rise up with proximate transport as a solution to the world's ills, rather than being Thoreau's idea of evil.[6]

In this vision, urban transport eliminates the toils of distance, has short-distance travel intrinsically linked to a vibrant and empowering neighbourhood; medium-distance travel that links communities to each other; and long-distance travel that completes the circle by connecting countries with a minimum of linkages.

Confluence of urbanisation and ageing

Global urbanisation coincides with the ageing of the world population. In 1950, there were 2.5 times as many people under the age of 5 as there were people over the age of 65. It was a young world, and many developing countries today still fit this description. However, by 2050 the relationship will be turned on its head. There will be 2.5 times as many over-65-year-olds as under-5-year-olds, which has never happened before. This demographic revolution will greatly affect everything from health insurance schemes to labour productivity. But what of cities and mobility?

The developed world is primarily urbanised and ageing. By 2050 its cities will be inhabited by a rather grey-looking citizenry. Cities need to adapt to this demographic transition and its resulting mobility needs. An older population needs better and more convenient transportation to get around.

Developing countries will eventually see a similar development; the Philippines, for example, had a population of 92 million people in 2010, which is expected to grow to 153 million by 2050. Its working population is expected to remain almost constant, increasing from 50% to 54% between 2010 and 2050. However, its share of senior citizens is expected to more than double in the same period from 6.8% to 15% of the population. Overall, in 2050 there will be a total of 462 million people who are 65 years or older in the ASEAN[7] region.

The mobility needs of an ageing population will reinforce the death of distance. Senior citizens have more difficulty bridging distance due to age-related health consequences. And broadly speaking, because of age, older people have less need to travel. They don’t need to get to work, kindergartens or schools. In ageing cities mobility will need to adapt to cover shorter distances.

Shifting sands

Over 60% of energy is used in cities. The transportation sector currently accounts for the second biggest share of urban energy consumption. This share will only become larger, considering the projected growth of cities. This means that energy will be used more efficiently, as an increasingly older and more urbanised world shifts mobility to more efficient modes and avoids some unnecessary travel altogether.

The death of distance is a result of providing more rather than fewer options. This may take the shape of shared electric cars plying the roads without noise or pollution, buses and light rail taking advantage of high-traffic corridors, and travel avoided altogether when citizens can fulfil their needs without the need for combustion.

What economists cannot quantify – charm, liveability, sustainability, happiness etc. – are the driving forces which will shape our cities and our mobility systems. This will result in the death of distance and a vastly diminished need for energy in transport. This will shift the sands on which the energy landscape is built upon today, but not forever. The cities that care for their citizens and make sure they can achieve their hopes and dreams will be the successful cities of the future.

Tali Trigg is an energy analyst and technology policy advisor, and a writer on transport. His work includes research and analysis on energy and transportation, with an emphasis on the role of cities in shaping transport energy demand and mobility solutions. Trigg has authored dozens of publications, and is an active public speaker and lecturer. He received his Master of Environmental Management from Duke University. Trigg is a native of Stockholm, Sweden.

Notes and references

1. A. Innocentia, P. Lattarulob & M.G. Pazienzac (2013). Car stickiness: Heuristics and biases in travel choice, *Transport Policy,* 25, 158-168.
2. Such a system was in fact pioneered in Amsterdam in the 1960s: http://content.time.com/time/magazine/article/0,9171,879340,00.html.
3. http://www.realtor.org/news-releases/2013/11/realtors-report-americans-prefer-to-live-in-mixed-use-walkable-communities.

4. L.M.A. Bettencourt (2013). The Origins of Scaling in Cities, *Science, 340*, no. 6139. 1438-1441.
5. http://www.worldbank.org/en/news/feature/2014/03/25/reforms-in-land-use-and-local-finances-will-help-make-chinas-urbanization-more-efficient?_ga=1.204376022.774405903.1389274980.
6. http://ngm.nationalgeographic.com/2011/12/city-solutions/kunzig-text.
7. Association of Southeast Asian Nations.

Food is fuel
A tale of bodies and cars

Walking and cycling have lower greenhouse gas emissions than driving, but not for everyone and not in all types of life-cycle analysis. Of car-driving vegetarians and meat eaters on bikes.

> *Grahame Buss*

Evolution has been kind enough to make many of the things that are essential to our survival also pleasurable. We move for the joy of movement, we eat for more than the prosaic need to sustain life. It is the pleasure of these things that drives us from necessity to indulgence and addiction. We bemoan the fact that 'everything we like is bad for us'. Even exercise can be addictive.

That food is foremost fuel is worth a closer look. Forget the pleasure a good meal brings, or the hugely important social ritual that eating is, and regard it the way you would regard a trip to the filling station. Food makes you go and keeps you warm. Just while hanging around doing nothing you are, in energy expenditure terms, a 100 watt light bulb, while in car terms you consume the energy equivalent of about a third of a litre of petrol a day.

When we think of food as fuel it is also reasonable to think of ourselves as a means of transport – moving ourselves around. This comparison, it turns out, gives an insight into the role of biofuels in agriculture.

Hungry or obese?

If you are chronically hungry, you eat simply to live – to have healthy children, to have the energy to work or study, and to avoid the diseases of malnutrition. Food is just fuel, having a choice of food is a luxury; the joy of eating is in appeasing hunger.

Conversely, if you have plenty of food, you could use more of it than is good for you. Recent statistics from the UN Food and Agricultural Organisation (FAO) show that when agricultural workers earn less than $1,000 (€900) per year, all their children show stunted growth (which means a child is very small due to prolonged malnutrition) at age five. If they earn between $1,000 (€900) and $5,000 (€4,500), still half of their children are stunted. For workers earning over $12,000 (€10,000), there is almost no stunting, but 3 out of 10 children are obese.

These are shocking statistics, which illustrate the transition from food as necessity to food as excess. We seek the former and we end up with the latter. Worldwide, 850 million people do not get enough calories. Many more get too many.

The calorie was the unit of energy when the branch of physics called thermodynamics was formulated in the 19th century. With the metric system, the joule became the preferred unit of energy, except that in the domain of food, the kilocalorie was kept (in some countries shortened to 'Calorie'). It takes about 2,000 kilocalories to run a marathon. If you spend the same amount of time, say four hours, ticking over at idle on the sofa, it is about 320 kilocalories. In petrol equivalent terms you need about a quarter of a litre to run a marathon.

Farm to fork

Between 1998 and 2001 David Coley from Exeter University and his colleagues published two papers looking at the greenhouse gases 'embodied' in food. We sometimes think this is just food miles but it means more than this. It is the emissions in the whole production chain from farm to fork, excluding the food itself. This is called a life-cycle analysis. For cars we call this analysis 'well to wheel' and include the emissions from the fuel in the engine if it comes from a fossil fuel source. David Coley made an interesting observation.[1] When justifying transport policy it is usual to use a life-cycle analysis of greenhouse gas emissions to assess the options, but not for walking and cycling, which are zero-rated even though food has considerable embodied greenhouse gas emissions and carries its own environmental impacts. I look at these numbers again in the light of recent reassessments of the greenhouse gas emissions of farming and food and compare them to the emissions of more recent transport alternatives.

A full comparison between modes of transport is needed, then. But we must keep in mind that considerations of energy use and greenhouse gas emissions do not account for the unique advantages that walking and cycling have: overall they are good for our health. For every person walking or cycling, there is a health benefit, but also an added risk of being hurt or killed in an accident. Recently the consequences of the London 'Boris bike' sharing system were analysed.[2] Evidence of benefits for women cyclists was lacking while the benefits for age group 19-25 were comparatively small and potentially negative. For older men, the benefits were significantly larger than the harms. Other studies suggest that the benefits are greater if the cyclist is unfit to start with, as he or she has more to gain.

These advantages might to some extent be used to advocate for walking and cycling even if they turn out to be not as environmentally friendly as is generally supposed. This is true of other forms of transport, which also have important personal and social value, as well as costs. Travel is frequently fun and too little travel can leave us socially isolated.

Walking or driving?

So what are the energy use and emission characteristics of transport by human muscle power?

First, a quick look at global energy use. It is estimated that the total greenhouse gas emissions from global agriculture and food,[3] converted to the equivalent amount of carbon dioxide, is between 9 and 15 billion tonnes per year.[4] This is between 19% and 28% of global greenhouse gas emissions. This excludes the carbon dioxide emissions from eating the food as this is in a closed loop with the growing crops. Biofuels are treated in the same way. The carbon dioxide emissions from burning a biofuel are balanced by the carbon dioxide taken up by the plant when grown. If left unchecked, other reports say that with population and demand growth "… the projected emissions from agriculture will approach 20 gigatonnes carbon dioxide equivalent per year by 2050".[5,6]

For life-cycle calculations, the main thing we want to know about a fuel is how much carbon dioxide (or other greenhouse gases, again recalculated to the equivalent amount of carbon dioxide) will be emitted into the atmosphere per unit of energy. A typical unit to express this is 'grams of carbon dioxide equivalent emitted per million joules of energy', or gCO_2eq/MJ.

For petrol this number is about 93 gCO_2eq/MJ and includes the emissions from the well to the wheel. Here the emissions from the car are counted, as the petrol is made from a fossil oil.

For food, it's more complicated. We have to calculate the greenhouse gases emitted due to many kinds of agricultural activities. For diets found in the developed world we get a range from 220 to 720 gCO_2eq/MJ.[7]

But a car is much heavier than a person and uses most of the fuel to move the weight of the car and relatively little to move the people inside. A bus is heavier still, but moves more people. A person just has to move herself. So a better way to compare these two energy carriers is: how far will a megajoule take a person walking or riding a bicycle or driving a car, and what does that mean for the emissions, say, per kilometre and passenger?

Again, for cars and other means of motorised transport this is relatively easy to find. For people, I have done my own calculations, based on the work done by David Coley, but using a typical weight for a person of 77 kilograms, that is, mid-way between the average man and the average woman aged 16 or over in the UK in 2009. Calculating the energy required to cycle or walk one kilometre and subtracting the resting energy use gives as the additional consumption of energy 116 kilojoules per kilometre for cycling and 180 kilojoules per kilometre for walking.

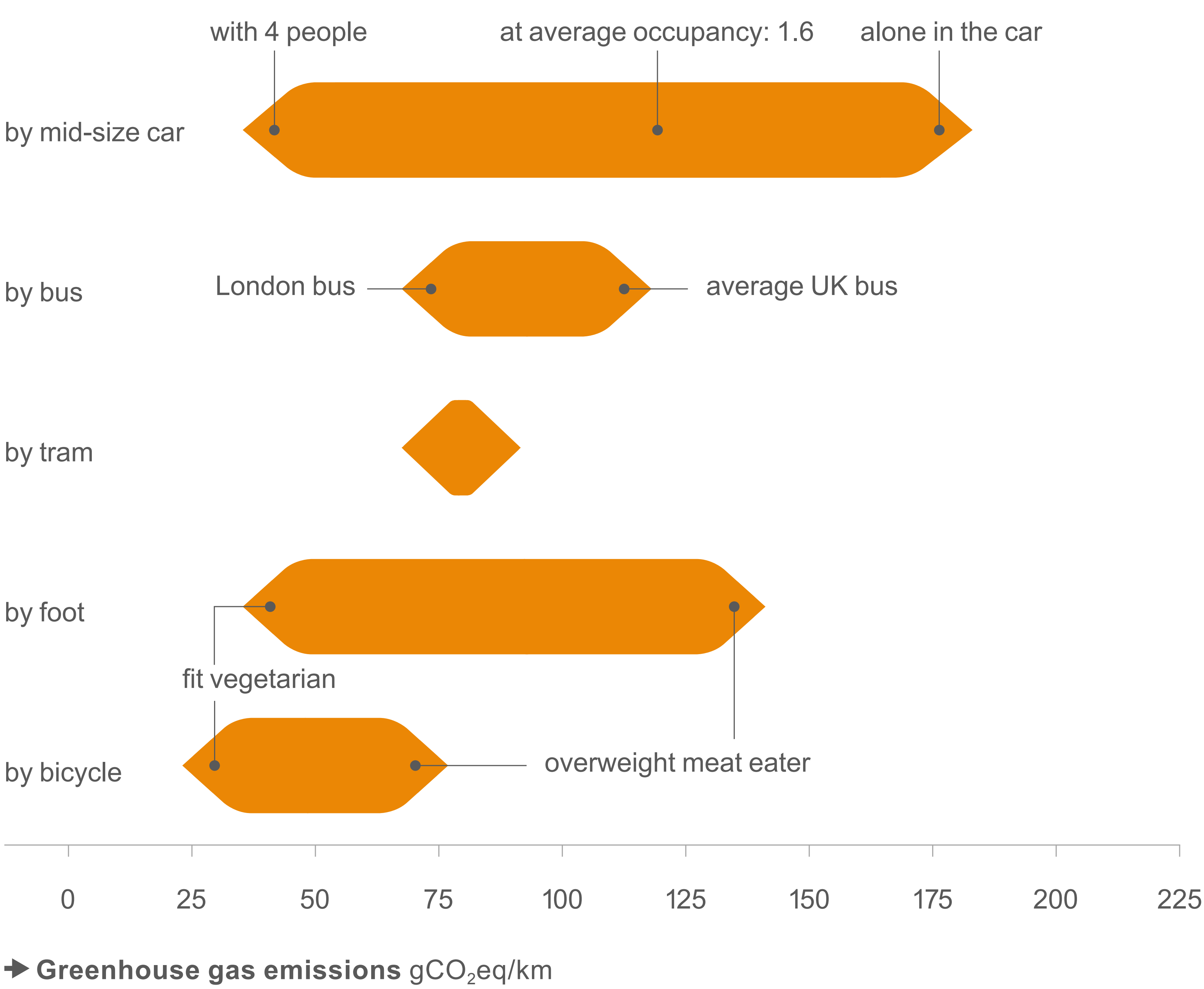


Figure 1: Emissions from walking, cycling, and travelling by car and public transport.

After conversion into carbon dioxide equivalent per kilometre, it turns out that cycling is the most climate-friendly mode of transport, at 28-81 gCO_2eq/passenger kilometre; walking is slightly less so at 39-128 gCO_2eq/passenger kilometre (see Figure 1).

Clearly, on average, cycling remains the best choice and brings many additional benefits. But on aggregate, the environmental benefit in greenhouse gases avoided by using human locomotion is not as great as is generally thought, because in many cases walking has higher emissions than a tram, or even a fuel-efficient car. And while the design of the human body will probably not change for a long time to come, emissions of other modes of transport will continue to decline as drive-train efficiencies are improved, fossil fuels are substituted by biofuels and renewable energy is used to produce electricity for public transport.

This is not the end of the story, as the average 77 kilogram person hides a multitude of people with very different activity levels, body weights and, consequently, food intakes.[8] Very active people of course need to eat more than sedentary people, and you need to eat more if you are carrying more weight. The food choices then determine the greenhouse gas emissions. High animal product and vegetable oil based diets will have higher carbon emissions than high fruit and vegetable rich diets. These factors (people's weights, level of activity and their consumption of meat/oil rich diets) will combine to give a distribution of emissions wider than the range shown. We will see overweight carnivores at one end of the distribution and skinny vegetarians at the other, with most people somewhere in the middle.

What to include

There is then slight and cold comfort from our current farming in providing an environmentally benign human-powered transport solution in our cities.

We can change our greenhouse gas emissions from transport by our choices. The extreme group is high-mass, high meat eaters whose choice is either to walk or use a light railway or very efficient car. This group would be better taking the tram or driving. Light low meat eaters with a large car should ride a bike.

Someone gaining weight who rides or walks to control their weight might argue that these emissions would have happened anyway. That person is eating for some other purpose such as pleasure and is then dealing with it by exercising.

We move into murky waters here. This argument is akin to saying that by taking a tram, one is contributing zero emissions as the tram was running anyway. This would be an abuse of method. We can change our position in the distribution of energy use, and collectively shift the distribution, but we can't remove ourselves from the group of energy users.

Likewise, how one accounts for food emissions may appear at first blush to depend on intention: they are transport emissions if you eat to walk, but lifestyle emissions if you walk to eat.

In the end, this argument takes us nowhere. Rather, we should see walking-to-eat or eating-to-walk as the same activity. By contrast, eating-to-do-nothing may be indulgent, and has its life cycle greenhouse gas emissions, but is unrelated to any choice between transport options.

The sensible middle ground when making choices is to hold oneself accountable for those activities over which one has reasonable control, and for their direct consequences, and not those that are indirectly consequential. We usually try to set the diameter of our circle of personal responsibility neither too small (nothing is down to me – the tram was going there anyway) nor too large (everything is down to me – never indulge).

Attributional or consequential

What to include in a life-cycle analysis (LCA) is an important discussion when evaluating the greenhouse emissions over the life cycle of a product or service. It is important to set the diameter of this circle of responsibility.

Attributional LCAs take only the greenhouse gas emissions that originate directly from the production, the raw materials that go into the product and its final use and disposal. Consequential LCAs include activities distantly but consequentially linked through long causal chains anywhere in the world, even things that have not yet happened – for example, if I plant a crop and someone else grows the crop I previously grew, and so on to any number of crop choices consequential on my decision made by other people. And, if I am required to account for the totality of the changes in greenhouse gas emissions from all these activities, this is called 'consequential'. It includes the entire knock-on effects like ripples through space and time. This raises the question of what to include and what not. How far back or forward in time do we extend accountability for greenhouse gas emissions or carbon captured? How far away do we extend ownership for one's activities through knock-on, causal, but indirect chains? For which things outside the chain of supply is one held accountable, while someone else freely chooses to do them? Indirect effects bring responsibility without agency.

Indirect effects bring responsibility without agency

An example of this is indirect land use change (ILUC) accounting, which causes significant disagreement in the debate of how to account for the emissions from biofuels. No one disputes the essential value of taking into account the emissions directly involved in the production of biofuels, as in attributional LCAs. But ILUC accounting from consequential LCAs are more difficult and have caused heated debate. It is one thing to do the calculation – regulators need to know what might happen as far out as they can. It is another to hold a party responsible for a distant activity undertaken by someone else.

In different jurisdictions ILUC is treated differently. In the USA ILUC is fully integrated into the Renewable Fuel Standard and is part of the calculation of the status of a fuel and the category of mandated volume of that fuel that is required. Under the Californian system (Low Carbon Fuel Standard) the value is calculated and reported separately as a 'risk adder'. A similar thing happens in the UK Renewable Transport Fuel Obligation. In the European Union rules this is still being discussed and a failure to reach agreement has stalled the policy negotiations.

Ultimately, consequential LCAs mean that everything will be double counted, as one person's direct responsibility is also someone else's indirect responsibility.

It should be clear that food needs to account for its attributional life-cycle greenhouse gas emissions. We cannot exclude agriculture in general from the responsibility of accounting for its contribution to climate change. The illustration of food as fuel should make this especially clear. When the IPCC calls for walking and cycling to be adopted as sustainable environmentally benign alternatives to cars, it needs to be true. It is not, though, reasonable to expect one food product to be held consequentially accountable for the emissions of another – for that way either no one is accountable or everyone is, and neither of these positions is a sensible place to design a policy.

Food cannot trump all other calls upon land irrespective of how much and what we eat. From a policy perspective a 'food first' position is bounded by food security at one end and sustainable land use with healthy consumption at the other. Only a balanced use of land makes sense to meet a range of pressing needs.

There is no doubt that we need to reduce the emissions from agriculture. There is also no doubt that responsible agronomy knows it needs to clean up its act, for which attributional LCA will be helpful. Sustainable agriculture and sustainable energy are linked.

A practical guide

There are very few options to take the fossil carbon out of transport fuels. For aviation, trucks and shipping, probably only biofuels are our best candidate. While hydrogen fuel cells and electric cars may some day play a significant role, they are as yet some way off. Rather than arguing about the place of biofuels in agriculture, we should find ways to make agriculture sustainable, which has benefits for biofuels too. These two sectors, agriculture and transport, together make up between 40% and 50% of global emissions. With sustainable agriculture and healthy consumption there is the land required to take the fossil carbon out of transport if we choose to do so.

All these agricultural activities can be guided by attributional LCA. From a technical perspective of LCAs we know how to proceed thanks to a growing body of guidance and good practice.

It is not clear which policy changes will help internalise the environmental costs calculated by an LCA in the face of rising demand. Some argue that direct action from industry is as important as government policies. But it is clear that attempting to hold agriculture accountable for ILUC will stall the urgently needed change towards more sustainable practices – as it does now for biofuels.

Walking and cycling are promoted as environmentally positive alternatives to motorised transport. The good news is that *on average* walking and cycling have indeed lower greenhouse gas emissions than driving; but, perhaps surprisingly, not for everyone. For many people, public transport or fuel-efficient cars have lower greenhouse gas emissions than walking and even cycling. When greenhouse gas emissions from transport fall, as is needed and expected, we need to reduce the life-cycle farm-to-fork emissions from walking and cycling too, if they are to remain favourable. Fortunately, there is considerable opportunity to reduce emissions from food and to achieve synergies with biofuels to take the carbon dioxide emissions out of transport.

Related essay

Fuel for thought
How to deal with competing claims on biomass
> *Iris Lewandowski and Angelika Voss*

Grahame Buss is Principal Researcher in Shell's Biodomain department. Formerly in GameChanger, a team set out to explore the latest developments in science and innovation, and the Fuels group, Buss moved over to the Biodomain department to manage a range of projects on biomass feedstock availability and supply. He has a strong interest in land use and sustainability.

Notes and references

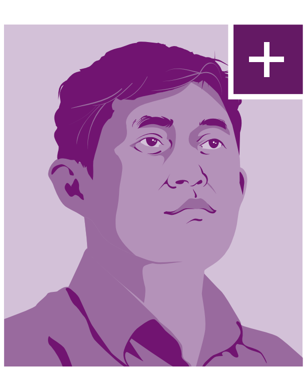
1. D. Coley (2002). Emission factors for human activity, *Energy Policy, 30*, 3-5. D. Coley, E. Goodliffe & J. Macdiarmid (1999). The embodied energy of food: the role of diet, *Energy Policy, 26*, 6, 455-459.
2. J. Woodcock et al. (2014). Health effects of the London bicycle sharing system, *BMJ, 348*, g425.
3. These are made up of fertiliser, energy use in animal feed production, pesticide production, farming inputs and land use change emissions, primary and secondary processing, storage, packaging and transport, refrigeration, retail activities, catering and domestic food management and waste disposal.
4. $GteCO_2$ is billions of tonnes of carbon dioxide. ‘Equivalent’ means that all the various emissions are converted to the mass of carbon dioxide that would have the same effect in the atmosphere.
5. P. Pradhan et al. (2013). Embodied Greenhouse Gas Emissions in Diets, *PLoS ONE*, *8 (5)*, e62228.
6. In terms of energy, global food consumption for 2008 was about 29 EJ, that’s 29×10^{15} kilojoules, or 6.9×10^{15} calories. 1 EJ $=10^{18}$ J, or a billion billion joules.
7. 220 gCO_2eq/MJ is the embodied emission from the ‘high’ diet assuming Vermeulen’s lower calculated global agricultural emissions. 720 gCO_2eq/MJ is the embodied emission from the ‘very high’ calculated assuming Vermeulen’s higher calculated global agricultural emissions.
8. T.D. Logan (2006). Is the calorie distribution log normal? Evidence from the nineteenth Century, *Historical methods: A journal of quantitative and interdisciplinary history, 39 (3)*, 112-122.

