WORLD ECONOMIC FORUM

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Industry Vision

Energy Vision 2013
Energy transitions: Past and Future

Prepared in Partnership with IHS CERA

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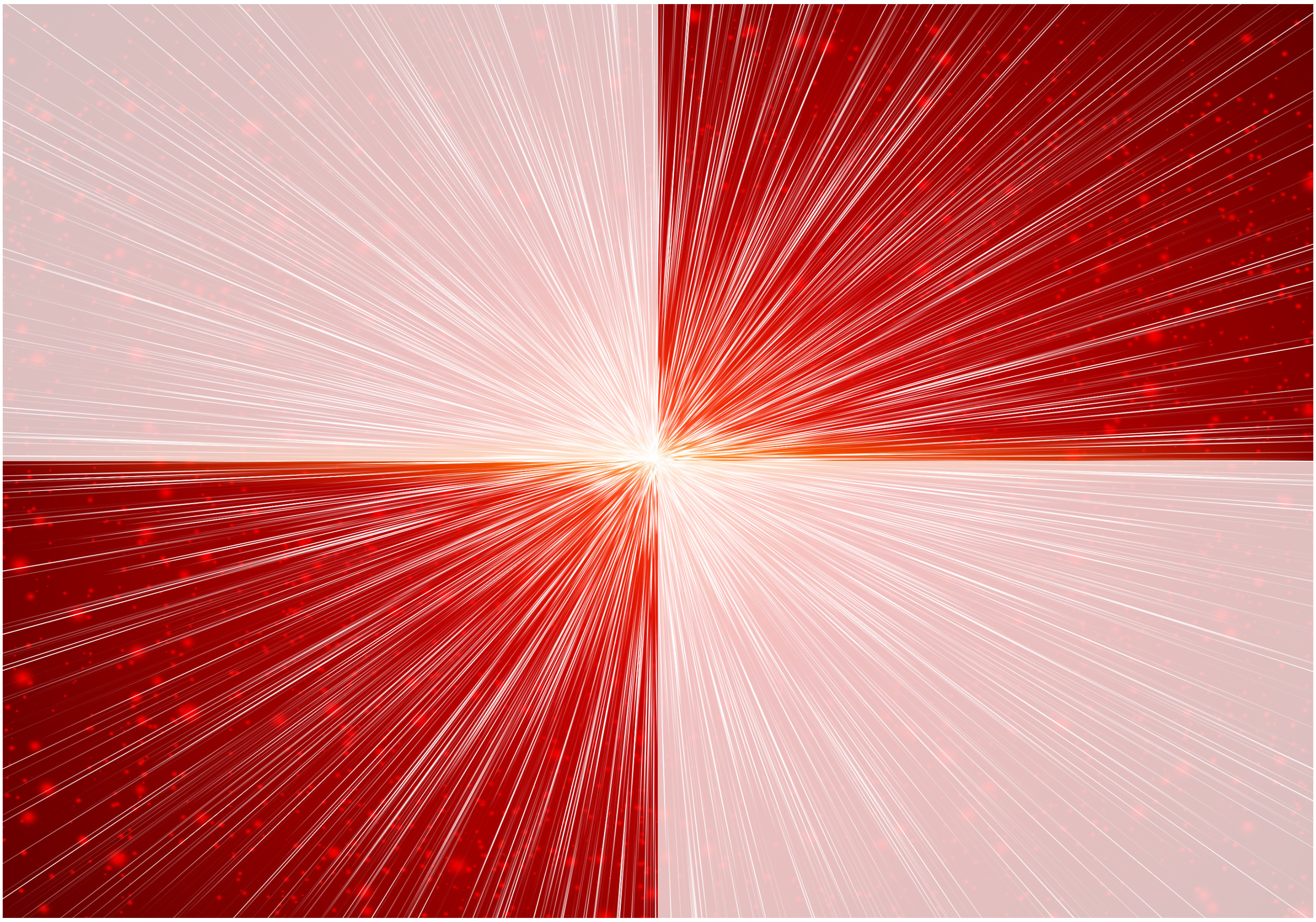

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The World Economic Forum is an independent international organization committed to improving the state of the world by engaging business, political, academic and other leaders of society to shape global, regional and industry agendas. Incorporated as a not-for-profit foundation in 1971 and headquartered in Geneva, Switzerland, the World Economic Forum is tied to no political, partisan or national interests. (www.weforum.org)

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IHS Cambridge Energy Research Associates (IHS CERA) is a leading adviser to energy companies, governments, financial institutions, technology providers and consumers. IHS CERA delivers critical knowledge and independent objective analysis on energy markets, geopolitics, industry trends and strategy. (www.cera.com)

IHS CERA's expertise covers all major energy sectors – oil and refined products, natural gas, coal, electric power and renewables, as well as energy demand, climate and efficiency – on a global and regional basis. IHS CERA's team of experts is headed by Daniel Yergin, Vice Chairman, IHS, author of *The Prize: The Epic Quest for Oil, Money and Power,* for which he won the Pulitzer Prize, and of *The Quest: Energy, Security, and the Remaking of the Modern World.* IHS is the leading source for critical information and data on which the upstream oil and gas industry operates worldwide, as well as for insight on the global economy, security and the standards under which the world's industries function. (www.ihs.com)

About the World Economic Forum Energy Industry Partnership

The Energy Industry Partnership (IP) programme of the World Economic Forum provides the CEOs and senior executives of the world's leading companies as well as select energy ministers with the opportunity to engage with their peers to define and address critical industry issues throughout the year. Identifying, developing and acting upon these specific industry issues is fundamental to the Forum's commitment to deliver sustainable social development founded upon economic progress. The Forum's Energy Community Chair for 2011-2012 is Daniel Yergin, Vice Chairman, IHS.

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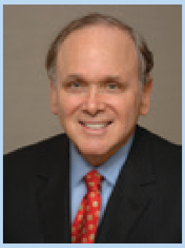
The Puzzle of Energy Transitions

Daniel Yergin

Vice Chairman, IHS, USA; Oil & Gas Community Leader 2012, World Economic Forum



Every year, the World Economic Forum's *Energy Vision* tackles a major theme in the energy arena. In *Energy Transitions: Past and Future – Energy Vision 2013* the topic is the energy mix – its evolution over time and the challenges for the next transition. This we accomplish through the essay that runs as the core through the work and through the Perspectives of distinguished contributors that provide different views of future energy transitions.

Previous energy shifts have unfolded over decades, the result of the gradual development and adoption of new technologies and new uses, and of relative prices and usefulness. But it was only after the 1970s that the focus on energy transitions became more explicit – because of a new quest for energy security, a rising environmental consciousness, the spectre of permanent "shortage," and the assumption that prices would remain permanently high, damaging economic growth. (To provide a framework on these shifts, we include the World Energy Timeline, derived from *The Quest,* which depicts chronologically how energy transitions have unfolded.)

Today there is a renewed and much more intense focus on what kind of energy transition might be ahead and what the timing might be. Two factors have converged to generate this focus. The first is the concern about climate change and the traction of carbon policy in many countries and international forums. The second is the worry that the current energy mix will not prove adequate to meet the rapidly growing energy needs of emerging market nations. The shifts in the balance within the mix will have direct consequences for all participants in the world's energy industry – incumbents, new entrants and innovators, governments and, of course, for all the peoples of the world.

In this year's *Energy Vision,* certain conclusions and observations stand out.

— A "transition" is not an abrupt change from one "reality" to another but rather a shift that unfolds generationally over considerable time, and one that may lead to greater diversity in