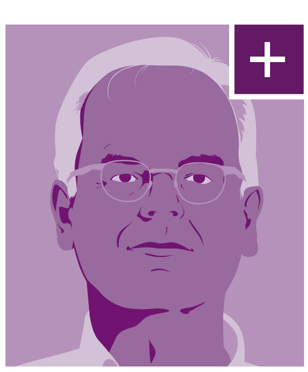
Regional vistas

The determination of the Chinese, the transformative thinking in the USA, the *Schaffensdrang* of the Germans, the economic rationality of the British, the tradition of *polderen* in the Netherlands and the enlightenment of the Nepalese.

The greening and cleaning of China
Low-carbon pathways for the world's largest energy consumer

The world's largest carbon emitter is also the number one investor in clean and green energy. There is a realistic pathway for China to use its coal more cleanly and build a sustainable energy system. For China to follow it would be of pivotal significance for the world.





> *Jiang Kejun and Alexander van der Made*

China is the largest coal user in the world. The country is still building three coal-fired power plants each month, is investing heavily in processes that use coal, and is using as much coal as the rest of the world combined to satisfy its ever-growing need for energy.

Yet the country is also the world's largest investor in clean and green energy, investing 70% more than the USA in 2014. It also has long-term deployment targets that far exceed those of other nations.

The pace and scale of development in China in the last two decades and into the next, and the side-by-side development of the good and the bad, of problems and their solution, make the course of development in China open-ended. In this essay we explore what options exist for China to steer its energy investments onto a path of low-carbon development towards a sustainable future.

Cheap domestic coal accounts for more than 70% of energy production, while natural gas is under 4%, which is far below the global average of 24%. China's oil production is limited, with close to 60% of its demand for crude oil being met by imports. Since China will grow over the next two decades from a developing nation into a developed nation, this will have important consequences for its energy use, emissions, and energy system – and, given its size, for the world as a whole. Whether China can find a pathway towards sustainability, including renewable energy, will be of pivotal significance for the world. China might be the problem, but can it also show the way towards a solution?

China is currently making decisions to provide for its growing energy needs. The new infrastructure and energy technologies that it chooses will have an impact for decades to come. Will China duplicate the predominantly fossil-fuel-based choices of the West ("grow first, clean up later")? Or will the country be able to leapfrog to an energy system that is based on low-carbon and renewable energy? In other words, can China take the global lead in developing a low-carbon energy system?

Chinese leaders understand the climate change challenge and appreciate that there are choices to be made. China is still in an advantageous position compared to Western countries. Carbon dioxide emissions and the use of primary energy *per capita* increased prior to 1990 in countries such as Germany and the USA (see Figure 1). However, after 1990 both emissions and energy usage declined as a result of improved efficiency, an economic shift to less energy-intense activities, and the replacement of coal by natural gas. Decarbonisation only came after an 'overshoot' with significant investments which in hindsight complicate the road to sustainability. Yet it was the economic logic of a time of cheap oil and expensive renewables.

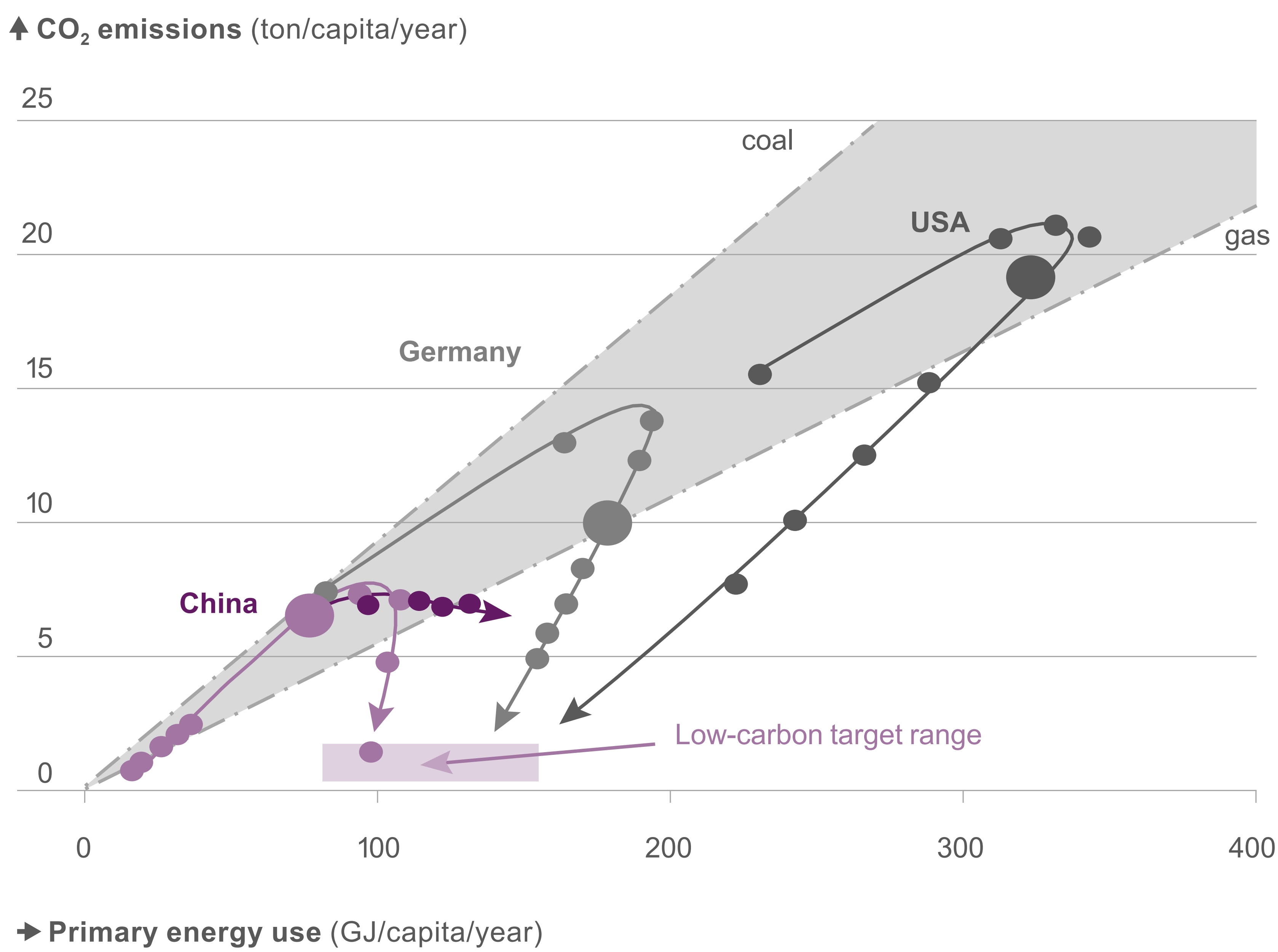


Figure 1: The trajectory of carbon dioxide emissions per capita per year as function of primary energy use per capita per year for the USA, Germany and China, from 1960 to 2050. The dots are at decadal intervals, with the larger dot denoting the 2010 situation. The forward-looking data for China are the Baseline (dark) and Low-Carbon Pathways respectively calculated using the China Energy Model (CNEM) described in this essay. The curves for Germany and the USA are based on Shell's 2008 Blueprints scenario.

Today, a different possibility arises because, unlike a generation ago, renewable energy technologies have become affordable and are scaled up to make a considerable impact. This trend is likely to continue, making clean and renewable technologies even more attractive.

China has the benefit of stepping in late. It can choose not to repeat the detour that was inevitable for the Western world. It can choose between a low- or a high-carbon future. Increasing the size of its energy system poses a number of challenges to China. The continuation of the current energy supply with predominantly fossil fuels creates mounting difficulties in terms of affordability, security of supply and longer-term acceptability of its high emissions. Lowering carbon emissions has short-term challenges with respect to affordability and scalability of technology.

Yet taking the lead in deploying low-carbon technologies will enable China to play a crucial role in driving down their costs and to create attractive export opportunities. The central issue is therefore if it is possible to make smart investments in China's energy system so that it may easily be adapted later should developments so require, and to balance short-term and long-term needs and challenges.

China's energy today

China's recent history has confirmed the well-established relationship between income and energy consumption. As people get richer, they use more energy. Total primary energy consumption increased from 18 exajoules in 1980 to some 112 exajoules in 2014, an annual average growth rate of about 5.6%.[1] Coal remains the major energy source, providing 71% in 1978 and 66% in 2014 of total primary energy use.

However, the relationship between income and energy use is not linear – a phenomenon called the 'energy ladder'. Below a GDP per capita of roughly €3,000 ($3,400), income is spent on only the most basic energy needs. That is why China's total final energy consumption grew only marginally between 1980 and 2000, from 21 gigajoules to 25 gigajoules per capita. Between €3,000 ($3,400) and €10,000 ($12,000), energy use grows linearly with GDP, as industrial production and consumer lifestyles take hold. China hit that limit in the early 2000s when the country began to be transformed from an agricultural to an industrial society, shifting its focus to manufacturing. By that time, per capita consumption had nearly doubled to 46 gigajoules. The country is now in the middle of this income interval. At GDP levels per capita above €10,000 ($12,000), economies start to shift towards services, which use less energy than manufacturing. However, countries around the world have shown considerable variations in energy demand growth and the economic level at which growth starts to slow, depending on lifestyle and infrastructure. It is low in Japan and highest in the US.

This will be no different for China. The challenge therefore is to stabilise energy usage as early as possible. The level at which growth in energy use stalls will depend on the success of choices that are made today, such as an economic shift towards higher value-added products and services. China could also choose to further expand its large high-speed rail network at the expense of domestic air travel and could limit the number of cars per capita by offering public transport as an alternative. Housing the over 400 million people that are projected to move to Chinese cities up to 2050 requires the addition of about twice the current total building stock of the USA. With the right choices, China could have a considerable share of energy-efficient buildings by 2050.

The heavy reliance on cheap, domestic coal is certainly a challenge on the way to a low-carbon future. Coal will dominate China's energy consumption in the coming decades. Yet the persistent 'Great Smog' that haunted northern China in early 2013 caused a public outcry and spurred the government in September 2013 to declare 'clean air' a key priority. This emphasis on a reduction in pollution (nitrogen oxides, sulphur and particulates) is luckily enough not irreconcilable with the reduction in carbon emissions. This gives an increased push to replace coal with natural gas, renewables or nuclear.

China is well under way in making its economy energy-efficient. This is also prompted by the wish to reduce pollution. Energy-saving and emission-reduction policies that came into effect in 2005 have already brought some improvements. For example, Chinese cement producers – making as much cement as the rest of the world combined – have reduced their energy consumption by 30%. Similar initiatives are now under way at

10,000 state-owned enterprises comprising the lion's share of China's emitters. As a result, energy consumption per unit of GDP has decreased by 19% since 2005.

Despite these efforts, China's energy efficiency still lags behind developed countries. The most energy-intensive sectors in China perform about 20% worse than international averages. With 10% of the world's GDP (or 14% on a purchasing power parity basis), China accounts for about 20% of global energy use.

However, China's target is to reduce carbon emissions per unit of GDP by 40-50% by 2020 compared to 2005 and considers limiting its energy use to 117 exajoules in 2015. The country is also experimenting with carbon-trading schemes, which are now being tested in seven locations.

Directions for the future

We have studied China's energy future up to 2050 with models that optimise the energy system for key outcomes, such as lowest overall cost, highest resilience or low (carbon dioxide) emissions, and consider infrastructural implications over time and across provinces (see Figure 2).

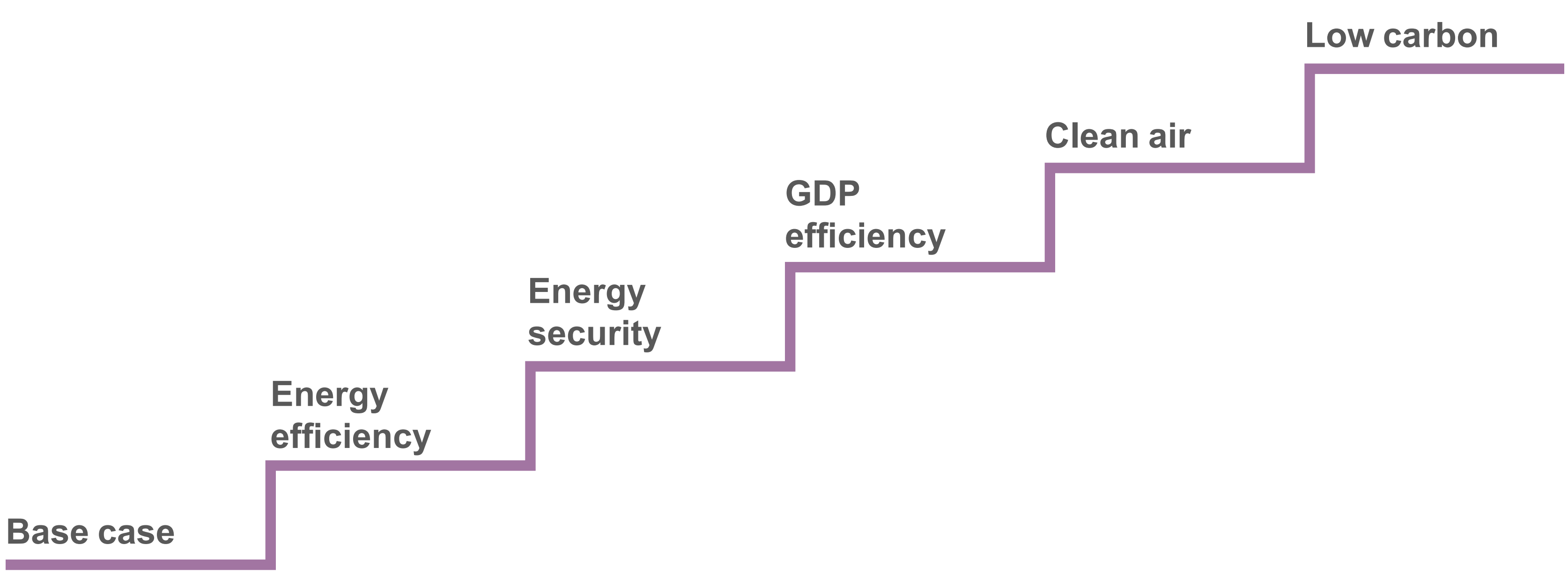


Figure 2: In a Low-Carbon Pathway China may achieve its goals of energy security, energy efficiency, resilience, reduced energy consumption per unit of GDP and clean air.

We chose the distant time horizon of 2050 because it takes decades to introduce a new energy technology and change an energy system.[2] Decisions about infrastructure and technologies have an impact for decades to come. Predictions are difficult to make over such long timescales, but *plausible* transition pathways can be formulated and tested for consistency.

For our studies we created Shell's China Energy Model (CNEM) and the Integrated Policy Assessment Model of China (IPAC), developed by the National Development and Reform Commission's Energy Research Institute (ERI).[3] This allowed us to explore business-as-usual, fossil-heavy and low-carbon futures. The use of models to study an energy system is highly advantageous because models force one to become quantitative and only models can exhaustively explore the daunting set of choices a large country like China is faced with.

We modelled a *Baseline Pathway*, which reflects existing policies and measures, as described in China's 12th Five-Year Plan. It includes binding goals for 2010 to 2015. Non-fossil-fuel energy should reach 11.4% of the country's primary energy mix by 2015 and 15% or even 20% by 2020. This represents a substantial increase from the 8.3% share in 2010. Most non-fossil energy is now supplied by hydropower (78% in 2014), but the country is also vigorously supporting the development of wind power, solar heat and power, nuclear power and other non-fossil energies. The 12th Five-Year Plan also aims to decrease energy consumption by 16% and carbon emissions by 17% (both per unit of GDP). After the current Five-Year Plan, our model assumes a continued investment in coal-based technologies with only a limited penalty of €9 ($10) per tonne on carbon dioxide emissions from 2020 onwards.

The other option modelled is a *Low-Carbon Pathway*, in which China will make major efforts to achieve an emissions target of around 2.1 gigatonnes of carbon dioxide per year by 2050. The target is derived by assuming globally equal per capita emissions targets. The maximum allowable global carbon dioxide equivalent emission is set at 20 gigatonnes in 2050 as described in the International Energy Agency's 450 Scenario – in which the world would actually try to reach the UN climate goal of limiting global warming to 2 degrees Celsius or stabilising atmospheric greenhouse gas concentrations at 450 ppm carbon dioxide.[4] This represents a 75% reduction in China's emissions from 2009. Harsh as this may seem for a developing nation, it is comparable to an 80% reduction target proposed for 2050 for the European Union, which is relative to *1990*.[5]

The decarbonising of an economy requires a combined deployment of renewables, clean fossil technology and nuclear power, accompanied by an aggressive search for efficiency. In the Low-Carbon Pathway, renewable energy and nuclear are used to their maximum potential, and carbon capture and storage is widely used to mitigate the emissions from coal. The future infrastructure will determine where energy use will level off on the energy ladder. Housing, industrial structure, urbanisation and mobility are key factors to consider.

We don't expect the emergence of a single dominant technology for each application. A mosaic of choices will be used to reduce carbon emissions. It may be helpful to set energy targets per tonne transported, per kilometre travelled, or per square metre of floor space. The market can then sort out the best solution. We used this approach in our energy model by specifying that, for example, in 2050 the efficiency of buildings has to improve by 60-80% relative to 2009 without specifying a technology choice. Setting sector-specific targets is relevant for all three major sectors (industry, buildings and transport) either because of their size (industry) or their rapid growth (buildings and transport).

The Low-Carbon Pathway includes a decrease in energy-intensive industries and a growth in service industries. By 2030, the efficiency of major energy-intensive industries would match Western values and new buildings would reach high energy-efficiency standards. The pathway includes zero-emission vehicles and a partial shift from air traffic to trains.
By relentlessly driving down costs, China becomes one of the global leaders in low-carbon technologies.

Pathways to 2050

Up to 2030, the energy flows and emissions in both pathways are almost identical. Yet the foundations for future reductions are determined before 2030, making the differences pronounced after 2030, with the coal share and total energy use declining in the Low-Carbon Pathway (see Figure 3).This will cause carbon dioxide emissions to peak between 2020 and 2030 at 8-10 gigatonnes per year for IPAC and CNEM respectively. An even more aggressive reduction in carbon prior to 2030 is not realistic or cost-effective.

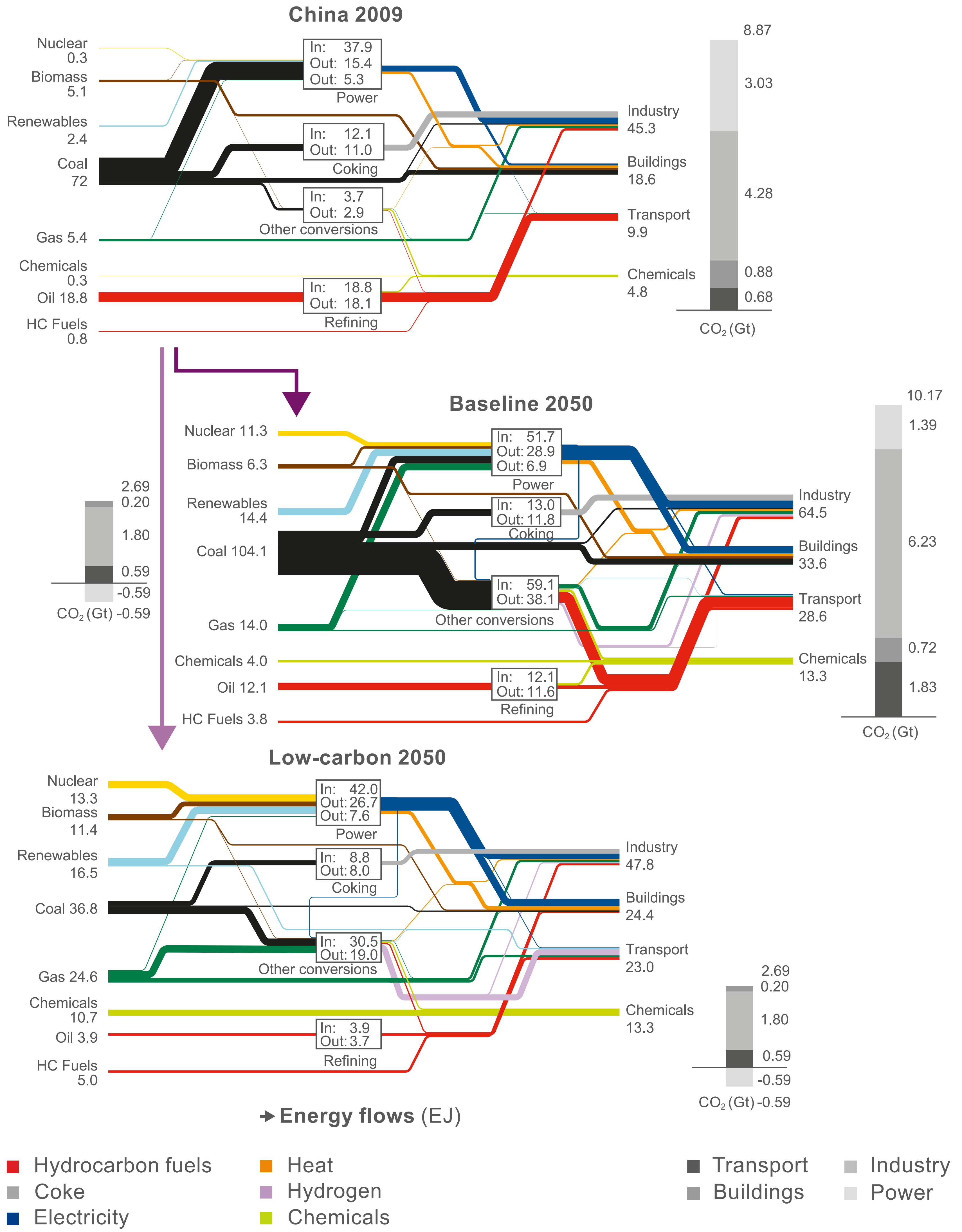


Figure 3: Energy flows from source to service in China in 2009 and in the Baseline Pathway and the Low-Carbon Pathway. Only after 2030 do major differences begin to show up.

In the Baseline Pathway, the Chinese target of reducing the carbon intensity of GDP by 40-45% between 2005 and 2020 is entirely feasible. This indicates that China has already set in motion many useful steps to curb its carbon emissions and to change its infrastructure.[6]

However, with no additional measures, carbon dioxide emissions would continue to grow and reach 12 gigatonnes per year in 2050. This is a dead end, as there is no further push for efficiency improvements and there will be continued investment in suboptimal buildings, economic activities and modes of transport. This can only be undone by huge divestments, which will take years before having an effect. It is for this reason that we believe that China can do better than the Baseline Pathway.

Urban coastal areas are already switching to natural gas to fight smog

Our tools CNEM and IPAC each came up with a somewhat different energy mix after 2030 in the Low-Carbon Pathway. For example, IPAC's results showed a higher use of hydropower and photovoltaics. CNEM deployed more biomass for power. This shows that the low-carbon goals, in spite of being very challenging, still offer room for alternative realisations. The room for manoeuvre may even be larger, since geothermal, wave and tidal energy are almost certainly under-represented in the proposed energy mix. Lacking suitable data,[7] we had to be conservative in the estimates of their costs and potential.

In the Low-Carbon Pathway, coal is partly replaced by natural gas. This would halve the emissions of most processes. The urban coastal areas, in particular, are already switching from cheap coal to clean-burning yet expensive natural gas to fight smog. This robust growth in natural gas demand in recent years has led China to become the third largest liquefied natural gas (LNG) importer and to accelerate development of its LNG and pipeline infrastructure.

About one third of the natural gas is currently imported (53 billion cubic metres), but China also has its own large gas reserves. According to China's Ministry of Land and Resources the technically recoverable conventional natural gas reserves are 3.9 trillion cubic metres. China's unconventional gas potential is even more significant, with recoverable reserves of 25 trillion cubic metres, the largest of any country in the world, and 10 trillion cubic metres in recoverable coal bed methane reserves.

In the light of the recent trend that Chinese cities are switching from coal to clean-burning, natural gas to fight smog our Low-Carbon Pathway may seem rather conservative in assuming a modest growth of 160% in natural gas consumption from 0.114 to 0.300 trillion cubic metres from 2009 to 2030. Yet, this is partly motivated by the current uncertainty about the *economic* recovery rates of China's shale gas resources. But over the longer term, natural gas still holds a significant potential.

The share of nuclear and renewables in China's primary energy mix increases to 15% in 2020, in line with government planning, and grows in the Low-Carbon Pathway to 43% in 2050. Following the Fukushima nuclear accident, China temporarily halted deployment of nuclear power, froze all nuclear plant approvals, and promised that 'full safety checks' of existing reactors would be made. However, after endorsing a new nuclear safety plan at the end of 2012, nuclear deployment is back on track.

There is still much to learn about renewable energy technologies such as wind, solar and geothermal. This means that costs can come down with scale, which is within reach, considering the high level of science and technology in the country. This is why it is sensible that China's policy set firm deployment targets. The expanding domestic market for new energy technologies can drive down costs and make Chinese manufacturing industry excel, offering excellent export opportunities.[8]

The increasing contribution of nuclear and renewables to China's energy mix is conducive to the country's strategy of securing its energy supply and not depending too much on imported energy. For example, the 12th Five-Year Plan for energy development, published in early 2013, included a measure to cap oil imports at 61% by the end of 2015. Next to low cost, energy security is a main driver for the continued use of domestic coal.

Since all of the non-fossil energy, as deployed in the Low-Carbon Pathway, is based on domestic resources, its growth increases energy security for China.

No matter how hard China tries to find alternatives, coal will remain its most important energy source for decades to come. Even in the Low-Carbon Pathway, 31% of primary energy in 2050 will be coal (with 68% in 2009 and 54% in 2030) and fossil fuels will total 40%.[9]

For this reason, continued attention needs to be paid to the efficiency and emission reduction of coal-to-power and coal-to-products technologies, such as substitute natural gas (SNG), olefins and fuels. While the focus may now be on ‘clean air’, it is important not to lose sight of the longer-term goal of ‘low carbon’. And there are other important challenges related to these technologies, such as water use. Although in general there is no water shortage in China, locally groundwater may be depleted by SNG production, with devastating effects to the environment.

In the Low-Carbon Pathway, CCS is inescapable. Chinese leaders do understand the climate change challenge and do seek control of greenhouse gas emissions in China, and consider CCS of significant value for Chinese medium- and long-term plans.[10]

The amount of carbon dioxide that needs to be captured in 2050 is between 1.4 and 4 gigatonnes per year, depending on the deployment of nuclear and renewable energy sources (which is different in the CNEM and IPAC simulations).

Prior to 2030, a large deployment is not necessary. Nevertheless, CCS technologies need to be developed and demonstrated by 2030 in order to reduce their costs as much as possible. The storage potential of China for carbon dioxide should be mapped[11] and validated. The goals of the Low-Carbon Pathway can only be met if today’s many new coal investments are made ‘CCS ready’, so that they can be easily retrofitted once the technology is affordable. Preparing for retrofitting allows China to focus first on clean air and subsequently on low carbon. Smart choices in technology will prevent costly investments or write-offs at a later stage. Our model shows that preparing for retrofit is especially cost-effective for a coal conversion process, where carbon dioxide is usually highly concentrated and relatively easy and inexpensive to capture. That makes it attractive to first build, for example, a coal-to-olefins plant and only do a CCS retrofit when it gets mandated after 20 years. Doing a CCS retrofit on a coal-to-power plant is typically less attractive.

China has much to gain by taking the lead in developing CCS technology, even considering that Western economies started emitting industrial carbon dioxide and have a responsibility too in mitigating its effects. Cheap CCS (retrofit) technology will allow China to continue to use its low-cost coal and to protect its current investments. In addition, we believe that CCS technology and knowhow may become an attractive export opportunity for China – as are other low-carbon technologies.

Carbon capture and storage is an essential bridging technology

CCS has also shown to be promising in combination with the use of biomass for power supply. The use of biomass as fuel for a so-called integrated gasification combined cycle (IGCC) power plant will allow a cost-effective capture of its carbon dioxide emissions. The carbon dioxide that was originally extracted from the atmosphere will then end up in underground storage, resulting in a net negative carbon footprint for the whole process. The Low-Carbon Pathway has a negative emission of 0.6 gigatonnes of carbon dioxide per year in 2050. This partly offsets carbon emissions by industry, which is the sector that is hardest to decarbonise. By that time only 5% of the power sector will still use coal, and more than 50% of the back-up power capacity will still be running on fossil fuel.

The amount of biomass needed – 11.3 exajoules (385 million tonnes of coal equivalent) – does not exceed China’s longer-term biomass availability or global endowment and does not jeopardise food production. However, it does limit the use of biomass for transportation fuels, simply because the same biomass can only be used once.

CCS can be seen as an essential bridging technology that will enable a transition in the long run to an economy based on renewables, nuclear and hydrogen. Hydrogen allows emission reduction in traffic and small industrial plants that may be hard to eliminate otherwise. Significant advances in hydrogen production, storage and application (in, for example, fuel cells) are still needed before hydrogen becomes an economically attractive option. Hydrogen production from coal and later natural gas, in combination with CCS, will facilitate a gradual phase-out of fossil fuels. In the Low-Carbon Pathway, hydrogen plays an increasingly important role after 2030 for transport and industry and as a storage medium for energy from intermittent renewable energy sources.

Following the pathway

Our modelling shows that it is entirely feasible to have a low-carbon energy system by 2050. Yet is this outcome also plausible? We have become confident that this is indeed within reach. China's leaders understand the challenges of climate change well – probably better than their international peers. The top-down political structure may facilitate the necessary transition. However, China's track record in dealing with environmental issues is not spotless, especially when it is at odds with short-term economic or energy security drivers. For example, it has been silently accepted for years that the costs of environmental and natural-resource degradation are close to 6% of GDP.[12] Too often, 'tiān gāo, huángdì yuǎn' (heaven is high and the emperor is far away) has been the way local governments have dealt with environmental directives from central government – and it certainly did not help that government officials were evaluated based on economic growth targets.

The Great Smog of January 2013, when much of northern China was shrouded for weeks in an unhealthy smog, may have been a watershed. For the first time, the effects of unbridled economic growth and the neglect of environmental issues became too serious to ignore. It caused an outcry from the general public. Government was quick to respond and continues to act with a growing number of measures and initiatives to promote 'clean air'. Initiatives that had been lingering for years were swiftly deployed. It is exactly here that China's system excels: when it is needed, the government applies an iron hand to bring change. China's successful drive to improve energy efficiency during the 11th and 12th Five-Year Plans demonstrates its commitment.

It would be prudent to continue existing policies and programmes on energy efficiency and conservation for two or three more Five-Year Plans. This would mean an extension of, for example, the Top-1,000 Energy-Consuming Enterprises Programme. Simultaneously, more effort should be put on low-carbon development, public awareness and lifestyle change, and the promotion of lower carbon transport.

The focus on 'clean air' – that is, a reduction in nitrogen oxides, sulphur and particulates emissions – is also an undeniable step towards 'low carbon'. The proposed switch from coal to natural gas and increased deployment targets for nuclear, hydro, wind and solar are all beneficial for a low-carbon target. If the government can transfer the considerable momentum of 'clean air' to 'low carbon', China and the world will benefit greatly. A practical approach would be the gradual introduction of carbon pricing and the extension of existing targets for polluting emissions to carbon dioxide.

As our modelling studies show, setting a low-carbon target also leads to clean air, improved energy efficiency, less use of energy per unit of GDP, and increased energy security. Therefore, none of the sensible goals that China has currently set for itself will be jeopardised.

China needs to prepare itself now in order to make a difference after 2030 – for example, with CCS technologies. Failure to do so would leave China with no alternative but to follow the bad example of the Western economies in developing a high-carbon energy system, which is difficult to adjust, while Western economies may be well on their way down the low-carbon path by that time. China is uniquely positioned to succeed because it is still expanding its energy system. As a result, new capacity could be low-carbon right away. Today's choices are different from those available to Western economies when building their energy systems. Even without a carbon penalty, wind and solar energy are becoming cost-competitive with fossil energy. China's domestic market, GDP and level of technical development are large enough to allow development of its own cost-effective energy solutions.

In embracing a Low-Carbon Pathway, China could become the greatest greening force in the world.

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Jiang Kejun is Senior Researcher at the Energy Research Institute in Beijing, China. He has been researching climate change and energy policy since 1993. At present, he is working on policy assessments of energy and the environment. His recent projects have included research in energy and emission scenarios for 2030, low-carbon emission scenarios up to 2050, and an assessment of energy and fuel tax. In the past, he worked with the IPCC on a Special Report on Emissions Scenarios.

Alexander van der Made is a senior principal researcher at Shell. He holds a PhD in physical-organic chemistry from Utrecht University, the Netherlands and an MBA from Nyenrode University / University of Rochester (the Netherlands/USA). Since 1989 he has been working in various roles (fundamental research, process development, innovation, strategy, business development) in several Shell companies. He is currently working in Beijing on future energy technologies, energy modelling and setting up R&D collaborations with Chinese partners.

Notes and references

1. Since coal is China's dominant energy source, the energy unit of measurement is typically tons of coal equivalent (tce). 1 ton of actual coal equates to roughly 0.68 tce; 1 million tce = 8.141 terawatt-hours, 29.31 petajoules, or 0.7 million barrels of oil equivalent.
2. Typically an energy technology requires 30 years to grow from being 'available' (at 1,000 terajoules per year) to being 'material' (providing 1% of the world energy mix). See G.J. Kramer and M. Haigh (2009). *Nature, 462*, 568.
3. Kejun Jiang, He Chenmin (2014). 'Energy Options and Predictions for China' (Chapter 31), in: T.M. Letcher (Ed.), *Future energy, improved, sustainable and clean options for our planet*, 2nd edition, Elsevier, Amsterdam, pp. 679-692. Alexander van der Made, Fu Xiao, Jérôme de Morant, Nort Thijssen (2013). *Low carbon options for China* (internal Shell report).

4. See http://www.worldenergyoutlook.org/publications/weo-2010/. We have opted for convergence by 2050 of per capita carbon dioxide emissions burden sharing, a method widely used by modellers to avoid the gridlock caused by political discussions on what metrics to use such as absolute carbon dioxide emissions or absolute accumulated carbon dioxide emissions or accumulated emissions per capita etc.
5. European Climate Foundation 2050 Roadmap, see www.roadmap2050.eu.
6. China has sufficient experience closing down small, inefficient plants to know that this process may cause local social problems and may thus not be actively supported by local governments. It took forceful government actions and massive investments (over $200 billion) in the "eliminating backward and small capacities" campaigns during the 11th Five-Year Plan (2006-2010). In the coal-power sector alone, China eliminated about 72 gigawatts of small power plants, which is more than the total thermal power-generation capacity of the UK. These days government is taking equally determined action to shut down cement, fertiliser and steel plants in an effort to curb emissions and overcapacity.
7. Recently, China increased emphasis on the research and development and utilisation of geothermal energy. For example, on September 12, 2013 the State Council published the 'Atmospheric Pollution Prevention Action Plan'. This plan puts the development and utilisation of geothermal energy in top position for the first time. On November 29, 2013 the first national research institution in geothermal energy was established in Shijiazhuang, Hebei by the China Geological Survey. In the next version of our models, geothermal energy will be represented better.
8. For example, Germany's successful solar photovoltaics programme hinges on cheap solar cells imported from China.
9. For now emphasis in China is on carbon dioxide utilisation (CCUS) such as CO_2-Enhanced Oil Recovery (EOR) rather than plain because utilisation is seen as a way to offset costs. There is a growing awareness that EOR will not be a large enough CO_2 sink ultimately; hence CO_2 sequestration after 2030 will have to involve deep saline aquifer storage as well.
10. Notice of National Development and Reform Commission (NDRC) on Promoting Carbon Capture, Utilisation and Storage Pilot and Demonstration, NDRC Climate Document No. 849, issued April 27, 2013.
11. *Regional opportunities for carbon dioxide capture and storage in China* (2009). Pacific Northwest National Laboratory: Richland, WA; Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, Hubei, China.
12. World Bank and China's (then) State Environmental Protection Agency, 2009 (nowadays Ministry of Environmental Protection).

The long journey The USA at the midpoint of its energy transition

The USA has for 40 years been working to diversify its energy supply and finds itself already halfway into its energy transition. The energy scene has already been reshaped through technology innovation, market innovation and policies to create demand for the new energy technologies. That will continue along with financial innovation enabling the further scale-out of renewables.

> *Michael Eckhart*

The use of fossil fuels in the USA in the 100 years from 1870 to 1970 ignited an unprecedented era of industrialisation, uplifting of the human condition, and mobility. In a sweeping transition, it created a new society that the world had never imagined. The USA discovered abundant petroleum, natural gas and coal, and put them to use. Oil supported automobiles, trucking, railroads and air travel. Natural gas supported industry and home heating. Coal supported low-cost, reliable, electric power generation. All of this occurred in Europe as well, and then spread around the world.

However, the unintended consequences of such massive and widespread combustion of fossil fuels included environmental destruction from extraction, processing and transportation; air pollution in the form of particulates, sulphur oxides, nitrogen oxides, carbon dioxide, elements such as mercury and water consumption and pollution.

A second transition has begun, in the form of a concerted effort by government and society at large to address and stem these unintended consequences. In my view, the USA and much of the world is now 40 years into a 100-year transition to a clean-energy-based future economy. It is a process of societal change that is taking time. There are two major efforts currently under way. One is the defensive strategy of restrictions. Through regulations, we are requiring fossil fuels to meet higher standards of pollution control, thus adding cost that reduces their economic attractiveness, increases their financial risk and, in some cases, precludes their use. The other is an offensive strategy of substitution. Through incentives and mandates, we are encouraging the adoption of new technologies such as renewable energy and fuels, energy efficiency, energy storage, and 'smart' ways of managing our energy supply and infrastructure.

It is, in many ways, an economic war between the incumbent fossil fuels and the new technologies, driven by public policies that are having a fundamental impact on the way society works. In my view, we are in the midst of a three-phase transition. We are coming from a 'cost-based' energy industry that set prices based on the cost of extraction, processing, transportation and delivery plus a profit to yield a return on capital investment. This has changed into a new ‘market-based’ energy system that lets market forces override the old cost-plus-profit model, adding efficiencies and liquidity to the market and offering greater risks and rewards. We are now seeing the advent of a ‘values-based’ energy economy that adds public sector payments such as tax credits and other incentives such as tradable renewable energy credits and carbon credits for the public benefits of ‘non-pollution’ and ‘non-emissions’.

In every aspect of these transitions is the presence of new technology that, through public policy, is being pushed and pulled into use, and the presence of old technology that public policy is seeking to block.

The past 40 years

The USA had just survived the crisis over racial discrimination in the early 1960s; the cultural crisis between the Greatest Generation of World War II and the baby boomers culminating with Woodstock in 1969; and the environmental crisis that led to the Clean Air Act in 1970 and the Clean Water Act in 1972. In 1973, the Vietnam War ended just as a new international energy crisis − the Arab oil embargo − unfolded. The country was already a bit frazzled when it hit.

And at the same time, the USA was contending with the Cold War, nuclear proliferation, space exploration, and internal issues such as education and poverty.

Three years later, in June 1976, I joined the energy consulting practice of Booz, Allen & Hamilton. I was young and impressionable, and struck with the realisation that energy is, in fact, the basis of modern society, that disruptions to energy supply represented fundamental threats to our country, and that increases in pollution represented fundamental threats to the existence of society as we know it.

There was a national consensus forming that only through new technology could society escape the control of the cartel owners of fossil fuels and rise to a higher and more secure level of happiness and economic prosperity in a cleaner world. I was hooked on the thesis that through new energy technology we could and would escape the threats and embrace a better society for all.

Looking back to the 1970s and seeing what has happened, it is my view that we have experienced four major sweeping phases of innovation. It started with over 35 years of technology innovation, which was followed by an overlapping 25 years of market structure experimentation and innovation with, for example, utility deregulation. Then came an overlapping 15 years of policy innovation seeking to drive demand for the new technologies with feed-in tariffs and other incentives, which in turn was followed by an overlapping five years of financial innovation in reaching the capital markets – with, for example, green bonds – which is ongoing today.

New energy technology push of the 1970s

The first phase began under Presidents Richard Nixon, Gerald Ford and Jimmy Carter. The USA and other OECD countries formed the International Energy Agency to deal with the new imperialism of the OPEC cartel, and began to establish and build strategic petroleum reserves. The USA created the Department of Energy in 1977 by merging the Federal Energy Administration, the Energy Research & Development Administration, the solar technology programmes of NASA, and advanced coal research programmes from the national labs.

Research, Development and Demonstration (RD&D) budgets were passed by Congress for wind power, solar energy, geothermal energy, hydropower, biomass energy, energy efficiency, fuel cells, advanced oil and gas development, advanced coal technologies, synthetic fuels such as coal gasification and liquefaction, shale oil and gas, advanced nuclear power such as breeder reactors, and others. The three Presidents called on American scientists and engineers to rise to the occasion and create a new technology-based future. It was an activist period.

There was a push to build a fleet of nuclear power plants using light-water reactor technology and develop the long-term technology called the breeder reactor. New laws were passed, such as the Public Utilities Regulatory Policies Act (PURPA), which required utilities to purchase power from non-utility power plants that were using either co-generation or renewable energy (then called alternative energy). We adopted tax incentives to spur initial investment in wind power, solar energy and other advanced technologies (much too early). We adopted new automobile efficiency standards and many other initiatives to make our society more energy-efficient.

In 1979, the Iranian crisis led to a second massive increase in oil prices and destabilisation of geopolitical forces, plus the hostage taking of 52 American diplomats and citizens in Teheran. In my view, this caused the American people to be 'fed up' with the energy crisis. Enough was enough.

Then in the 1980s, there was a reversal of policy and fortune. Perhaps the American people were tired of the strife and stress of the energy and environmental topics by then. After all, for 100 years, the energy industries had said, "Just flick the switch and fuel your car, and don't be concerned about how it gets there; we will take care of the details." And now the government, from the President on down, was saying that we all have to be concerned about these things. Of course, the average American does not even know what electricity is, much less how it is made and delivered.

In 1980, President Reagan ran on a theme of "getting the government off the backs of the American people". The budgets for energy RD&D programmes were slashed. Then the bottom fell out as oil prices collapsed in 1985. Natural gas prices collapsed in 1986, making renewable energy and other new technologies completely uneconomic. The lights went out on the great new energy technology push of the 1970s.

Market deregulation in the 1980s

One law that was enacted back in 1978 continued on and is the backbone of the utility industry structure we have today: PURPA, which led to the independent power producers as we know them today.

PURPA was initially used only by small hydropower projects. Then, in 1981, General Electric (GE) received a request from Big Three Industries in Houston for a 300 megawatt natural-gas-fired co-generation power plant under PURPA. Looking back, one can see that this was the beginning of a revolution.

GE had to align its operating divisions – gas turbine, steam turbine, transformer, installation engineering, and GE Capital – to submit a joint bid for a turnkey power plant with financing, which had never been done before. This was actually forbidden by a Justice Department decree from the 1950s which did not allow GE Capital to finance the sale of GE equipment. GE got clearance from the Justice Department, got approval from the GE Board of Directors, formed a power-sector-wide marketing council (of which I, as strategic planner of the power sector, was the secretary), and hired the law firm Skadden Arps in New York City to prepare the many legal documents. These included the site lease, gas supply agreement, gas pipeline capacity agreement, engineering, procurement and construction contract, operations and maintenance contract, power sales agreement, steam sales agreement, and all else needed to provide a $300 million (€270 million) power plant with no investment by the host customer.

An interesting anecdote is that the draft legal documents came back for review stating that GE, not Big Three Industries, would be on the hook for the loan from GE Capital if the project failed. Big Three Industries would only sign the steam sales agreement. Needless to say, the lawyers were sent back to rewrite the loan agreement so that it would be 'non-recourse' to GE, just depending on the project cash flows and looking through to the creditworthiness of Houston Lighting & Power for purchase of the electricity and of Big Three Industries for purchase of the steam. That became the basis of today's worldwide independent power producers, financing power plants on a non-recourse basis and looking through to the creditworthiness of the off-takers. It happened because GE declined to be recourse to GE.

This basis of doing business under PURPA swept the US power markets in the 1980s as companies like AES, Dynegy, Calpine, Ormat and many others were founded to develop non-utility generation plants, while the utility companies were hounded by their regulators to implement 'least-cost planning' and 'integrated resource planning' which pushed them to issue requests for proposal and accept bids from the non-utility generators – later called independent power producers. This also coincided with a period of very low natural gas prices, in the neighbourhood of $2.00 per million Btu (€0.18 per cubic metre) and the delivery of new, highly efficient gas turbines by GE, Westinghouse, Siemens, ABB and other suppliers.

It was one of those perfect storm moments. PURPA required utilities to buy the output from non-utility generation plants. A legal construct of non-recourse financing had been created. Low-cost, highly efficient gas turbines were becoming available, and natural gas prices were at historical lows. Independent power producers swept the nation with gas-fired plants in the late 1980s to 2000. This development also moved to Europe in the 1990s and to the rest of the world in the 2000s.

Independent power producers swept through the USA with gas-fired plants

One of the turning points was the Energy Policy Act of 1992 (EPAct 1992), which had begun life as the 1987 Independent Power Producer Notice of Proposed Rulemaking at the Federal Energy Regulatory Commission. EPAct 1992 had two vitally important provisions. It eliminated the PURPA limit of 49% ownership of non-utility generation plants by utility companies, and created a new category of exempt wholesale generators that could be any kind of power plant (lifting the PURPA requirement of co-generation or alternative energy). This opened the door to the deregulation of power generation over the coming decade. EPAct 1992 also enacted the Production Tax Credit for wind power. All of these elements would be key to the US power markets 10 years later.

EPAct 1992 kicked off a decade of restructuring the electric utility business model under the theory of ‘deregulation’ and ‘market forces’. A widespread reorganisation of the utility industry ensued, with attendant massive redirection in the flow of capital from utility balance sheets to the independent power producers.

It happened by the creation of new corporate structures. Utilities established holding companies as parent companies, which then created sister 'non-regulated' generation subsidiaries that could develop and own independent power producers anywhere in the country *except* in the service territory of the regulated sister company. This was decided in a famous case in the Supreme Court about Mission Energy doing business with its sister company Southern California Edison. One saw, for example, Baltimore Gas & Electric (BG&E) form a parent holding company called Constellation Holdings, which created a non-regulated independent power producer subsidiary called Constellation Energy, which developed, financed, owned and operated power plants everywhere except in BG&E's service territory. Many others did the same.

The late 1990s was a period of tremendous change, with state regulators deregulating the utilities at a wholesale generation level and, in a few cases, at the retail level (in Maryland, I can still buy wind power from non-utility sources, and do). This occurred everywhere except in the South-east, where utilities remained fully integrated. Then there was the restructuring of grid management from power pools and reliability regions into independent system operators and transmission system operators, the creation of electricity trading markets, and a further push towards procurement of power from independent power producers (many being subsidiaries of other utilities). But the deregulation movement stopped mid-stream when things crashed in California and 'the smartest guys in the room' at Enron went bankrupt in December 2001, taking down the accounting firm Arthur Andersen and many others with it. Today, the utility industry is in a state of structural disarray, ranging from fully integrated utilities in the South-east, to partially deregulated utilities in most of the country, to fully deregulated (and then again reregulated) utilities in Texas, Maryland and several other states.

The early shift to renewable energy was a part of these changes, and was especially rooted in California, where solar energy subsidy programmes were enacted in 1998.

Driving demand in the 2000s

While the attention of the USA was consumed with utility restructuring, the rest of the world was shifting to the theme of global warming, adding climate change to the pre-existing alarm about pollution. The 1996 Kyoto Protocol set the stage for European leadership on the matter. It was never ratified or enacted by the USA. It was in Europe where governments seriously began to address global warming and climate change, calling for a shift from fossil fuels to renewable energy (such as wind, solar, hydro/ocean, geothermal and biomass) and greater investment in energy efficiency.

Germany established the feed-in tariff in a series of legislation from 2000 to 2004, championed by legislator Hans-Josef Fell as a mechanism to attract long-term debt capital to renewable energy projects. I was a participant in the debate and writing of the feed-in tariff in Germany, and can say first hand that it was not intended to be a ‘subsidy’ as people call it today. It was designed to attract low-cost debt capital to renewable electricity to help lower the cost of electricity. It only became a subsidy over time as the cost of renewable energy systems came down faster than governments lowered the feed-in tariff rates. Indeed, the German feed-in tariff was based on US regulatory practice – it is PURPA with Nuclear Pricing called ‘revenue requirements’. I shared these US practices with the Germans in 1998-2004, and it was a basis for the feed-in tariff.

One interesting anecdote of the times is about how the feed-in tariff started out as a five-year commitment and became a 20-year commitment of guaranteed revenues. After a day of discussing the need for 15-year loans to finance solar energy, the late Hermann Scheer, a member of the German parliament (*Bundestag*) and solar energy leader of Europe, asked me how to get Wall Street to finance his solar energy revolution. I said, “Take the five-year feed-in tariff and make it 20 years, and then stand back and watch the debt capital come in.” He asked, “Where is this written?” I said, “I don’t know. It is just a basic lending practice that you need assured cash flows longer than the term of the loan.” He said, “Come with me,” and we walked down the street in Bonn to the offices of KfW, Germany’s development bank. We went up to the president’s office. They spoke in German. Then the president said in English, “Yes, Dr Scheer, Mr Eckhart is correct.” So Hermann Scheer said he would get the change made by the legislature, and the president of KfW said that, if it happened, he would establish a new loan programme for solar energy in Germany, which he could do on his own authority. And that's how it happened. Hermann Scheer went to the *Bundestag* and saw a bill that was passing easily that week. He added an amendment that no one seemed to mind. It said, "For previous law abc, in line xyz, change the number 5 to the number 20." It was the most important piece of legislation in the history of renewable energy, and the legislators did not know what they were voting on.

The philosophy that governments must enact policies to support a transition to renewable energy swept the OECD countries in the decade of the 2000s. Whereas the utility deregulation movement flowed from the USA to Europe, the renewable energy movement flowed from Europe to the USA. For example, the American Council On Renewable Energy (ACORE) was founded in 2001 as a direct outgrowth of conditions in Europe.

The renewable energy movement flowed from Europe to the USA

Things snowballed in the USA as 29 states and the District of Columbia enacted Renewable Portfolio Standards that required utilities to have a specified fraction of their electricity from renewables by designated dates. Even today, this is driving many utilities to procure renewable energy from the independent power producers.

In addition, some 45 states adopted Net Metering, a rule that allows customers to generate their own electricity and offset their retail purchases of electricity from their utility. Net Metering, like PURPA, would prove to be a landmark change. Under PURPA, independent power producers sell electricity to utilities on a wholesale basis and get paid wholesale rates (typically \$0.04-0.08, or €0.035-0.07), which are then marked up and resold to retail customers at retail rates. Under Net Metering, customers offset their purchases of electricity from the utility, in effect selling the solar electricity at retail rates (\$0.08-0.16, or €0.07-0.14, and in some areas much higher).

These three laws – PURPA, EPAct 1992, and state-level Net Metering – establish the legal structure for the transitions we have experienced and are still experiencing today. Then, the Energy Policy Acts of 2005 and 2007, the Economic Act of 2008, and the American Recovery Act of 2009 added tax incentives, financing guarantees, mandates, and other encouragements for investment in clean-energy solutions.

Through the 2000s, things were building rapidly in renewable electricity in the USA, and this was happening in renewable fuels as well. In 2000, the USA produced less than 1 billion gallons (4 billion litres) per year of corn (maize)-based ethanol. Then, the Environmental Protection Agency ordered the petroleum industry to blend in ethanol as an oxygenate to replace the chemical methyl tert-butyl ether (MBTE), which had proved to be carcinogenic. Production rose quickly to meet the regulatory requirement. Then, the Energy Policy Act of 2005 (EPAct 2005) established the Renewable Fuels Standard on blending ethanol into petrol. Corn (maize)-based ethanol production boomed in the 2005-2010 period, reaching 13.5 billion gallons (51 billion litres) in 2010, representing 10% of the petrol market – and also taking 100% of the growth of the petrol market for 10 years. In addition, there was a booming market for biodiesel made from food crops and waste.

International growth in renewable energy was even greater. Europe exploded with demand for wind power, solar energy and biomass energy after the 2003-2004 era when the feed-in tariffs were enacted. This was led by the work of Germany’s Wolfgang Palz, head of renewable energies at the European Commission for more than 25 years, who among other things wrote a landmark white paper in 1997 that kicked off the European move to renewable energy. There was also great leadership from the European Renewable Energy Council, chaired by Arthouros Zervos and managed by Christine Lins.

China enacted a Renewable Energy Law in 2006 that was written by Li Junfeng of the Energy Research division of China’s central planning agency, the National Development and Reform Commission. China immediately launched a massive investment in wind power and hydro power, and supported a new manufacturing industry making wind turbines, hydro turbines and solar photovoltaics.

Financial innovation after 2008

Then came the financial crisis in 2007-2008. The USA enacted economic recovery legislation which, in September 2008, extended the wind Production Tax Credit and enacted the 30% solar Investment Tax Credit.

The American Recovery legislation in February 2009 promulgated loan guarantees, a cash grant in lieu of tax credits, and massive increases in RD&D for renewables and efficiency. This occurred in large part because after President Obama was elected in November 2008, his climate-oriented transition team led by Carol Browner worked in December and January to prepare a climate and clean-energy policy initiative. When the government needed a 'stimulus package' to pass on a crisis basis in February 2009, the transition team's programme was ready to go, and the President introduced it as his economic recovery package.

Several years later in 2011, in a meeting between the White House Staff and ACORE's US Partnership for Renewable Energy Finance (US PREF), the Chief of Staff said, "Understand what pressure the President is under from the fossil and nuclear industries, because you guys [from renewable energy and energy efficiency] got 100% of the stimulus funding in 2009, and they are demanding that it is their turn. So don't be surprised to hear the President call for an 'all the above' energy policy for the country. Just understand where we are on this now."

The Chief of Staff was correct. Renewables and efficiency received all of the stimulus incentives. This resulted in over 50,000 megawatts of renewable electricity projects getting built under the loan guarantees, tax credits, cash grants, and a vast array of new technologies including concentrating solar power, advanced batteries and electric vehicles, and the new, advanced biofuels (previously called cellulosic ethanol). While the US economy sank and struggled in the 2008-2012 period, this was ironically the 'boom period' of renewable energy and energy efficiency investment.

Energy independence in the 2010s

The energy transition continues to evolve very rapidly today. Oil prices have stabilised recently at about $100 per barrel, after being at $25 plus or minus 20% throughout the 1990s. This has improved oil company profitability tremendously, but has also attracted many forms of alternative oil supply such as enhanced oil recovery in old fields, deep-water exploration and production, shale oil, and oil sands from Canada. Oil prices might sag in the coming years due to the new production that came on at $100, but the transition from $2.00 in 1973, to $25 in the 1990s, to $75-100 in the 2000s seems to be in place. A current issue in the oil industry is the continuing decline in the productivity of new capital investment. It takes more and more capital to bring on the next barrel of supply, combined with new challenges from climate advocates that such investment is unwarranted because much of the oil reserves will be stranded by climate policy. On the demand side, it looks like a slow decline as market share will be taken by ethanol, electric vehicles and natural gas. It is a challenging time in the oil business.

Natural gas supply is going through a metamorphosis following the emergence of hydraulic fracturing ('fracking') and horizontal drilling in shale formations in the USA and possibly around the world. Gas prices have dropped to the range of $4-5 per million Btu (€0.18-0.23 per cubic metre) due to the oversupply, and the topic of liquefied natural gas (LNG) has been turned on its head, from imports to proposed exports. A world market in LNG is being discussed, against a backdrop where gas prices are $4 (€0.18) in the USA, $8 (€0.36) in Europe, $12 (€0.54) in China, and $16 (€0.72) in Japan (in dollars per million Btu and euros per cubic metre). Natural gas and LNG are in a period of rapid change, capital investment and market creation – a dynamic time.

The situation in coal is also in transition today, with consumption in the USA declining due to environmental regulations on local pollution, mercury and carbon emissions, all of which adds cost, further disadvantaging coal versus natural gas. Oddly enough, given Europe's goals for climate, coal consumption is increasing there because gas prices are higher, and cheap coal is being imported from the USA, complicated by gas prices from Russia. China continues building coal-fired power plants but has declared war on pollution, much as the USA did in 1970, so coal consumption could be peaking soon. Many are concluding that the world's consumption of coal will be peaking in the near future and then entering a long-term decline, led by the USA.

North America is looking at becoming energy independent within 5-10 years – more than 40 years after President Nixon first called for it – and the perceived threat of oil supply instability from OPEC has, for all intents and purposes, diminished.

Indeed, the Middle Eastern countries are worried about running out of oil in the coming generations, and are rushing to replace their consumption of oil for electricity generation with natural gas and renewables.

New commitment to renewables

Meanwhile, circumstances are changing everywhere. Europe is backing off its earlier commitment to renewables, looking out to 2030 goals with installation levels about half of what they have been. China continues ahead with terrible levels of air and water pollution and booming levels of renewable energy installations including hydro, wind, and recently huge levels of solar photovoltaic installations. The development of renewable energy is likewise booming in South Africa and to varying extents across all of Africa. Installations are starting to be made across Latin America. Australia has had a boom in wind and solar, but this is now cooling off as the government has reversed its policies.

This globalisation of renewable energy policy has been and is increasingly fostered by support from the United Nations, the International Renewable Energy Agency, the Renewable Energy Network for the 21st Century (REN 21), and more recently by the development finance institutions such as the European Investment Bank, Asian Development Bank, International Finance Corporation and others.

One of the great phenomena of the 2010s decade is innovation in clean-energy finance, as new banking regulations are pushing banks away from ‘high-risk’ renewable project finance, just as institutional investors in the capital markets perceive the same as ‘low-risk’ investment opportunities and increasingly purchase shares in so-called yieldcos, asset-backed securitisations in solar and efficiency, and green bonds.

The USA is experiencing rapid changes in renewable energy installations due to current conditions and incentives. The wind power

Production Tax Credit has expired again, but is good for projects that started construction by the end of 2013, so construction continues but new development has declined; the future is uncertain. The boom of new concentrated solar power projects with federal loan guarantees is coming to an end. There are no additional projects in the USA and developers are looking to the Middle East and North Africa (MENA) region for growth. A perfect storm for immediate growth of photovoltaic residential rooftop installations has occurred because of the confluence of Net Metering, a 30% solar Investment Tax Credit and accelerated depreciation, the recent sharp decline of photovoltaic module prices from China, and low interest rates. The advanced biofuels industry is gradually emerging as the first commercial-scale facilities are being financed (with difficulty).

In sum, the current energy transition is one of rapid change in this decade of 2010-2020, all due to equally rapid changes in the fundamental drivers: new technologies ready for adoption, historically low cost of capital, and government policies that favour cleaner energy, economic growth and jobs.

The next 40 years

We know that the future is uncertain, but it is not totally uncertain. The world economy needs a reliable supply of energy resources, so there will be a continuing demand for fossil fuels.

The world also wants a cleaner and more sustainable future, and is trying through public policy to move away from fossil fuels and their attendant pollution and impact on global warming and climate change.

The world is in a great contest with itself, trying to choose between a strong economy based on lowest-cost energy and a sustainable society based on more expensive but cleaner energy. This contest will be played out in the next 40 years, and on into the 21st century. The uncertainty is not the direction of things − the direction is known. In my view, in the absence of ‘black swan’ events such as nuclear war, society is moving towards sustainability. The question is how fast and to what degree. Technology is coming faster and faster, not slower.

We will see renewable energy technologies being deployed. We also will see deep-water drilling for oil and fracking for natural gas. We will see carbon capture technologies being developed for coal.

We have experienced the Three-Mile Island, Chernobyl and Fukushima nuclear power accidents and the attendant social rejection of nuclear power in the USA, Europe and Japan. However, China is proceeding with nuclear power and will become the principal supplier to the world, so the future course of nuclear power is a big question.

The 2020s should be the deciding decade. The generation that grew up on oil, gas and coal from the 1950s to the 1980s will soon be retired, and the generation that grew up on renewable energy in the 2000-2020 era will soon be taking over. The tenets of sustainability will experience a generational change, and become the new normal.

An electric utility executive said in his retirement speech to the industry's research community in 2010, "Your job is to keep the nuclear and coal options alive, while wind, solar and natural gas take everything for the next 10 years." In my view, his sense of the future was correct, and his sense of what will win the market was correct, except that I believe it will not end in 10 years; it will continue.

The move to cleaner sources of energy will continue because there are other technology enablers entering the market at the same time: digital controls, smart grid, demand response (controls), more energy efficiency, and energy storage allowing 'the system' to be better optimised and controlled.

The future of nuclear power is a great uncertainty, as it has transitioned from being an electric power option to being an element of geopolitical power and influence. Its future is in a different orbit from the others.

So the 40 years from 2010 to 2050 will be the period in which the war between fossil fuels and their new competitors will be fought. Both sides are suited up and on the field of play, head to head.

The end game

As stated at the beginning, I believe we are 40 years into a 100-year transition to a clean-energy economy. But then what happens? Just to get a sense of the end game, let's ask how will we be powering society 300 years from now?

Of course, here comes the saying that the Stone Age did not end because they ran out of stones. Technology intervened to move society forward. In those days, it was the wheel, fire and metals. Today it is renewable energy, fission, fusion, the Internet, cloud computing, smart grid, demand controls, and many others we cannot imagine. We cannot see all of the new discoveries, but we can be confident that they will appear, yielding the next great uplifting of the human condition.

In the end, after fossil fuels, I believe we will be running the world on nuclear power, solar energy and hydrogen, with contributions from wind power, hydropower, geothermal energy and ocean power. The Age of Pollution will be over. The Age of Sustainability will be in place. The question is, how soon will we get there?

Michael Eckhart is a managing director and global head of Environmental Finance at Citigroup in New York. In this role he supports Citi's goal to be the leading financial services firm in renewable energy, energy efficiency, clean water and related areas. Previously, he was the founder and president of the American Council On Renewable Energy (ACORE) in Washington, DC. Earlier, he developed financing for solar energy under the SolarBank Initiative in South Africa and India, was Chairman & CEO of the power generation development firm United Power Systems, vice president of the venture capital firm Areté Ventures, a strategic planner of General Electric Company's power systems sector, and a principal with the energy practice of Booz, Allen & Hamilton where he conducted many of the original national studies on new energy technologies in the 1970s.

Facing a wealth of renewables
How Germany can advance its *Energiewende*

Germany is the first country that at times has to cope with an excess of renewable power. New technologies and market innovations will be needed to progress the energy transition.


> *Michael Weinhold and Klaus Willnow*

In the autumn of 2010, the German government changed the country's energy policy so drastically that the policy soon earned the name *Energiewende*, literally the 'energy turnaround'. This energy transition started with the goal of a carbon dioxide reduction of 40% by 2020 and as much as 80-95% by 2050 (both relative to 1990, following previously agreed European Union targets).

This would of course have major consequences: given that transport will be mostly fossil-fuel based for decades to come, reaching this goal would require the almost complete decarbonisation of the entire power sector. To achieve it, a number of energy-related targets have been adopted: relative to 1990, power consumption is to be reduced by 10% by 2020 and 25% by 2050; the amount of renewable energy in the power mix is to be 35% by 2020 and 80% by 2050. In addition, in the wake of the Fukushima nuclear disaster in 2011, the German government decided to phase out nuclear power by 2022. To avoid energy shortfalls, much new generation capacity will be required.

There is a broad consensus in Germany that these goals should be met mostly by energy sources located in Germany, and by continuing the country's pioneering role in the use of renewables. The German electrical power sector is widely recognised for being a forerunner in decarbonising the energy system. As the *Energiewende* has a drastic impact on the power sector, this is the main focus of this essay, but we also consider cross-over effects to other infrastructures.

In 2014, almost 27.3% (157 terawatt-hours) of the electrical energy produced in Germany came from renewable energies, 56% from wind and solar power and 44% from hydropower and various forms of bioenergy. After coal, renewables are now the second largest electrical energy source in Germany. Beyond the power sector, biomass (both solid and gaseous) also has a significant role in the provision of heat.

A main driver of the expansion of renewables has been the promise of favourable feed-in tariffs, guaranteed by law for 20 years, for the operators of renewable energy installations. The tariffs, differentiated by technology and location, are designed to make economic operation of the installations possible. Although they are constant for any individual installation, every year the new installations that come online start with lower tariffs. This keeps the pressure on manufacturers and operators to follow the learning curve of new technologies and make the installations less expensive and more efficient. The policy thus aims for renewable energy to become established in the market without an incentive mechanism in the long term.

The above-market price that operators receive for electricity from renewables is passed on to the transmission system operators, and again to the electricity supply companies, in the end resulting in a surcharge on each kilowatt-hour they sell to the end users. Owing to the enormous amount of incentivised renewable power production taking place, the overall sum of incentives paid out to the owners of renewable power plants will probably be more than €27 billion ($30 billion) in 2014. In 2015, the surcharge was €0.062 ($0.068) per kilowatt-hour, and this already exceeded the average wholesale price of electrical energy from non-renewable sources, which stood at about €0.04 ($0.045) per kilowatt-hour.

Energy-intensive companies can apply for partial exemption from this surcharge, so that they will not suffer an undue competitive disadvantage as a result of comparatively high domestic energy prices. Residential customers, on the other hand, have to pay the full surcharge for every kilowatt-hour. This has become controversial, and has led to intensive discussions about the feed-in law and the design of the electricity market.

Meanwhile, the rest of the energy market is hardly quiescent. Low prices for coal and lignite, and for carbon certificates in the European Union Emissions Trading Scheme, have made it possible for power plants using these energy sources to outcompete power plants burning natural gas. Many gas-fired power stations are now idle for many hours a day and turn losses. Hence the operators of many of these have applied for permission to shut them down. In spite of the growing share of renewables, the power sector's carbon emissions have actually risen from 2009 to 2013. In 2014 the carbon emissions have decreased the first time after four years. They are now the second lowest level since 1990.

The shuttering of natural gas plants can be problematic, even to the extent that the regulators may forbid it, in which case a plant will be operated by the transmission system operator. The reason is that there are only small amounts of energy storage in the electricity grid, and this presents a challenge in circumstances when energy from renewables isn't being generated. Wind power can be generated only where and when the wind blows. Solar power is generated only when the sun shines. Hence, network operators cannot rely on their permanent availability and have to make arrangements accordingly. Some part of the peak load plus an adequate reserve capacity must be covered by the conventional power plants fleet. Also, as will be discussed later, gas plants may play a major role in an energy storage scheme where surplus electricity is used to produce hydrogen from water.

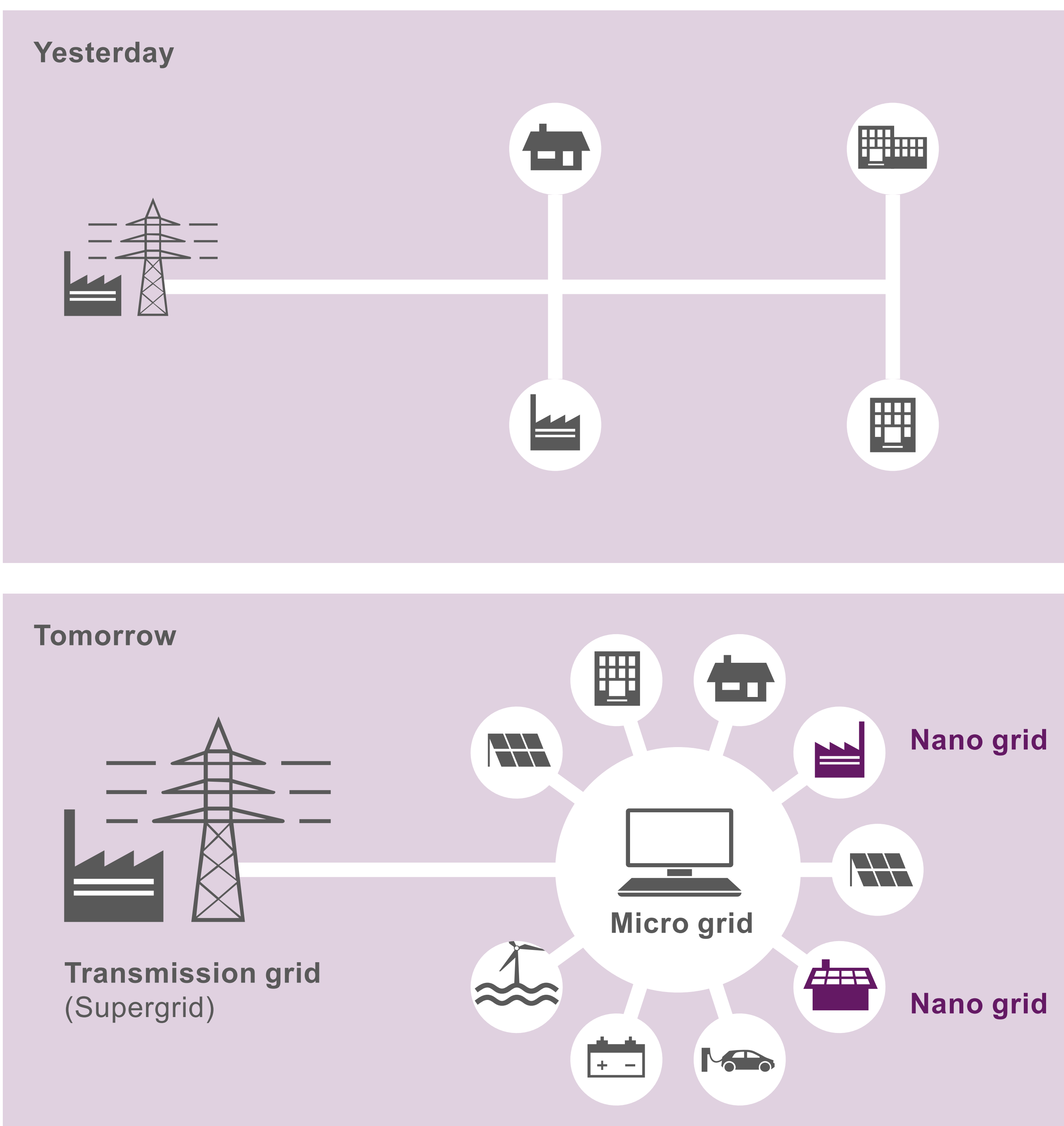

Figure 1: Evolution of the electricity system from a set-up based on central power plants, via a complex system of central and distributed power plants, to an energy cell structure.

For this reason, part of the ongoing discussion about redesign of the energy market also centres on possible incentive mechanisms to provide a profitable environment for system-relevant conventional power plants.

The geography of renewables

Another unresolved question is the proper share of centralised versus distributed power generation. Whereas coal and gas plants deliver their electricity to the high-voltage grid used for long-range transport, many of the wind turbines and photovoltaic installations are connected to the medium- and low-voltage electricity grid, the part that is used for distribution to consumers. Most of the renewable installations were designed and configured to ensure maximum revenues for their owners, without much thought or regulatory input concerning the overall optimum operation of the electricity system. In some distribution grids, under sunny conditions the large amount of roof-top photovoltaics even causes the aggregate power flow to reverse. In sum, there is now a huge complexity concerning location and type of power generation in the German electricity grid, extending to all voltage levels (see Figure 1). This does not help to achieve transmission system enhancement or load flexibility.

There is a strong geographical component to this complexity. Owing to the large build-up of renewables far away from the load centres – especially wind power plants – electricity must be transported on average much farther today than just a few years ago, and no end to this trend is in sight. In past decades, the grid was built around the main fossil and nuclear production plants, giving rise to a network that is not well adapted to the new sources.

Grid expansion is therefore urgently required. According to a study by the Deutsche Energieagentur (German Energy Agency), Germany will need up to 3,600 kilometres (2,200 miles) of additional extra-high-voltage lines by 2020. Some of these lines could be high-voltage direct current (HVDC) transmission, which carry twice the amount of direct current power compared with alternating current transmission on the same trajectory. An 80% share of renewables by 2050 would necessitate significantly more lines than that, and we will have to think about entirely new technical solutions, for example the use of large-scale energy storage with hydrogen.

Overcoming intermittency

As mentioned earlier, when it comes to harvesting the increasingly important renewable sources, fluctuations in their availability, either day-to-day or from one season to another, pose a number of challenges. How these can be overcome will depend on circumstances that will differ from country to country. So there is no silver bullet, but there are five key elements that have to be considered, in various forms and to different degrees, in any solution.

Photovoltaic systems and wind turbines can act as one virtual power plant

The first key element is renewable power generation itself. The most important consideration is that power must be produced at a competitive cost in the medium-to-long term and no longer be dependent upon subsidies. In addition, differences in the nature of the renewable resources have an enormous influence on the importance of the other key elements.

For example, a renewable power share of almost 100% in overall production in Norway poses few challenges, nor do Switzerland or Austria have problems with a 50% share – because all these countries have enough readily controllable hydropower.

In Spain, by contrast, the grid operator Red Eléctrica, which has a green power contribution of 35%, reports problems in coping with fluctuations in wind power, which accounts for around half of the renewable power generated nation-wide.

In such cases, new concepts of market integration are needed. For example, power plants with different energy sources could be operationally combined into so-called virtual power plants, which integrate photovoltaics systems, wind turbines and combined heat and power (CHP) plants so that they act as one plant in the grid. An IT-based management system controls the individual power plants and trades the combined output on the electricity market, just like any other power plant. The operation of the individual power plants, which may be spread out over a large geographical area, can be made quite predictable, with, for example, targeted analysis of weather.

The second element is the power grid, which must not only be expanded on a national scale, but also extended across borders. For instance, a very attractive solution for the problem of fluctuations in wind energy generation seems to be the connection of the wind farms in northern Germany with Norway via an HVDC cable, so that excess wind energy can work in combination with its huge hydro reserves (> 80 terawatt-hours). If there is excess wind power in Germany the hydropower plants could lower their output so that German wind energy may be used in Norway. If there is not enough wind in Germany, power flows from the hydropower plants through the HVDC lines to Germany.

In continental Europe, a super-grid connecting generation and load centres much more efficiently than it does today has huge systemic attractiveness. It will allow countries to build wind power plants and solar power plants where they have the best energy yields and highest capacity factors, at many locations. Conditions at these dispersed locations will average out in such a way that only minimum back-up conventional power generation or energy storage is needed. Examples are off-shore wind farms in the North Sea and solar power plants in southern Europe.

In addition, an off-shore transmission grid connecting off-shore wind farms with the neighbouring countries would allow for re-routing of electricity to the load centres where it is needed. Low-loss long-distance lines using HVDC that could serve as the backbone of the grid are available and have long been tried and tested; all necessary components are available today. Hence it is only a matter of political will and regulation to begin the design and building of a super-grid.

In power distribution, the already commercially available controllable transformers to cope with reverse power flows may be needed at certain locations. Looking ahead, we may see the application of low-voltage direct current for electricity distribution in commercial buildings or at residential buildings. This will make sense due to the changing load patterns in these domains. More and more of the load consists of LED-lighting and direct current electronics, while on the supply side roof-top or building-surface-mounted solar panels already generate electricity as direct current. There are already industry initiatives formed to foster the integration of these two trends.

Third, in addition to expanding the transmission networks, balancing generation peaks and troughs may be accomplished by controlling consumption in an intelligent distribution network, known as a smart grid. More than three quarters of a regular household's power demand goes into space heating and maintaining a supply of hot water. Both of these can be managed with comparatively low rates of energy use changes, or even time-shifted by hours. This approach offers great potential: a high-efficiency electric heater, for instance in the form of a heat pump, could be integrated and controlled in a smart grid. More 'intelligence' is needed as well in the distribution network, to co-ordinate inputs from myriads of decentralised power generators so as to avoid perturbations.

Fourth, high-efficiency and flexible conventional power plants on standby will always be needed to take over when the wind is not blowing or the sun is not shining. Without them, boosting renewable power generation is not feasible. The power plants of the future may be equipped with on-site energy storage enabling them to operate continually in optimal efficiency mode when their energy is not needed, while being able to quickly respond to load requirements.

This energy storage is the fifth crucial element to any energy system that wants to include renewables to the extent envisioned by the *Energiewende*. One technology that would be available quickly is conversion of excess electric power into hydrogen, for which efficiencies of over 70% should be achievable. Hydrogen could then be fed into the natural gas system that is already in place. A hydrogen content up to a few per cent is possible, depending on location and time of year. Germany has the highest natural gas storage capacity in Europe and can stockpile a quarter of its annual gas requirement. In slack wind periods, hydrogen could be converted back to electric power by burning it together with the natural gas with an efficiency of 60% in high-efficiency power plants.

Overcoming the limits of integration

If we dare to look further, towards 2050 or even beyond, we can imagine that the developments around the German *Energiewende* are the first steps towards a full integration of energy and IT-based communication connecting the different infrastructures. This vision is based on the assumption that we see a continuing electrification of society as well as a strong trend of digitisation.

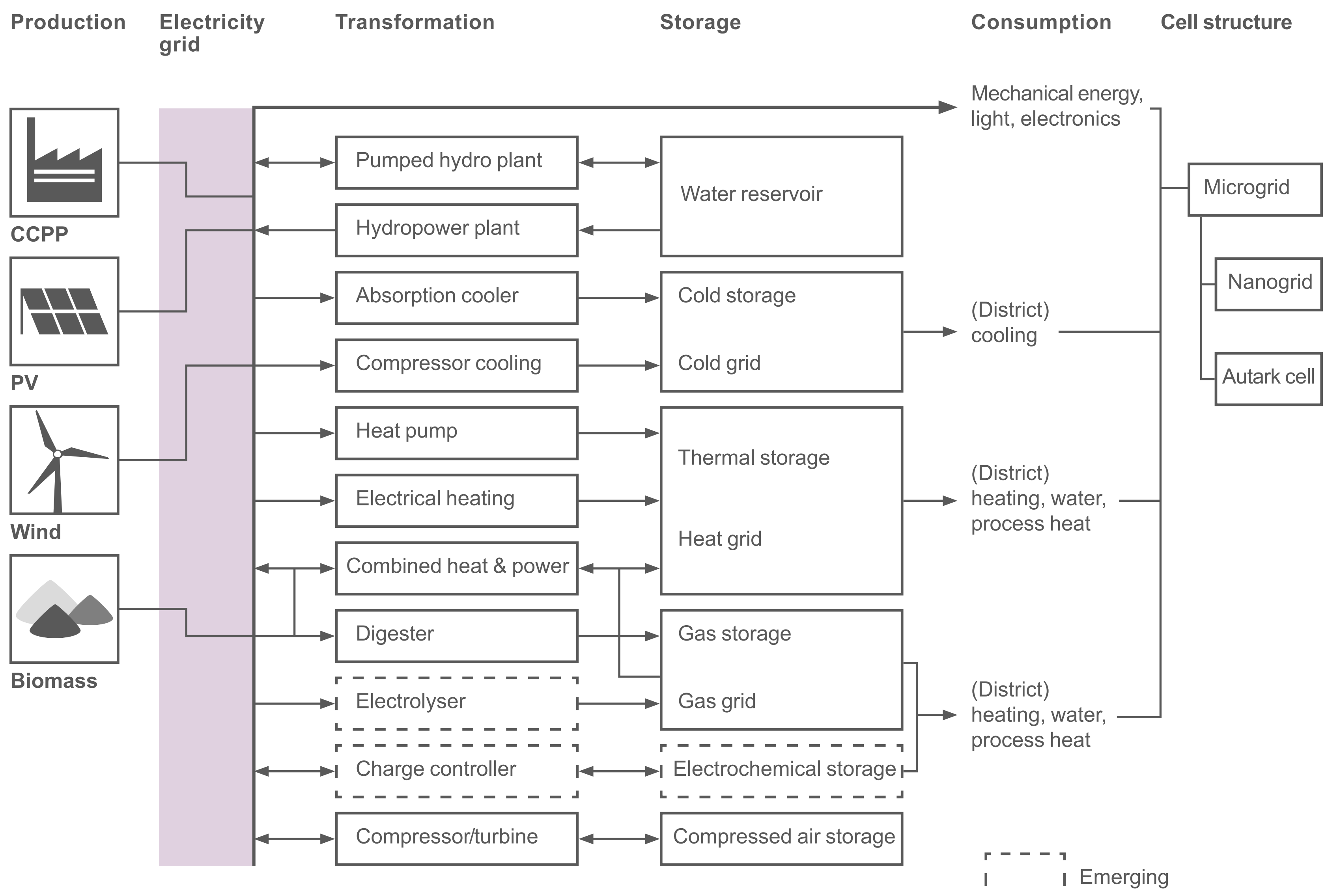

Figure 2: Cross-over between energy carriers using energy storage (source: Siemens).

The formerly independent infrastructures of energy supply and telecommunication will become more and more connected in a cell structure. These cells may be city districts, villages or factories, and from a power supply viewpoint may be regarded as micro-grids. Inside the cell, electricity, gas and heating/cooling will be managed using cell-based heat and power generation, energy storage and cross-overs between the energy carriers as needed (see Figure 2). Examples of technologies to be used for this are CHP generators, heat pumps for heating or cooling of buildings, and batteries, installed on-site or grid-connected wherever it makes most economic and technical sense. System control will be the job of a cell-controller that interacts with individual households, which will have their own interplay of energy generation and use – in effect making them nano-grids.

The cells of course will connect to the overlying electricity and gas grid. Applying the super-grid technologies discussed earlier will allow tapping into renewables or other, balancing power resources which may be far away. In many cases, for reasons of cost-effectiveness it will be economical for a number of energy cells to team up and together operate one highly efficient central gas-fired power station, preferably with heat extraction for district heating networks. The gas will be rich in hydrogen, originating from electrolysers splitting water whenever there is excess electricity. Many of these cells will also be able to exploit the possibility of synergy with nearby chemical industry, via hydrogen or carbon dioxide electrolysers or other processes.

The build-up of this truly integrated energy system should be done with cost-effectiveness, security of supply and environmental awareness in mind. The German *Energiewende* is a major, government-driven turnaround of energy policy, inspired by concern for climate change and spurred on by the nuclear disaster of Fukushima. Its objective, to transform Germany's energy system into a nuclear-free as well as decarbonised electricity system by 2050, is a huge challenge but also offers huge opportunities.

Besides researching and applying the necessary technology options, it is essential to draft a design for the energy market, channelling the interests and impacts of the various market players, small and large utilities, the grid operator and different kinds of energy users. And last but not least, the German *Energiewende* can only be a success if the public will support these radical changes, not only in theory, but also in practice, by accepting the new infrastructure that will have to be built – possibly in their proverbial back yards.

Only then will Germany's energy transition bring the country to where it needs to be: into the new world where electrification and digitisation combine in a sustainable energy system.

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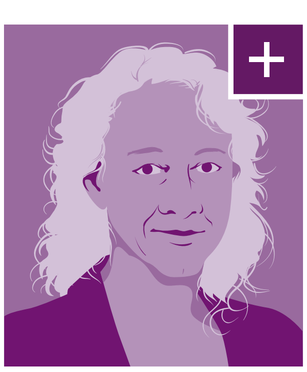
Michael Weinhold is chief technology officer of Siemens Energy Sector, heading the Technology and Innovation staff department. He has been with Siemens since 1993. He has been an adjunct professor at the Technical University of Denmark since 2011. In 2008, he was promoted to the status of 'Siemens TOP Innovator'. He studied electrical engineering at the Ruhr University Bochum (Germany) and Purdue University (USA).

Klaus Willnow has headed the Innovation Co-operations department at Siemens Energy since July 2008. He has worked for Siemens Energy for 15 years in various roles covering nuclear, fossil power generation, transmission and distribution. He studied civil engineering at the Ruhr University Bochum (Germany) and economics at the Fern-Universität Hagen (Germany).

Targets, technologies, infrastructure and investments
Preparing the UK for the energy transition

The UK was one of the first nations to take the climate challenge seriously and give the transition an institutional framework. This has allowed it to take an integral approach to the journey to 2050. It starts with preparedness.



> *Jo Coleman and Andrew Haslett*

The UK's North Sea oilfields began production in the 1970s and in the decades that followed the country grew accustomed to near-self-sufficiency in primary energy. Domestic oil and gas output eventually began to taper, however, turning the UK into a net importer by 2004. By 2012 the UK was importing almost half its primary energy.

Energy security remains a key priority, yet it is far from clear what threatens this security most: geopolitical risks and dependency on imports, or domestic issues such as ageing infrastructure, lack of investment, rising energy prices and extreme weather events. Either way, the need to simultaneously remake the energy system in response to these risks and to climate change represents a significant opportunity.

We have been struck by how little it is appreciated that the supply and use of energy need to be understood as a set of complex, interlinked systems underpinned by substantial investments in infrastructure. Many proposed solutions seem to ignore this. That is why the UK Energy Technologies Institute (ETI), a partnership between the UK government and six large energy and engineering companies, seeks a broader approach. ETI's detailed understanding of the UK highlights how very different the energy systems of different countries are and how likely they are to diverge further. The discussion in this essay is based on extensive techno-economic analysis by the ETI, experience gained from over fifty ETI projects, and the expertise of our public- and private-sector members. This has enabled us to develop a broad and detailed understanding of how the UK should rise to the challenge of meeting its citizens' needs for energy services while reducing the catastrophic economic and social consequences of uncontrolled climate change.

Support for change

There is no time to invent and deploy a set of novel breakthrough technologies, and the cost of adaptation will inevitably be higher than the cost of mitigation. The UK can allow itself a 35-year transition to low carbon, by developing, commercialising and integrating known but currently underdeveloped solutions. In the decade ahead the UK's low-carbon energy policy should focus on ‘preparedness’. We have to develop options and explore trade-offs, while also testing our technical, operating, business and regulatory models at a sufficient scale to give stakeholders the confidence they need to commit to full-scale implementation.

This comes at a difficult time for change. Although the UK enjoys some of the lowest energy prices in Western Europe, the rising cost of gas is the main reason that household energy bills have doubled in the past decade. Over 80% of British homes are heated by natural gas, with a similar volume of gas going towards power generation. The price of energy has become a major political issue. Following the recent Scottish independence referendum and local, national and European elections there is an increasing shift towards devolving power to individual nations and regions within the UK. Regional priorities and plans will need to evolve within the context of UK policy and EU market rules and regulation. Rising energy prices, combined with patchy customer service and episodes of mis-selling by energy retailers, mean that the trust needed to embark on fundamental changes is currently lacking.

The UK passed the Climate Change Act in 2008, making it the first country to introduce a long-term, legally binding framework to tackle climate change. The Act set the target of reducing greenhouse gas emissions by at least 80% relative to 1990 levels by 2050, and required carbon budgets to be fixed for successive five-year periods. The government announced in 2013 that it had achieved its first carbon budget and was on target to meet the second and third (2013-17, 2018-22). However, a substantial proportion of the reduction in emissions since 2008 is a consequence of the economic downturn. Consumers have faced the triple whammy of stagnating or falling household income, higher energy prices and electricity surcharges to fund the parallel drive for greater efficiency and more renewables. The burden has fallen disproportionately on poorer households, which are more likely to use electricity for heating.

The UK’s unique opportunity

Whilst there are many commonalities between the energy systems of different countries, each country is blessed with its unique opportunities and challenges. These need to take advantage of global technology platforms such as low-carbon vehicles, but each country will find its own unique packages of solutions. The UK starts from a relatively unusual but fortunate position in that regard. Many of its ageing power plants need replacing: out of a total capacity of approximately 90 gigawatts in 2010, 16 gigawatts will be decommissioned by 2015, primarily to comply with the EU's Large Combustion Plants Directive. A further 5 gigawatts of gas-fired plant capacity has been closed, mothballed or derated for economic reasons, and most of the UK's remaining nuclear capacity will have to be replaced by 2035.

The energy potential of the UK's offshore waters is immense

Although UK power demand has fallen since 2010, the capacity margins have been reduced and various organisations have highlighted the possibility of shortfalls in capacity as early as winter 2015-2016. Some of the 21 gigawatts of the closed capacity needs to be replaced to maintain capacity margins. Furthermore we need to consider the increase in demand that can be anticipated as emissions reduction targets drive electrification of our home heating and cars on top of the growth in demand that generally accompanies growth in the economy and population. For a modest incremental cost we have the choice to make this new capacity low carbon.

The energy potential of the UK's offshore waters is immense. It has been estimated that offshore wind could generate 400 terawatt-hours of electricity a year, together with 60 terawatt-hours of tidal and 50 terawatt-hours of wave power. This is on top of 70 terawatt-hours of solar and 50 terawatt-hours of onshore wind potential. To put that in perspective, the UK currently consumes just under 400 terawatt-hours of electricity annually.

Biomass, too, has much potential. The UK has a total land area of about 240,000 square kilometres (60 million acres), of which built-up regions account for around 15%, agricultural land for 72% and forests for 18%. In total 73% of the agricultural land is grassland, on which animal stocking rates have reduced in recent years. If these rates were to return to their 1990 levels, some 20,000 square kilometres could be released for energy cropping with no detrimental impact on food production. Much of the agricultural land was formerly wooded and could, if reforested, yield around 7.5 million oven dry tons (odt) annually. Our existing forests, meanwhile, are not always managed optimally. The UK has the lowest forestry output per capita in the European Union after the Netherlands, despite a land resource per capita almost twice the Dutch level. The UK's forests are the worst managed of any European Union member state.[1] Even without reforestation, the country could achieve additional production of 4.2 million odt simply by better forestry management.

Another opportunity is the offshore capacity for carbon storage. The UK is ideally placed to achieve a significant proportion of its emissions reductions to 2050 and beyond through carbon capture and storage (CCS).[2] The country has more than enough potential CCS capacity in the shape of saline aquifers and depleted offshore oil and gas reservoirs. ETI has identified 78 gigatonnes of unrisked potential storage capacity in UK waters, of which 14 gigatonnes has been selected for further evaluation, based on risk and cost factors. This stacks up very well against the 3 gigatonnes we estimate the country will need by 2050. There is also potential for providing storage capacity to other Western European countries.

The British public has not displayed any significant hostility to storing carbon dioxide offshore and – in stark contrast to attitudes in Germany or Japan – its attitude towards nuclear has not been undermined by the 2011 Fukushima incident. Although nuclear enjoys relatively low public support (34%), this level has remained consistent since 2005. At the same time, the proportion stating that they are fairly or very concerned about nuclear power dropped from 58% in 2005 to 47% in 2013. People living close to existing nuclear plants generally value the jobs they bring and the boost they give to the local economy. Although public support for renewables is greater, backing for wind has declined sharply from 82% in 2005 to 64% in 2013, while backing for solar has fallen from 87% to 77%.[3] The fall-off in public support for renewables possibly reflects an increased awareness of their cost and the impact this is having on energy bills. The findings of this research into public attitudes suggest to us that British people will accept CCS and nuclear as part of a coherent strategy that also involves affordable renewables.

Challenges for the UK

Some of the challenges facing the UK are shared by many countries and will be tackled on a global scale, such as reducing the cost of zero-emission vehicles and increasing their range. Other issues are more specific to the UK, beginning with its housing stock. Around 80% of today's homes will still be around in 2050, and the vast majority are poorly insulated and highly inefficient in terms of energy use. The government is seeking to improve this poor performance by offering households free surveys and financial support for energy-saving improvements. Nevertheless, the deep cuts in emissions that will be needed if the UK is to meet its 2050 targets will be both expensive and disruptive.

Solar power presents a limited opportunity in the UK. The UK has a relatively low solar gain, which diminishes the further north you go. The largest solar gain tends, moreover, to be found in areas with the highest land and amenity values. The seasonal variation in insolation is strong and utterly out of sync with demand for residential energy, which peaks during the dark hours before dawn and early evening in the winter.

The UK likewise has to contend with a significant peak demand for heat. Heating buildings and water is one of the UK's largest and most difficult energy challenges. It is hardly surprising that demand for heating should be seasonal in a country with a temperate climate. What is less obvious, however, is that this demand can vary as sharply as it does in the course of a single day. During a cold winter, demand for heating can increase at a rate of 130 gigawatts per hour, from 60 gigawatts overnight to a peak of 300 gigawatts, before falling away again almost as quickly. The inherent storage capability and low distribution costs of the natural gas grid mean it can readily cope with these variations. They will become a significant challenge, however, as the share of heating delivered by electricity increases. To meet that challenge, we will have to improve heating efficiency, heat storage and demand response, while simultaneously altering usage patterns with the support of more advanced heating controls. Several days of exceptionally cold weather combined with very low wind across Western Europe presents a huge design challenge for a more electrified system.

The other specific challenge confronting the UK is the hype surrounding shale gas, which is having such a dramatic impact on energy prices and security in the USA. The UK does indeed boast a significant potential shale gas resource (estimated at between 23,000 and 37,000 billion cubic metres, which is 800,000-1,300,000 billion cubic feet, or 860-1,400 billion MBtu[4]). However, no production has occurred yet, and it is too early to say how much, if any, will prove commercially viable. Geology, population density, land-ownership practices, safety and environmental regulations and the relative immaturity of an onshore-drilling supply chain all suggest that shale gas is unlikely to develop to the same extent or at the same pace in the UK as it has in the USA. However, this has not discouraged shale gas advocates from hailing it as a silver bullet for all the UK's energy issues, including climate change. Whilst additional home-grown energy sources are naturally more than welcome, the hype surrounding shale gas has fed through into an anti-renewables message heard increasingly loudly in the boardrooms of companies considering investment.

An affordable UK energy transition

Delivering affordable, secure and reliable energy to end users when they need it is the key objective of any energy system. The wide range of energy sources and uses, and the different technology and network infrastructure options that have to be integrated, make this a complex challenge. The way the various parts of the system interact is critical to delivering effective overall solutions. As the UK moves towards a low-carbon economy, the interdependencies between the heat, power, industry and transport sectors, and the infrastructure that connects them, will become increasingly important. The system-level analysis, modelling and design we do at ETI are crucial to our understanding of these interactions. Energy system designs need to be robust against a range of scenarios that take account of the many uncertainties we face in the future. The UK will embark on a wholesale transformation of its energy system from around the mid-2020s. To ensure the country is prepared for that, we need to develop and test a portfolio of proven solutions that will give it the best possible chance of achieving an affordable, secure and sustainable energy system.

Our analysis highlights the enormous potential of CCS and bioenergy across the full range of future scenarios. Missing out on one of these technologies would double the cost of delivering the climate change targets from around 1% of GDP to 2% and if neither were to be developed, it is difficult to see how the UK would be able to meet those targets at all. People are often surprised to hear this, partly because they tend to focus on a single sector, such as electricity; and partly also because they concentrate on unit cost – comparing technologies on a pound per energy basis, which fails to capture the value of a particular technology, the timing of its production or its role across multiple sectors. CCS has to be central to any national strategy to meet carbon targets cost-effectively, as it enables flexible, low-carbon electricity generation, supports renewables and cuts emissions from industrial processes. CCS can even deliver 'negative emissions' when used with biomass, by capturing and storing the carbon that plants and trees take from the atmosphere. This delivers a net reduction in atmospheric carbon dioxide, offsetting emissions from activities such as transport, which are particularly expensive to decarbonise. CCS can also produce flexible, low-carbon fuels such as hydrogen or synthetic natural gas through the gasification of coal or biomass.

CCS has experienced a number of false starts and frustrations in the UK. Two development projects are currently under way, but we need to ensure that these are not just one-offs. They need to form the backbone of a future network capable of transporting and storing carbon dioxide from power generation and industrial sources. Additional storage locations must be appraised over the next decade, to persuade businesses that sufficient storage will be available to support investment in new capture facilities.

Different energy system designs require very different infrastructures, but the role of CCS cuts across all of them. Without it, renewables – predominantly offshore wind – would have to contribute a much greater share: upwards of 90 gigawatts potentially, resulting in prolonged periods of oversupply. This would require the UK in turn to install additional dispatchable capacity to meet demand when the wind drops. Enhanced storage and demand response could help, but the country would most likely still need a significant amount of reliable, flexible generating capacity in the form of hydrogen or gas turbines. No CCS would mean no hydrogen generated from fossil fuels or biomass, so we would have to turn to electrolysis during periods of wind oversupply instead. Bioenergy would not be in a position to generate negative emissions either, and so the optimal role for biomass would switch to the production of biofuels for transport.

These two worlds – one with CCS, the other without – entail fundamentally different infrastructures across the entire energy system. It would be a mistake to build both sets of infrastructure: this would result at best in underutilisation, and at worst in the sidelining of huge investments as the optimal solution emerged. If the UK is to prepare effectively and avoid wasting investment, it must therefore take crucial decisions about the design of its future energy system. The country will have to reorganise its energy distribution infrastructure, build major new networks and adapt its buildings and vehicles. The scale of these efforts will be such that key decisions need to be made by the mid 2020s if these options are to have sufficient time for mass rollout by 2050. This timing is critical to the UK's transition to low-carbon energy. The work required to develop the options and demonstrate them at scale so that the country can make informed, evidence-based choices is likely to take the best part of a decade. Our conclusion is that there is still just enough time, but that every year spent deploying options which ultimately may not be required will cost a considerable amount of money.

Preparedness

Whether we work backwards from 2050 or forwards from 2014, the next decade will be critical in preparing for the transition. Consequently, the metric of success for many technologies in the run-up to the mid 2020s will be preparedness rather than mass-scale deployment. The country has to develop options and explore trade-offs, proving the technical, operating, business and regulatory models at sufficient scale to give stakeholders the confidence they need to commit themselves to action. Preparedness also means building enough UK capacity to provide a launch pad for implementation. This ambition is not for free, but it invests resources where they will have the most effective economic leverage in the long term.

The priority throughout all this will be to develop and test the technologies that are likely to offer the key choices on the path to 2050. In the case of CCS, the appraisal of a further seven storage locations and the development of 3 gigawatt power generation with carbon capture will demonstrate that this is a viable route and that adequate storage capacity exists. It will also foster confidence in the capture technologies, while showing that the benefits of co-ordination can mitigate the counterparty risks. For nuclear, preparedness means at least two operational plants. The situation for bioenergy is more complex: here we have to test the credibility of negative emissions, which will require us in turn to assess the sustainability issues and the availability of land in the UK and internationally. We need a clear picture of the most appropriate pathways for bioenergy use and the right combinations of feedstock, pre-processing and conversion technologies. The UK has to develop market, regulatory and policy mechanisms (spanning farming and energy) that will support development without compromising food production, and to address issues of public acceptance.

The focus for other renewables over the next decade should be on driving down costs rather than on the speed of rollout, although a certain amount of deployment will be needed to achieve this. For offshore wind, lower costs will require larger turbines with longer blades in deeper waters than we see today, which should be the focus of future licensing rounds. A focus on offshore wind as the most credible renewable technology hedges against slow progress in either CCS or nuclear.

From one perspective, the cost of preparedness will only be a fraction of the hundreds of billions of pounds that will have to be invested in buildings, vehicles, pipelines, wires and power stations in the next 35 years. All the same, the billions the UK will have to find over the next decade to support CCS projects, nuclear plants, offshore wind, retrofits, vehicle-charging infrastructure, hydrogen vehicle infrastructure, district heating schemes and so on remain very large investments. It is vital that they are designed in such a way as to deliver the evidence, confidence, learning and capacity needed to scale up successfully.

The only areas in which the focus should be on immediate, large-scale deployment are efficiency measures and generating energy from waste. The net cost of many such measures is modest or even negative in the case of new assets, whereas considerable time is needed to retrofit existing assets skilfully and cost-effectively – not least because of limited access windows or slow asset turnover. This makes efficiency an urgent development priority. Waste offers another immediate opportunity, driven by the Landfill Directive. Waste gasification allows heat or electricity to be generated locally and syngas to be injected into the gas grid, with the prospect of cheaper flue-gas clean-up, reduced emissions and higher efficiency compared to incineration plants.

UK government spending on these types of activity is scheduled to rise to £7.6 billion (€10.5 billion, or $11.9 billion) in 2020-21, which is considerably lower than the £23 billion (€32 billion, or $36 billion) Germany has earmarked for power subsidies in 2014.[5] The planned UK spend is probably sufficient, so long as it is targeted at technologies that are likely to be key choices in 2025 for the transition, and which fulfil the aforementioned scale-up requirements. Preparedness is therefore a relatively low-cost investment, which will help us achieve our climate change targets while itself reducing emissions. It lays the foundations for managing deployment post-2020 and will successfully position the British economy within the broader global political and economic landscape.

Building investor confidence

Our analysis highlights that CCS is critical to achieving the UK's climate change targets affordably. Planning regional networks and getting a clear picture of transport and storage costs will be vital in terms of fostering investor confidence. The detailed analysis we have carried out at ETI[6] shows that if we plan and co-ordinate development properly, we can limit the infrastructure required in the years to 2050 to six shoreline hubs feeding fewer than 20 storage facilities. The net present cost would be under £5 billion (€7 billion, or $7.8 billion). Transmission-scale systems like this can be developed at national level, while choices and plans for distribution systems have to be developed locally and regionally. Plans to decarbonise buildings must be informed by major national and local choices of this kind, but can only be made with sufficient knowledge of the details of each building and of consumer requirements.

It has long been recognised that the UK economy suffers from low investment in physical infrastructure compared to OECD benchmarks. Many local authorities see energy infrastructure as a critical factor in maintaining their attractiveness as places to live, work and do business. Furthermore, investing in infrastructure is an attractive way of strengthening the economy in the present climate. A cost-effective and resilient energy infrastructure is an important foundation for a successful mixed economy, and appropriate public-sector investment will provide the confidence for greater levels of private investment.

When it comes to major infrastructure sub-systems there are several critical issues, beginning with that of sequencing. Infrastructure investments in areas such as CCS, heating distribution and vehicle fuel supplies need to be made early enough to build investor and consumer confidence. Public-sector investment has to generate consumer confidence: it cannot work the other way around. Existing infrastructures will have to be supported until it becomes realistic to ‘buy out’ the remaining users. Since the latter will consist disproportionately of users who are economically and socially vulnerable, a clear, up-front strategy is needed, which will also prevent other users from taking advantage.

Practicality is a second critical issue affecting major infrastructure sub-systems. All sorts of technical and regulatory details can derail a proposed solution unless they are addressed by means of full systems development and validation. It is important to check the practical details thoroughly, so legitimate concerns can be responded to, while also rebutting challenges by parties with an agenda of their own.

The next issue is that of consumer and societal acceptance. People have to want and accept what is being proposed. There is a substantial risk that solutions that are unfamiliar to consumers, potentially more expensive and possibly underdesigned will significantly delay market uptake. Acceptance by society has significant implications for transition planning.[7]

The issue of investability is likewise critical. The investments needed to deliver the UK's future energy system will be an appropriate combination of public and private, collective and individual. The technical, market and policy risks associated with these investments need to be addressed as the UK prepares for transition.

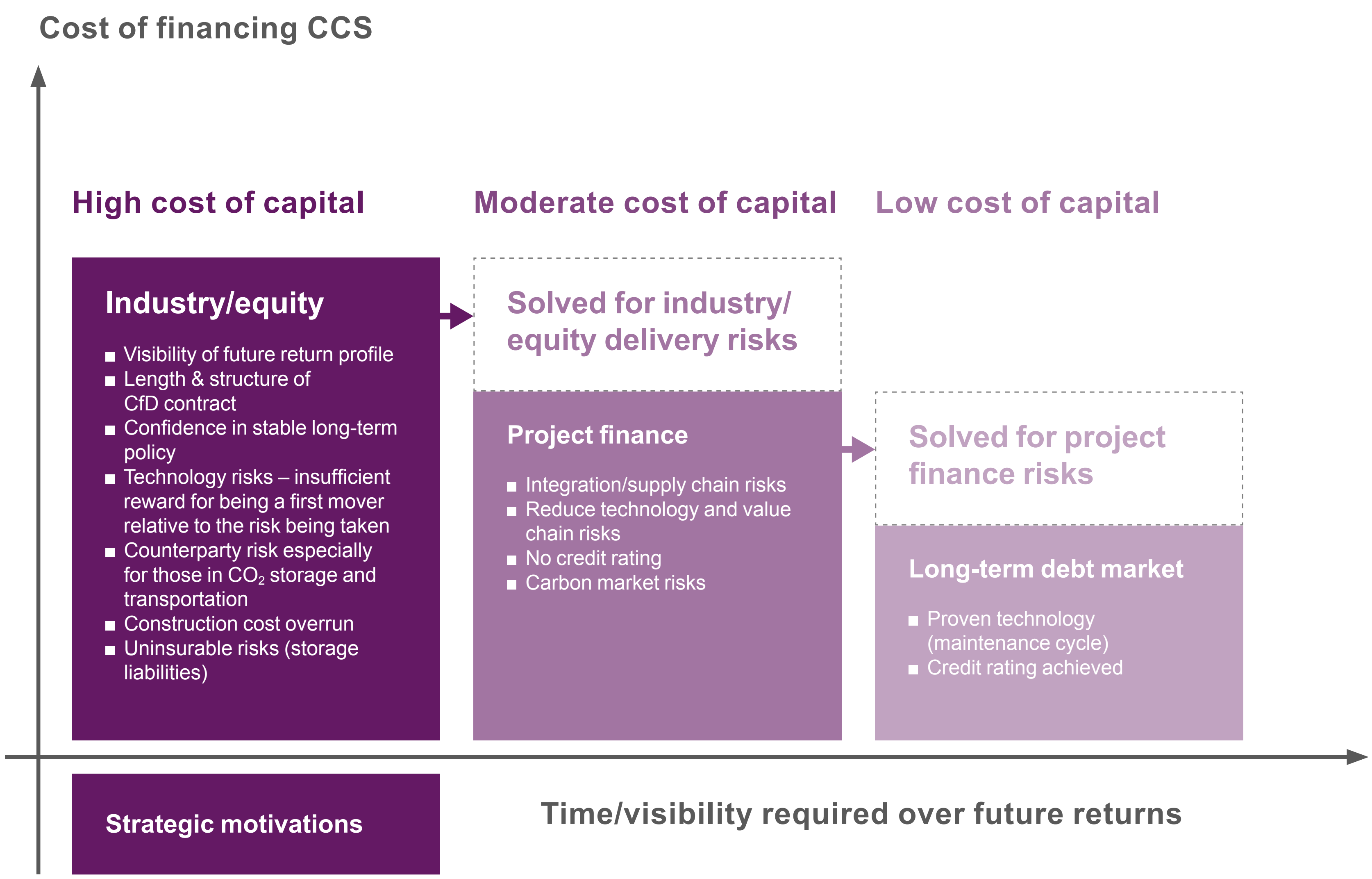


Figure 1: A model for financing carbon capture and storage.

Although CCS preparedness is back on track thanks to two large projects that are now being developed – the White Rose and Peterhead projects – market mechanisms for supporting further initiatives are untested and are not found beyond the power sector. The work we have done at ETI with the Ecofin Foundation and the financial community offers a generic model for the funding of large-scale technology development (see Figure 1).[8] Policy (market) risk was highlighted here as critical. Electricity Market Reform has been introduced, including Contracts for Difference for low-carbon power generation, but the details are still emerging. An early indication of how this approach will work in practice, together with the overall funding available for CCS, will be needed in order to give lenders confidence. A clearer understanding is also required of the risks in terms of the regulatory and long-term operating requirements of carbon storage – in particular, the basis on which potential leakage liabilities would be shared between government and storage developers.

Appropriate business structures must also be developed to reduce counterparty risk and to share the rewards fairly between the different actors across the value chain (power, capture, transport and storage operators), each of which has a different risk appetite and expectation of reward. This applies to the initial value chain but also to developments tying into the infrastructure after the initial development phase. Lastly, no policy is in place to encourage investment in CCS beyond the power sector, even though most of the value of CCS ultimately lies in industrial deployment, negative emissions, synthetic natural gas, and hydrogen generation. Unless support mechanisms are created in these areas, the full value of CCS will remain elusive, along with the UK's ability to meet its targets cost-effectively.

Current market structures are unlikely to deliver the changes needed

Business development, governance and leadership

Although current market structures are unlikely to deliver the changes needed, it is not clear how best to facilitate the process of change. Small adjustments can be encouraged by financial incentives, but this model breaks down when large-scale changes are desired, such as retrofitting heating systems in 20 million homes. There would appear to be two main options, both of which ultimately rely on a long-term expectation of consistent carbon prices. The first is a free-market approach, underpinned by a carbon price rising to around £150 (€210 or $235) per tonne by 2030 and then £350 (€490 or $550) per tonne by 2050. The challenge posed by this approach is twofold: how to create the expectation of a consistent carbon price in a free market? And how to ensure that investments happen in time to meet the targets?

The European Union's commitment to creating a common energy market does not allow for national carbon pricing, yet EU-wide pricing looks set to remain ineffective for the foreseeable future. The challenge of investment timing is highlighted by zero-emission vehicles. These are expected to require a carbon price of over £250 (€350 or $390) per tonne, and so would not be deployed at scale until after 2040, leaving insufficient time for roll-out given the rate of vehicle turnover. The alternative is more government-led support, including penalties and incentives tailored to each sector until a carbon market is firmly established. The national plans this would take boil down to 'picking winners' – something the government prefers to leave to the market. This approach would also require the free market's efficient allocation of resources, innovation and deep technical skills to be combined with the government's democratic legitimacy, social acceptance and protection of consumers. In which case, the outcome risks encapsulating the worst of both these worlds.

Whichever of these approaches is adopted, European and global support for climate change will be crucial, as the UK cannot go it alone and risk becoming uncompetitive. There are many scenarios about how and when global concern for the climate will finally elicit a commitment to act. Some believe that a global agreement is the key, while others pin their hopes on national and bilateral agreements. These, they argue, will crystallise into action by blocs of key nations, which will then force others to act through trade agreements and border pricing of embedded carbon. It is also possible that – as island nations begin to disappear and other countries suffer extreme weather events that are clearly linked to climate change – the threat of international lawsuits will result in accelerated action.

Insurance companies and banks are starting to think about these possibilities. Others are simply crossing their fingers that the scientists from 39 countries who agreed the IPCC's Fifth Assessment Report[9] got it wrong. Some place their faith in our creative ability to develop as yet unidentified solutions and to adapt. Our view at ETI is that action will accelerate as extreme climate events become more commonplace and the first successful lawsuits are brought for damages. Societies that have prepared pathways for integrated, whole-system solutions, structured around component sub-systems that have already been demonstrated at scale, will enjoy an advantage. Those that have not will suffer from unfavourable terms of trade and lawsuits against their major companies.

Wherever you stand on the issue of climate change, preparedness in the course of the next decade represents a relatively low-cost pathway. It creates options for the UK, while also showcasing solutions that will support decarbonisation of much larger nations with more significant emissions than the UK's. The UK needs to continue on the path marked out by the Climate Change Act, to show leadership and to create scope for prompt action and economic advantage in what will ultimately be a global marketplace for low-carbon technologies and supply-chain capacity.

Related essay

Dealing with fossil fuels
Carbon capture and storage in a global context
> *Ron Oxburgh*

Jo Coleman is Strategy Development Director at the Energy Technologies Institute (ETI) – a partnership between the UK government and six large energy and engineering companies. The ETI has been tasked with accelerating the development, demonstration and commercial deployment of technologies that can contribute to a cost-effective UK energy transition. Prior to joining ETI, Coleman worked for Shell from 1989 to 2011. She received a degree in Engineering Science from St. Catherine's College, Oxford (UK) and an MBA from the University of London (UK). She is a Fellow of the Institution of Mechanical Engineers.

Andrew Haslett is Chief Engineer at the Energy Technologies Institute (ETI). He worked at ICI as Group Science & Technology Director until 2008. He is a Fellow of the Royal Academy of Engineering, of the Institution of Chemical Engineers and of the Royal Society for the encouragement of Arts, Manufactures and Commerce.

References

1. AEBIOM (2013). *European bioenergy outlook* (Annual Statistical Report on the contribution of biomass to the energy system in the EU27), AEBIOM: Brussels.
2. D. Gammer (2013). A picture of CO_2 storage in the UK: Learnings from the ETI's UKSAP and derived projects, http://www.eti.co.uk/wp-content/uploads/2014/03/A_Picture_of_Carbon_Dioxide_Storage_in_the_UKUPDATED1.pdf.
3. W. Poortinga, N. Pidgeon, S. Capstick & M. Aoyagi (2013). *Public attitudes to nuclear power and climate change in Britain two years after the Fukushima accident*, 19 September 2013: REF UKERC/WP/ES/2013/006, http://www.ukerc.ac.uk/publications/public-attitudes-to-nuclear-power-and-climate-change-in-britain-two-years-after-the-fukushima-accident.html.
4. British Geological Survey DECC (2013). *The Carboniferous Bowland Shale gas study: Geology and resource estimation*, https://www.gov.uk/government/publications/bowland-shale-gas-study.
5. D. Buchan, The Oxford Institute for Energy Studies (2014). *Recasting EU energy and climate policy*, 27 February, https://connect.innovateuk.org/documents/3132264/11521341/Recasting%20EU%27s%20energy%20and%20climate%20policy_27%2002%2014%20webinar%20presentation.
6. Ref. 2 *supra*.
7. K.A. Parkhill, C. Demski, C. Butler, A. Spence & N. Pidgeon (2013). *Transforming the UK energy system: Public values, attitudes and acceptability*, Synthesis Report, UKERC: London.
8. ETI & ERF (November 2012). *Carbon capture and storage: Mobilising private sector finance for CCS in the UK*, http://www.eti.co.uk/ccs-mobilising-private-sector-finance-for-ccs-in-the-uk/.
9. *Climate change 2013: The physical science basis. Working Group I*, http://www.ipcc.ch/pdf/unfccc/cop19/cop19_pres_plattner.pdf.

A collective approach to change

Negotiating an energy transition in the Netherlands

Forty parties, together representing a broad cross-section of Dutch society, have agreed on a route towards a low-carbon future in the Netherlands. This uniquely Dutch approach has value for other countries too.

> *Wiebe Draijer*

In September 2013 a large number of civil society organisations in the Netherlands agreed on a plan to achieve a completely sustainable energy supply by 2050. Trade unions, industry and environmental organisations had negotiated it for a year. This agreement, the *Energieakkoord*, includes details about how to reach the important milestone of 16% sustainable energy in 2023. Negotiating it was a risky and painful process for all the participants. The environmentalists had to make concessions regarding the pace of change, and industry had to accept that some investments would be written off. The signing of the deal was an emotional moment for many people. Quite a few – if not all – had gone further than they expected. This came about only after many months of negotiation during which it became evident to all that this was the only feasible way forward. The agreement will spark change and should succeed precisely because it now has such broad-based societal support.

Just as Germany has its *Energiewende* and the UK its Committee on Climate Change, the Netherlands now has its *Energieakkoord*. The success of any of these is determined by how well they are embedded in the national socio-political traditions. This is the best and perhaps the only way to obtain the long-term, broad-based support to see the energy transition through to its end. So while the *Energieakkoord* is quintessentially a Dutch answer to the energy challenge, I believe it holds useful lessons for other nations as well.

Polderen

The Netherlands has a long tradition of consultation and of involving a broad strand of the population when it comes to solving pressing issues. Some say that this dates back to the communal battle against the water. Building, maintaining and defending dikes demands a collective effort, which the Netherlands has traditionally organised via ‘polder boards’ (*waterschappen*) – one of the earliest democratic institutions in the world. These are responsible for the quality of dikes, canals and polders. Broad support has always been necessary for these tasks. When a storm hits and the water comes crashing over the dikes, thousands of people get to work with sandbags, monitoring equipment and boats. Everyone plays their part and many take personal risks.

With reference to this ancient institution, consultation leading to collective action has come to be known in Dutch as *polderen* – literally 'to polder'. This bottom-up approach has been given institutional form in the Social and Economic Council (*Sociaal-Economische Raad*, SER) – a government advisory and consultative body, in which business and union representatives work closely with experts appointed by the crown. Since its creation in 1950, SER has become a crucial part of economic and social development in the Netherlands. A kind of 'social contract' exists, according to which the government accepts the outcome of this socio-economic consultation and takes responsibility for implementing it.

This was the mechanism, for instance, through which Dutch people collectively decided to exchange income for free time, to such an extent that the Netherlands now has one of the lowest number of working hours in the world. The Dutch were also quicker than their neighbours to agree an increased retirement age.

Collective negotiation of this kind is firmly rooted in the conviction that people are capable of considering things rationally. Ten years ago, I organised a national opinion survey in which 150,000 people were questioned about socio-economic issues. It was clear from the results that a large part of the population can weigh up options for the future wisely and insightfully. If one presents the pros and cons of important issues in a careful and unbiased fashion, most people will form their opinions with thoughtful care. In this survey, many came out in favour, for instance, of far-reaching measures to tackle problems in areas such as pensions and mortgages. A genuine choice obliges people to think clearly and to go beyond their own self-interest or gut instinct. Better results are achieved through dialogue, in which the partners are given the space and privacy they need to explore points of connection despite their differing interests.

Sense of frustration

A group of very different parties came together at SER in the late summer of 2012 to seek an agreement on how to make energy in the Netherlands more sustainable. The 'New Energy for the Netherlands' (*Nederland Krijgt Nieuwe Energie*) movement had pressed for the talks. This civic initiative, which includes socially engaged businesses, is campaigning for a transition to ‘clean, affordable and reliable energy’.

Parties who would normally avoid each other at all costs sat round the table together for the first time: employers and ecologists, energy idealists and big industrial players. They included the likes of Netherlands Railways, Greenpeace, transport sector representatives, pension funds and the Dutch SME association. There were 40 parties in all.

They sat round the table together for the first time

What brought them together and what they initially shared was the frustration that insufficient progress was being made in terms of energy policy – frustration, rather than a sense of urgency. The environmentalists were frustrated that sustainable energy was failing to get off the ground, while industry was struggling with the uncertainty that surrounds current energy policy. The unions, lastly, were frustrated by rising unemployment, which new initiatives might help tackle.

We threw our doors open to anyone interested in engaging. Young people from a variety of organisations presented their visions of the future. They understood the importance of increased sustainability – better, sometimes, than the older generation does. We also asked citizens to suggest how to combine sustainability and economic growth. Almost 80,000 views were submitted on how energy policy should be shaped. This approach certainly obliges everyone to think about the issues. The consultation process got us moving and the agreement we concluded more than a year later was not far off what all these independently thinking citizens had come up with based on their own wisdom and insights.

Soft and hard

We invested a lot of time making sure that the negotiators around the table would trust each other. This approach is often portrayed in management literature as ‘soft’, but it was very important in this case.

We provided a lot of space so that, for instance, the director of Greenpeace Netherlands and the chairman of VNO-NCW, the largest employers' federation, could really talk to each other. This made them move beyond their usual 'professional antagonism' and allowed their solution-oriented personas to come out. At the beginning of each meeting, we systematically gave participants a chance to explain their point of view and their interests. A surprising degree of openness and understanding of the others' position gradually developed.

Not that everything went perfectly smoothly. Far from it: at times the tone was harder than I for one would have liked. And some involved were still out there to campaign: direct action does not end for the duration of negotiations. While we were busy trying to build confidence, we had to accept that the parties at the table needed to campaign to retain their credibility in the eyes of their respective grassroots, so that they couldn't be accused of selling out.

Yet it was clear to all that these negotiations were taking place with our backs to the wall, considering how far the Netherlands needs to go to reach its sustainable energy targets – renewables contributed only 4% of Dutch energy in 2013, a long way from the 16% target for 2020.

Everyone agreed fairly quickly that the long-term goal should be a fully sustainable energy supply by 2050. That is a clear and sufficiently distant objective, to which absolutely everyone could sign up. The direction of the negotiations was thus set, but considerable disagreement remained as to the route we needed to follow in order to get there.

Many voices

It is far from easy to discuss with many different parties. So we began the negotiations with four separate tables, each with its own topics and objectives, chair and secretariat. One table, for instance, was devoted to energy saving in industry, and large-scale generation of sustainable energy. There were many people around each of the tables, and a wide variety of interests was voiced. This broad approach, in which everyone could express their views and opinions, quickly made it clear that an agreement would be extremely complex and that the interests involved are ultimately irreconcilable: we couldn’t succeed if everyone got what they wanted.

Several major barriers had to be talked through. At a time of economic weakness and austerity, the government, for instance, felt unable to commit more than what it was already spending on incentives. Not a cent more was available, which left little in the way of ‘loose change’ to facilitate the negotiations. For the environmental organisations, the restriction in use of biomass was an absolute red line, as was the achievement of 16% sustainable energy by 2020. The energy sector, meanwhile, insisted that past investment in power stations had to be respected: there could be no question of early closure of coal-fired installations. And the unions would not agree to anything unless they were confident that 15,000 new jobs would be created.

Each of these bottom lines was hurled back and forth across the table. That is the moment to invite some at a smaller table to give the Rubik’s cube a twist. When things got really tough, we held a lot of one-to-one discussions, in which we tried to explore solutions in private. People gradually began to understand each other’s interests and wishes more clearly, which was vital if we were to agree the main outlines.

Behind the scenes, Dick Benschop, President Director of Shell Netherlands, was one of the prime movers behind the project’s success. He was naturally motivated by the environmental promise of natural gas. This is also an interesting element, but we still faced a challenging jigsaw puzzle, into which the interests of the coal sector had to be fitted as well. Tjerk Wagenaar, chair of the Netherlands Society for Nature and Environment (*Stichting Natuur en Milieu*), proved similarly willing to take risks in a decisive way. At the same time, it was crucial to them both personally to come up with a successful agreement.

I too had no idea how all the positions could eventually be reconciled. Negotiating in a group of this size is a high-risk strategy – a lot more is at stake for everyone than merely searching for common ground, which would be nowhere near enough to achieve the goal.

At the end of the day, everyone had gone further than they thought possible. The tears that were shed when the agreement was finally signed didn’t close the gap that still remained between our hearts and our heads.

We knew we had taken a big step, but we also realised it would be hard to persuade the grassroots. Part of the value of these discussions is that they almost oblige people to do just that: personal courage and leadership had to be shown. Therefore, there would also be consequences if we failed to reach an agreement – it could set us back a long way.

Multi-dimensional jigsaw

We have a long tradition at SER of negotiating wage agreements. In a sense, this is a one-dimensional process: employers are at one end of the spectrum and the unions at the other, and both try to pull hardest. The same approach doesn't work in more dimensions. And in the case of energy, even the short-term goals had a lot of different facets, such as creating jobs, ecological benefits, economic growth, boosting exports, reducing government spending and meeting the environmental targets set by Europe. This meant, however, that the long-term goal could be framed in terms of gains for all the stakeholders around the table. The reason we ultimately succeeded was because the agreement enabled everyone to achieve some of their objectives.

It certainly helped that we had some expert number-crunchers around the table. This is another important Dutch tradition: since the 1950s, economic policy and forecasts in the Netherlands have been scrutinised by the Central Planning Bureau (CPB) – an independent government advisory body. The CPB can assess the consequences of the specific measures being discussed at SER. The Bureau was joined at the energy agreement negotiations by scientists from energy and environmental research organisations, whose role was to calculate the impact of the proposals and ideas. Together they were able to state whether the suggested means matched the agreed ends. Their calculations will also enable the government in due course to accept the agreements we reach. So it was frustrating that our number-crunchers were unable to demonstrate much in the way of job creation: innovation is seemingly hard to capture in econometric models and the jobs created fall well outside the CPB's remit. Ironically, job destruction is a much more certain process from the econometric point of view.

Give and take

In the end, we gained hugely by allowing a little more time to achieve the 16% sustainable energy target, which moves to 2023 rather than 2020. This created a little more financial leeway. The three extra years gave us the opportunity to achieve the goal with greater support and, ultimately, economic benefit.

In return, the environmental movement got an agreement on the maximum amount of biomass that can be burned in coal-fired power stations. This will make it slightly easier to close old installations, which burn a great deal of biomass, earlier than planned. Three coal-fired units will be decommissioned on 1 January 2016 and two other stations will close on 1 July 2017. This was plainly a difficult issue for the energy sector, but that sector will benefit from the scrapping of a supplementary tax on coal, which will make more recent coal-fired power stations more profitable.

A key element in achieving the target is that substantial savings are also made on domestic energy consumption. This will require investment in insulation – something that quickly pays for itself, but which can be hard for homeowners and tenants to implement because of all manner of rules and practical problems. An agreement between the pension funds, banks and construction companies helped in this respect, as these are the institutions that ultimately have the ability to fund such investments. It will therefore become easier and more cost-effective for citizens to invest in energy conservation and power generation. This, combined with other savings, will mean that the Netherlands consumes 1.5% less energy each year.

Another important part of the agreement is wind power – an attractive method of generation in a windy country like the Netherlands. Yet this is also one of the world's most densely populated nations, making it hard to find new sites for wind turbines. We believe this can still be achieved, provided we give local residents the opportunity to participate in wind projects. We also agreed to install about half of the new turbines offshore. This is more expensive than locating them on land, but we will be doing it on such a large scale as to create the world's largest wind farm. Industry estimates that the costs can be reduced by about 40% when we roll out the project on this kind of large scale. In so doing, we will also create an attractive export product and the overall agreement is likewise expected to add around 15,000 new jobs.

The incentives the government has earmarked to implement the agreement is only one part of the funding. The combined contributions of industry, the financial sector and Dutch citizens will be about ten times greater, estimated at a total of €13-18 billion ($15-20 billion) for the period 2013-2020. The costs will be met in part through energy bills, which will rise by about €200 ($225) a year for households. Labour costs will rise to a much lesser degree, so that employment and potential economic growth are not affected. This is important, given the economically challenging phase in which the Netherlands finds itself.

The result is a structure in which each piece of the jigsaw fits precisely with the next: everything depends on everything else. The moment when we presented the agreement to the public was, therefore, tense: the agreement remains fragile and vulnerable. There were immediate objections from the coal sector, and the cost savings we factored in for maritime wind energy came in for criticism. Luckily, the agreement proves solid enough, because if one piece is removed from the jigsaw, the whole picture is affected.

Next steps

The agreements for after 2023 are considerably less specific. We have set a target for total Dutch carbon emissions to be cut by 80-95% by 2050, compared to their 1990 level. Residences must be energy-neutral by that date. But the route to achieving that has yet to be sketched out.

The measures we have agreed at this stage will not produce the necessary vision in themselves. Only in the next round will we address the long-term perspective. In two years from now, I expect that we will be able to show genuine progress and may address the question where new measures are required to secure our objectives. Four or five years from now, we will have to discuss how we can move towards an 80% – and perhaps even 100% – reduction in carbon emissions. This will entail a number of choices that are even more painful than the ones we were able to reach at this point. We will inevitably have to bid farewell to some forms of power generation.

We will only be able to make those choices if the *Energieakkoord* proves successful. After all, we cannot embark on a fresh round of negotiations on the back of a shared frustration. That would mean that the *Energieakkoord* had not succeeded. New negotiations can only begin with a shared sense of success and mutual trust – once we have created wind farms and everyone can see that they are not as ugly as feared and once it has become clear that we can sell this technology around the world. We need to show we have created something new and promising before the dismantling of existing structures can be discussed. Creation has to come before destruction.

Reality will impose the next set of choices at a time when we are in a position to make them, whether that means technological innovation, public acceptance of nuclear power or some other shift. Time will create these openings too.

Gaining momentum

It is vital for this first energy agreement to achieve momentum. Once people see that it works, we will start to feel thousands of nudges in the right direction. Individual citizens and businesses need to take steps themselves in order for us to move towards a sustainable economy. The agreement only sets the minimum level, but I actually expect us to make much faster progress. I would have liked to incorporate some extra stimuli: a small subsidy, for instance, when citizens invest in energy saving. That was not possible, but perhaps it will happen in the years ahead in order to keep up the momentum.

The agreement is not the revolution for which some were hoping. There was a great deal of opposition from certain scientists and groups in society who tend to think in very black and white terms. Those who have glimpsed the promised land of sustainability will not find their dream future in this agreement. In technical terms, it represents the maximum that could be achieved. I believe that a gradual transition is possible rather than the creative destruction of existing interests and the high costs this would entail. Rhetoric about how painful a transition would be and what radical choices it would demand does not get us very far. Change will come through technological innovation and confidence in the fact that a feasible road map exists.

New openings

The Dutch negotiating model is not a recipe that can be applied wholesale elsewhere. Yet the lessons it provides could be relevant to other places too. The support needed to achieve fundamental changes in the energy field is lacking in many countries. Talking to people in California, Sweden, Singapore and elsewhere, I have sensed a frustration that it has not been possible to build support for the transition. The traditional top-down approach has run into opposition from local communities, political parties and environmental organisations. There are lots of great plans out there, but their implementation remains difficult.

The way to address this is to engage in open negotiation with a wide range of interests represented around the table. I would not necessarily wish our approach on anyone else: it is stressful and it takes trust and personal courage to pull off. We will know in a few years' time if the Dutch model has worked by whether it delivers the results we have just agreed.

We are taking a first step in the right direction at a speed with which everyone can keep up, confident that we will know how to continue at a later stage. We are also confident that the process will accelerate in the future. The precise nature of this acceleration is not clear at this point, but 10 years from now it will prove to be a decisive part of the transition.

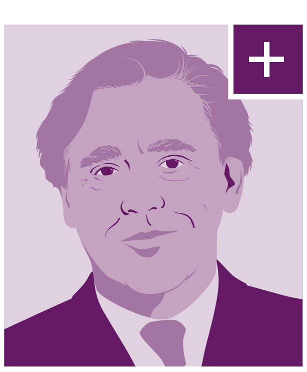
Related essay

Sustaining the transition
Towards a European energy agreement
> *Ed Nijpels*

Wiebe Draijer became chairman of the Executive Board of Rabobank in the Netherlands in October 2014. At the time of writing (spring 2014) he was chair of the Social and Economic Council of the Netherlands – an authoritative advisory and consultative body for employers, employees and other social partners. Prior to that, he was an adviser and partner at McKinsey. Draijer studied mechanical engineering at Delft University of Technology in the Netherlands and earned an MBA at the Insead Business School in Fontainebleau, France. He is a former journalist at the Dutch national daily newspaper *NRC Handelsblad.*

Sustaining the transition
Towards a European energy agreement

The unique Dutch approach to the energy transition is beginning to work. A motley crew has now come together to shape it. Their success can be repeated at the European level.



> *Ed Nijpels*

An unlikely assembly of 47 parties is now steering the Netherlands through the energy transition. Wiebe Draijer, who led the negotiations, describes beautifully elsewhere in this book how the tears flowed when opponents who otherwise avoided each other put their signatures to the *Energieakkoord* (‘energy agreement’), which lays out targets and measures for sustainable growth. The motley crew on board ranges from employers’ organisations to the Association of Dutch Municipalities, from public housing corporations to the Climate Alliance, from environmentalists to utilities. They now all bear responsibility for a common energy policy.

The central targets are clearly set. The share of sustainable energy must increase (to 14% in 2020 and 16% in 2023), 15,000 new jobs are to be created, and 100 petajoules of energy savings must be found. This is no small task for a country that has only a 4% share of renewables.

Yet the consistent course over more than 10 years that the *Energieakkoord* sets out is important for the success of this transition. The agreement is a welcome answer to the inconsistent policies implemented over the past 10 years, in which five different governments with different political visions determined the course. The *Energieakkoord* brought an end to the series of surprises that made it difficult to invest and to initiate multi-year developments. Social organisations, businesses and consumers have ended the succession of new energy policies by stepping outside their usual boundaries and agreeing on common targets and measures.

The signing of the *Energieakkoord* was only the beginning. The broad coalition that agreed on measures to cap carbon emissions is also bound to carry out the promised actions. All the parties pledged to participate in a steering committee (*borgingscommissie*).

That was the point at which I came on board. In this essay I will give a taste of my day-to-day experiences over the first year, especially in some sectors where measures proved hard to take. And I will share some insights that might help Europe to streamline its energy transition.

A motley crew

Chairing this – to put it mildly – rather heterogeneous group of interested parties is a unique experience. It quickly became clear to me that no voice could be missed, and that indirect representation wouldn't work. We therefore soon decided to hold regular plenary sessions with all parties involved in crafting the *Energieakkoord*. Not to take decisions, since those had already been taken and are established in the *Energieakkoord*, but in order to keep an eye on its implementation. In these plenary sessions, we keep each other informed and monitor progress.

So far, it has worked well and we have kept those 47 parties together. There are even some other organisations that would like to join, such as industry or social organisations. But it does not make sense to admit people who reconsidered once the *Energieakkoord* was successful. And we are not going to negotiate with anyone, not even with the parties that have already signed the agreement. If we start negotiating again, it will become an endless task.

That does not mean that the parties currently involved always keep quiet outside. That would be a miracle. Environmental organisations, for example, continue their campaigns. In fact it would not be good for them to be silent. If we want to see a successful implementation of the agreement, it is necessary to be open. Everyone has to be able to follow what is happening. That means that the meetings of the steering committee are public. Everyone can enjoy the contrasting opinions, the arguments, the chagrin and the joy. There is also a website on which progress can be followed (www.energieakkoordser.nl) and where all 134 agreed action points are listed. Progress gauges indicate how much has happened. We can thus check whether everyone has done their homework.

The effect of measures

Establishing subsidies, changing laws and regulations and taking other kinds of action won't automatically have the desired effect. A second important part of our auditing is therefore to assess the effects of the measures taken. Do wind turbines deliver as promised? How much does the insulation of houses contribute to energy savings? These and similar issues are assessed by the planning agencies that have a long tradition of following policy in the Netherlands, especially the Netherlands Environmental Assessment Agency (PBL) and the Energy Research Centre of the Netherlands (ECN). We agreed that they would produce an annual public report, the *Nationale Energieverkenning* (National Energy Outlook), as an X-ray of what is happening. The report shows what the effect of the measures is and how that contributes to the central targets of the energy agreement. This closes the audit cycle.

We have succeeded in de-linking energy use from economic growth

The first report came when we had only been working for five months. As might be expected after such a short time, a number of things were not included, because they had not yet been fleshed out enough to be quantifiable. That was widely publicised in the media, but we did not want to hold off on the report. It is important to report consistently from the outset, so that everyone can clearly follow what is happening. The blank spots were primarily in four areas in which the *Energieakkoord* makes only global agreements. That applies for mobility and transport, heating, greenhouse farming and a remainder category in which 186 petajoules of sustainable energy projects had to be found – mostly small-scale projects with very diverse technology that do not lend themselves to one all-inclusive agreement. We are going to fill that in with supplementary measures as quickly as possible, so that the following report is more complete.

Including an estimate of these blank spots, we will achieve 88% of the target for sustainable energy in 2020. This is lower than we need, but the signatories to the agreement accepted that at the time, in the hope that they could set a dynamic in motion that would deliver more than could then be calculated. According to the latest progress report, we have already succeeded in de-linking energy use from economic growth. That means that the transition to sustainable economic growth becomes visible. A somewhat larger share of renewables is needed, but we still have five years to reach the target.

Uncharted waters

Only a naïve person would think that the implementation of the *Energieakkoord* would be without hiccups. Not a day goes by without a new issue landing on my desk. Sometimes these make it into the media, like the question of whether old coal-fired plants could really be closed. The Dutch Authority for Consumers and Markets thought that this agreement would disrupt the market. But at the same time, the closure of those coal-fired plants is one of the pillars of the energy agreement. The government has now found another way to realise that. It also shows that, with the *Energieakkoord*, we are following a new path, on which you sometimes collide with existing rules. There is also a continuous stream of adjustments to laws and regulations. There are now approximately 100 officials working on the laws needed to implement the *Energieakkoord*.

But the difficulties do not lie only in the area of laws and regulations. Sometimes, there are simply disagreements between parties aboard the *Energieakkoord*. That applies, for example, to the co-firing of biomass in coal-fired plants. It was agreed that the environmental movement and energy companies would together establish sustainability criteria for the use of biomass. The two parties were close to agreement, but could not agree, in particular about the timetable for the changes to be realised. Such disagreements are unfortunate and it does not help when parties fight out their differences in the media. But the parliament called on them to resume negotiations. That has happened, and it finally led to an agreement to only use wood from sustainable forests, with stricter requirements than any other country imposes.

With wind energy, we are also well on track. The government has designated the locations for offshore wind projects, and the legislation is being prepared. In the run-up to the *Energieakkoord*, the industry stated that a 40% saving would be possible. This would be achieved through economies of scale and continued innovation. An example is the building of substations, which collect the energy generated by the wind farms, convert it and transport it to the mainland via just one collection point in the seabed. With that ‘socket in the sea’, the wind farms no longer need their own connections to the coast. The potential savings have been heavily debated in the media. Yet leading industries have confirmed that the costs savings are realistic. In order to stimulate the industry to deliver on its promises, the 40% savings are a firm condition for the granting of permits.

The allure of transformation

The greatest challenge of the *Energieakkoord* is the energy savings in the urban environment. That is a troublesome and complicated part of the agreement, especially because it deals with so many relatively small projects. We are talking to all 393 Dutch municipalities, thousands of contractors, thousands of installers and – ideally – 17 million citizens. Ultimately success in this sector will rely on our ability to make a cultural shift. Contractors and installers have to begin approaching consumers proactively. They have to show citizens what changes can save energy in their homes. Municipalities are now establishing 'energy desks' that encourage the construction industry to approach citizens in this way. The government also has funds available for these desks, but the municipal councils have to take action.

There are many technological options for energy savings in the urban environment, but my foremost concern is: How do I get the contractors' vans into the street? It is primarily about unburdening the citizen. When things become too complicated, they don't work, as shown by one of the setbacks we experienced. An energy-savings fund was started for individual residences. It grants citizens low-interest loans for the implementation of energy-saving measures. In 2014, there was €300 million available, but just €16 million of that was distributed. Apparently, it is still too complicated to convince citizens. We need to make progress easy and visible. That is the success of another project, *Stroomversnelling* (literally: 'rapids'), which shows how houses can be remodelled in four days into energy-neutral residences. It targets typical Dutch row houses, which were built across the country en masse from the 1950s to the 1970s, but which are often draughty and poorly insulated. The remodelling is a project for construction companies and housing corporations in collaboration with banks, municipalities and provinces. This transformation costs the residents nothing extra. They just continue to pay their usual energy charges to finance the modification. As a result, a great deal of energy is saved and the residence becomes much more comfortable and attractive. It gets, for example, an elegant overhanging roof for the solar panels and a more interesting facade. These transformations will also create a great deal of extra work; until 2020, there is 9,000 man-years' work needed to make rented houses energy-neutral.

Further steps

Now that the *Energieakkoord* has been concluded, an important task is to keep the agreements intact, even if a new government comes along. The current government and parliament have agreed with the *Energieakkoord*, and with that have bound their successors for the coming 10 years. In addition, we are quickly documenting the rights and obligations so that they are irreversibly established in law. The criteria for subsidies are thus fixed. That makes them administration-change-proof.

There is a planned evaluation in 2016. We are not going to review the goals then, because those are established. The evaluation is about the effectiveness of the measures. Are we achieving the goals, or do we need additional measures? At the same time, we will also look ahead beyond 2023. The *Energieakkoord* contains targets up to 2050, yet no measures have been formulated beyond 2023. We will simultaneously discuss the shorter term and the longer term. That makes it possible to evaluate whether the measures that we have already agreed upon fit with what has to happen in the longer term. We need to prevent longer-term goals from being frustrated by shorter-term measures.

One bottleneck has already appeared. In all EU Member States a transition to renewable energy is under way, but a common approach is lacking. The nationalisation of energy policy has resulted in a patchwork of subsidies for renewable energy generation, subsidies to cushion their impact, surcharges for power transmission and so on. This incoherent policy has undesired cross-border effects and costs Europe billions. Co-operation is necessary in order to eliminate unnecessary costs. Moreover, existing regulations are not applied coherently. The European Commission has now announced its Third Energy Package of measures, but previous measures are still only 30% implemented. There are 10 countries that have not done anything at all. The interconnectivity of power networks, for example, is still far from how it was planned. That has to improve, because the peaks and troughs that many sustainable energy sources have are much easier to compensate for when networks are connected. Furthermore, we need collective technology development for, for example, energy storage. That is urgently needed as the share of sustainable energy increases. Additionally, the financial measures that the different Member States have taken in order to stimulate sustainable energy need to be harmonised; otherwise they can work against each other. Finally, we can best collectively ensure that we are less dependent on imports. Europe imports more than 50% of the energy that it uses, at a cost of more than €1 billion per day. Russia is by far the largest supplier: a third of the raw oil for European refineries comes from Russia, and a bit more than a third of the imported gas. A common energy policy can make Europe more resilient to interruptions.

A cohesive European energy policy can save billions

A cohesive European energy policy can save billions if we are successful in working not against but with each other on it. It is therefore necessary that we dare to transfer a number of authorisations over to Europe; otherwise, energy policy will never become a cohesive whole.

The European Commission has to get to work on these points. But, in addition, it would be good to get the different industries around one table at the European level, the way the Netherlands managed to do with the *Energieakkoord*. There is a representative trade union movement and an organisation of enterprises at the European level. The environmental movement also works together internationally. The European Commission should also come to the table. Those parties can collectively manage to make agreements.

Furthermore, successful measures in the Netherlands can also be repeated in other countries, such as the *Stroomversnelling* to transform houses or the mechanisms to implement offshore wind. Conversely, we can learn from other countries, since we are of course not the smartest kid in the class. There are other countries that have progressed further with the transition to sustainable energy. Yet we all deserve a stable, consistent policy that puts an end to dependence on imports and secure investments in the energy transition. The Dutch experience shows that consistency and a broad agreement help to advance the transition.

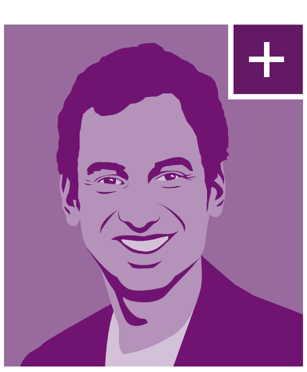
Related essay

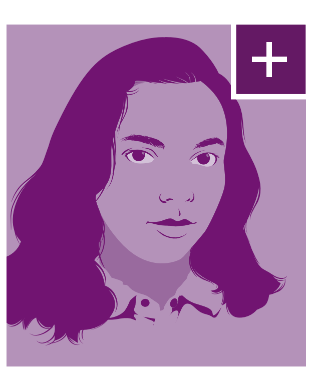
A collective approach to change
Negotiating an energy transition in the Netherlands
> *Wiebe Draijer*

Ed Nijpels is chairman of the steering committee which implements the *Energieakkoord*. He is a former politician of the People's Party for Freedom and Democracy (VVD). He was Minister of Housing, Spatial Planning and Environment from 1986 to 1989, mayor of Breda from 1990 to 1995, and Queen's Commissioner in the province of Friesland from 1999 to 2008.

Empowering women to power the world
How solar lanterns brighten life in Nepal

Bennett Cohen and Anya Cherneff wondered why people in Nepal continued to rely on kerosene lamps when solar lights could dramatically improve their lives. That set them on a journey to empower local women to become entrepreneurs and build a sustainable market for clean energy.





> *Bennett Cohen and Anya Cherneff*

The sun is setting over the mighty Himalaya, and Manju, a young mother in rural Nepal, sees the fumes thicken above her village. Her neighbours are lighting kerosene lamps to provide some light in the dark of night, and stoking indoor fires to prepare dinner. Without these dim flames, the village gets dark on moonless nights in a way those of us in cities can scarcely imagine. It's a darkness that is increasingly rare on such a crowded planet as ours. Yet, there are still roughly 1.2 billion people, or 20% of the global population, living in the darkness of energy poverty.[1]

Some of the households in Manju's village have access to the power grid but this night, as usual, it is down. The capital city, Kathmandu, has priority when it comes to rationing the measly amount of electricity flowing through the rickety Nepali grid, and much of that is rumoured to be hogged by government facilities. Nepalis are starved of energy, despite their much-lauded potential for domestic hydropower, because such large projects and grid expansions require stability, infrastructure and an effective central government. Like countless people in developing countries, Nepalis have been waiting for generations for these potentials to be met. Less than half the population has access to the grid, which is down more than half the time. Those tired of waiting for centrally driven solutions have increasingly taken power into their own hands.

Rather than lighting the kerosene lamp – the default lighting 'solution' for the world's poor – Manju reaches over and flips the switch on her 'd. light S20'. It is a solar lantern that provides bright LED light from dusk to bedtime, and will last for many years. Since acquiring it, her home has become a bright spot in her rural village, where a literacy class meets, women gather to work and children come to study. When provided the option, more households like Manju's are choosing to go solar, using just one or two affordable watts at a time to meet their basic lighting needs.

Seventy per cent of the people living in energy poverty are women and girls, largely because men migrate to cities or abroad in search of work.[2] This leaves women like Manju increasingly responsible for growing the rural economy that is plagued with energy poverty, yet they are denied the same financial, technological and social resources as men. Forced to rely on kerosene, women like Manju know all too well its high costs – kerosene can account for nearly a third of household expenditure.[3] In addition to the constant expense, kerosene lighting is also dangerous for women's health: the air pollution from indoor combustion results in the death of around 2 million women and children globally each year, and scars from burns are all too common; in Nepal, exposure to kerosene increases women's likelihood of tuberculosis ninefold.[4] Because of the low socio-economic status of women, Nepal is one of the only countries where men have a higher life expectancy.

Having sacrificed so much for lighting in the past, Manju's decision to buy a solar lantern was an easy one. It paid for itself in a few months and came with a two-year warranty. Because Manju knows the local solar retailer well, she has faith that the warranty will be honoured, and feels like a valued customer, rather than just a remote consumer. Financing from her local savings and credit co-operative allowed Manju to pay for the light over time, in similar instalments to her previous kerosene purchases.

Manju has become a sales agent and a champion for solar products in her community. The trust other women have in her affords them the confidence they need to go solar as well. Over time, Manju has earned enough money from her kerosene savings and sales commissions to buy an additional solar light, this time the €27 ($30) 'd.light S300'. It provides more and even brighter light than the 'S20' (at $13 or €11.5) and also charges devices via a USB port. It is now possible to have a reliably charged mobile phone as well.

Manju's story illustrates the life-changing potential at the intersection of distributed clean-energy technologies and the empowerment of women into the workforce. In developing countries, women often serve as the household energy managers, responsible for obtaining fuels such as kerosene and biomass, and burning them – usually indoors – to provide energy for lighting and cooking. Just collecting the required fuel can take up to eight hours of a woman's day (a full-time job). Imagine the opportunity to unleash this wasted time and human capital.

Our journey begins

We, Bennett and Anya, created Empower Generation to turn energy from a life-threatening struggle into a life-changing opportunity for women in developing countries. Empower Generation is the marriage of two transformative passions: Anya is an international development professional with a focus on female empowerment and the abolition of human trafficking and forced labour, while Bennett is a clean-energy specialist with a passion for entrepreneurship. We are a married couple who found that that there is a tremendous opportunity for social, environmental and economic impact at the intersection of our work.

Our journey with Empower Generation began gradually. We would sit on our couch in Brooklyn, New York and talk about the opportunity to help women in energy-starved areas become catalysts for the clean-energy transition. Through our work in the non-profit and energy management sectors, we knew that a top-down approach could not address energy poverty or lead to true gender equality. After a few years of developing our ideas, we set off for Asia, where Anya had professional experience. In 2010, we travelled through Nepal, Laos and Cambodia, talking with local communities, non-governmental organisations, government agencies and business leaders to learn about what was already happening in clean-energy deployment and women's economic empowerment, and to see if there was a need for our concept: empowering women to run clean-energy distribution businesses. We listened more than we spoke and noted the many challenges we would face. Overall, we concluded that our concept, which others were also pursuing, had vast potential to positively affect the lives of many.

We observed that, even in 2010, new solar-charged, battery-powered LED lamps were extremely competitive with kerosene lamps and that there were several international companies developing these products specifically to meet the energy needs of the world's poor. We wondered why the people whose lives they could improve dramatically did not have access to these products in large numbers. Distribution and finance rose to the surface as the two biggest challenges to tackle, and local women seemed to hold the keys to both.

Most efforts to include uneducated women in the workforce were focused on transferring sewing and cosmetology skills, but with energy provision and use at the core of women's responsibilities, clean-energy distribution seemed like an even more promising opportunity. As household energy managers, women feel the most pain from energy poverty and have the most to gain from a transition to clean and modern energy. We believed that a rural network of women entrepreneurs could become a robust distribution system for clean-energy products, and a strong female presence in Asia's emerging economies. On the need for customer financing, women in Nepal (and many other countries) commonly pool savings to provide loans to one another for important investments such as livestock, education, small businesses or medical services. Loans for clean-energy businesses and products appeared to be a logical addition to the list of financial products available through microfinance. Women's microfinance programmes have proved to be an effective tool for development worldwide.

"I really want to bring solar power to my community"

In Chitwan, a district in southern-central Nepal, we connected with Sita Adhikari, a passionate local leader, and the founder of her local women's savings and credit co-operative. When we met her, she was also heavily involved with running the women and children's section of her community library. Sita was proud of all these community initiatives she had worked on, unpaid, throughout her adult life, but remarked (unprompted), "What I really want to do next is bring solar power to my community. We all really need it and I want to start my own business."

Sita became our pilot entrepreneur in 2012. Through a crowd-raising initiative on Kickstarter.com, we raised enough money to give Sita a start-up loan to buy solar inventory and a motorbike and enrol her in training for small-business management and solar-energy technology. We introduced her to d.light's Nepal distributor, supported her in negotiating terms and consulted as they established a trusting, professional relationship. We also seeded a few 'Clean-Energy Funds' at local savings and credit co-operatives in her target market, giving her customers the option to pay for the solar lights over a six-month period.

This whole pilot project cost under €7,000 ($8,000). Our goal was to learn how to be successful employing the Lean Startup philosophy of going to market with a minimum viable product with just enough features to test the market and gain as much validated customer learning as possible ("fail fast and fail cheap"). As a social enterprise, our product was our entire impact model of identifying and training capable women, supporting their businesses with capital, customer financing and awareness building, and giving assistance connecting and negotiating with international clean-energy product suppliers.

We saw realistic pricing for clean-energy products, marketed to the poorest of the poor, to be a key validation of our impact model. We do not see a future in highly subsidised or free products for the world's energy-poor. This approach has already been tried by countless organisations and governments, and with limited success in achieving widespread clean-energy adoption. This is due to beneficiaries not valuing that which comes for free, a lack of any local buy-in or participation in programme implementation, the crowding out of local players from emerging clean-energy markets, and an endless need for external funding that leads to a destructive culture of donor-dependency. In an extreme case, solar home systems were 90% government-subsidised in 'very remote' unelectrified areas of Nepal. This resulted in the government support programme effectively *being* the end customer, and local installers quickly putting up large, shoddy systems to claim subsidies without considering the needs of their customers or what products were appropriate in the local market. We have seen systems that stopped working months after they were installed with no way for the customer to contact the installer to maintain them. Since the installers had already collected the subsidies, there was no incentive for them to return.

The test

When our first solar products arrived in Nepal, we were nervous. Would people actually buy the lights at a sustainable market price? Could Sita actually make enough sales to turn a profit?

To our extreme delight, the lights sold steadily at the manufacturer's suggested retail price. Sita began to relay stories of children studying and women making handicrafts at night using bright, clean, and safe solar-charged LED lights. Of course, not everything went smoothly – far from it! But the learning offered from our early mistakes and challenges was well worth the cost of the pilot project. In her first year of business, Sita sold over 500 solar products.

Today, around two years later, Empower Generation is scaling up its impact. By the end of 2014, we were supporting seven solar retailers in different regions of Nepal; Sita's business has vertically scaled to become a national distributor of d.light solar products and has sold over 4,000 solar products. By the end of 2014, Empower Generation's distribution network had deployed over 12,000 solar products, which have provided bright, clean and safe light to 60,000 people.

The impact of even a modest deployment like this should not be underestimated. The average household size in Nepal is 4.9 people and the lights run for at least 3.5 hours on a charge. They are guaranteed to run for at least two years, with the lights having an expected life of five years. Adding this up, each kerosene-replacing light provides a household with around 12,500 people-hours of productivity that would have otherwise been lost to darkness. With bright LED light, activities such as studying and fine handiwork become possible. Deploying 13,500 solar lights could add up to over 170 million additional productive people-hours in Nepal. These staggering calculations reveal the true promise of affordable clean energy for all. This deployment would also avoid over 2,000 tonnes of carbon dioxide from kerosene combustion and reduce household energy expenses by over €100,000 ($120,000).

The social impact can also be vast. Each business Empower Generation supports provides full-time employment, access to training and increased social capital for the entrepreneurs chosen to lead them, as well as income-generating opportunities for the network of women, like Manju, working as village sales agents. So far all the women in Empower Generation's network have children; most were married at a young age and left school before receiving their high-school diploma. It's a true inspiration to witness their extraordinary transformation from shy housewives to deal-making clean-energy CEOs and savvy sales agents.

Of course, Empower Generation's impact in Nepal is just a drop of light in the global bucket of energy-poverty darkness, but many collaborators are working towards the same goal of delivering clean, super-rugged and affordable solar-power kits to the energy-impoverished, while encouraging social entrepreneurship and local market development. The movement is gaining momentum. In 2014, an increasing number of top-tier venture investors entered the space – most notably, Draper Fisher Jurvetson and Khosla Impact – pouring investments into solar companies targeting developing countries. Generally, these companies are raising money to increase distribution, improve their designs, and invest in new technology.

The next chapter(s)

Today's entrepreneurs selling solar lights and mobile chargers are planting the seeds of a bottom-up, distributed clean-energy system. Growing an energy system based on distributed renewable energy and storage makes more economic sense for unelectrified countries than building a centralised system based on early 20th-century economics.[5] Developing countries have the potential to leapfrog past massive power plants and miles of high-voltage transmission lines to distributed generation and micro-grids in the same way that many have famously forgone fixed landlines in favour of cellular phones and towers.

In addition to lower system cost and cleaner energy, a distributed energy system has a crucial advantage over the centralised paradigm in a developing country context: speed. A system based on small investments has the potential to be delivered much faster in areas with considerable market risk, due to the ability of customers to take power into their own hands. By making small, gradual investments in clean energy, customers can climb the energy ladder one affordable rung at a time, and with low risk.

Mega-projects, on the other hand, such as hydroelectric dams and high-voltage transmission, are notoriously challenging to finance in areas that are unstable or have weak rule of law and infrastructure.

The proliferation of wireless communication and distributed clean-energy systems in developing countries may mutually reinforce each other. Several companies now offer solar lights and home energy systems with cellular technology embedded to enable weekly payments from scratch cards purchased at the local market. Embedded bluetooth chips allow local retailers to lock and unlock solar home systems based on whether the customer is keeping up on their payments. Such schemes bring down the upfront cost of these systems and allow people to pay for energy as they use it (like most of us living in developed countries). Wireless technology also enables solar entrepreneurs to access customers dispersed in hard-to-access, extremely remote areas. From this perspective, mobile phone companies may be poised to become the electric utilities of the future. They certainly have a natural motivation to enable customers to keep their phones charged. A solar-charging entrepreneur programme organised by MTN (Africa's largest telecommunications company) resulted in a 14% increase in average revenue per user in Uganda.

We can already see the beginnings of a virtuous cycle. Solar-powered light and phone charging increases productivity and reduces energy costs for previously stranded households. Increased income and savings enable households to invest more and climb another rung up the energy ladder to light their whole houses and maybe even power a low-wattage direct current television. Several more rungs up lies the modern, cleaner energy security many take for granted in other countries. Access to modern energy leads to progress in virtually every area of economic development, including education, health and income-generating opportunities.

Solar photovoltaic power supply is allowing people in remote areas to generate electricity affordably, and without constant fuel delivery (the sun takes care of that). The costs of solar photovoltaics have plummeted by 80% in the last four years, but even with photovoltaics costs falling, without super-efficient use of the electricity generated, solar-based energy systems would still be unaffordable for the world's poor. The super-efficient light-emitting diode (LED) lights that frugally sip on the solar-electricity stored in a lantern's battery are what enable just a few watts of photovoltaic power to light a small home for an entire evening. Powering an incandescent bulb, for example, would require around 10 times as much power, making the whole proposition entirely unaffordable. Thus, growing the energy system from the bottom-up may lead to a radically more efficient society, as super-efficient appliances follow LED lighting, limiting the amount of supplied energy required. The world's poor cannot afford to be inefficient.

When the end customer lives at the base of the economic pyramid (BoP) on less than €1.80 ($2) a day, there is a necessary pressure to keep prices as low as possible. This can result in margins being squeezed, making it difficult for all links of the distributed solar value chain to survive. A balance must be struck between the necessity to deliver to the poor at low cost and the need for margins to be high enough to keep manufacturers, importers, distributors and most importantly retailers interested in extending the clean-energy market to the hardest-to-reach customers. For international solar suppliers, the prospect of entering a remote and unfamiliar market can be daunting. For example, Nepal's import/export laws are opaque, and steep import taxes alone are enough to make the whole proposition too expensive. Solar products for the BoP can be tax-exempt, but the process of getting the exemption is convoluted and slow.

In general, shipping goods to developing markets can feel like a leap of faith. Indeed, none of Empower Generation's shipments have arrived in Nepal without a few solar lights 'falling off the truck' somewhere along the way, or without serious delay. For international investors, the prohibitive foreign investment laws and barriers to trade can overshadow the impact and potential social, environmental and economic returns that investments in clean-energy distribution in the developing world can make. The same poor governance and lack of rule of law that make investing in traditional power plants and grids too risky can also stall the bottom-up approach.

Keys to success

Two overarching keys to success are “start with lean social innovation that comes from the needs of the community you serve” and “build a self-sustaining market with a built-in exit strategy”. Regarding the first key, every market – indeed, every village – is unique. Outsiders wishing to develop clean-energy products or markets for the BoP must first understand current household energy needs and practices. Empower Generation’s lean pilot project allowed us to fail fast and correct our model. Each enterprise that Empower Generation supports is independently branded, owned and operated – they have different identities and can grow in different directions. One advantage of this approach is that if one business fails, it will not bring down the entire network’s reputation. The independent identities of the businesses we support fit the vision of a community-led, bottom-up energy transition. The willingness to try new ideas quickly and without a massive investment remains important, especially since technology rapidly evolves.

Most importantly, our willingness to listen to the ideas of the entrepreneurs we support, follow their business plans and take their advice on how best to reach out to their communities as customers is what allows us to be successful. So many well-intentioned development projects fail because the needs, concerns, opinions and motivations of the beneficiaries are not properly integrated. A great piece of technology is nothing but an object without the appropriate contextual understanding of how to advertise, distribute and use it. This year, in partnership with Mercy Corps Nepal and funded by the UK’s Department for International Development, Empower Generation is piloting and extending its training programme to girls who had to drop out of school before getting their high-school diploma. These girls will become sales agents, servicing 30 schools in Kailali District, in one of Nepal’s poorest regions, where the education rates for girls are lowest. Girls will sell solar lights at their schools to current students and teachers to improve and extend study time.

The second key is to always be driving towards a self-sustaining market. It surprises people (particularly potential investors) to hear us say that our goal is to become redundant in the markets we create. People in developing countries can and must run their own solar show, especially at the retail level. Clean-energy markets cannot work if they rely on foreign aid and management indefinitely. Therefore, the capacity building of local people to own and operate business in their way is crucial. One lesson from international development efforts in the 20th century was a shift away from trying to offer solutions towards building local capacity to solve problems. Customers certainly see the benefits of solar versus kerosene lighting, but to serve them over the long term, local actors must be profiting from the value chain and be incentivised to provide after-sales service to their customers. Empower Generation helps its entrepreneurs register their business independently and we aim to provide all the tools and training they need to eventually feel confident operating their business on their own.

Clean power is a chance for women to become leaders of the energy sector

One goal for Empower Generation is to use clean energy as an opportunity to bring about a gender-equal economy. Women around the world are trapped in restrictive gender roles, with limited local economic opportunities. With household energy management falling largely on the shoulders of women, clean power to the people means a chance for women to become leaders of the energy sector, which would be good for the entire world. According to *The Economist*, women entering the workforce in the developed world have contributed more to global GDP growth over the past few decades than any other factor, including the internet or the rise of China and India.[6]

Training local women to be clean-energy entrepreneurs who create local economic opportunity is a huge social boon. Pabitra, Empower Generation's second entrepreneur, has three daughters who inspired her solar business's name: Tri Urja, or "Three Powers". Watching their mother step out of the traditional Nepali gender roles as a housewife and social volunteer and grow in capacity and confidence as an income-generating business owner has increased her daughters' expectations for themselves and their future. Solar power from the people and for the people is brightening the world in more ways than one.

Related essay

Energy efficiency
The rest of the iceberg
> *Amory B. Lovins*

Bennett Cohen is a member of Shell's Future Energy team. He is also is the chair and co-founder of Empower Generation. He has worked with Rocky Mountain Institute, Shell, CPower and the Federal Reserve Bank of New York. Cohen graduated from Delft University of Technology (the Netherlands) and Columbia University (USA).

Anya Cherneff is executive director and co-founder of Empower Generation. She has also been a founder and associate director of the Human Trafficking Clinic and a Princeton-in-Asia fellow in Malaysia. She holds a Master's degree in Human Rights from the University of Denver (USA) and a Bachelor's degree in Anthropology from Columbia University (USA).

References

1. Estimates vary, http://web.worldbank.org/WBSITE/EXTERNAL/TOPICS/EXTENERGY2/0,,contentMDK:22855502~pagePK:210058~piPK:210062~theSitePK:4114200,00.html.
2. UNDP (1995). *Human development report*, http://hdr.undp.org/sites/default/files/reports/256/hdr_1995_en_complete_nostats.pdf.
3. http://e360.yale.edu/feature/solar_power_off_the_grid_energy_access_for_worlds_poor/2480/.
4. A.K. Pokhrel (2010). Tuberculosis and indoor biomass and kerosene use in Nepal: A case-control study, *Environ. health perspect., 118*, 558-564.doi: 10.1289/ehp.0901032.
5. A.B. Lovins (2003). *Small is profitable: The hidden economic benefits of making electrical resources the right size*, Rocky Mountain Institute: Snowmass, CO.
6. Women in the workforce: The importance of sex, *The Economist*, 12 April 2006.

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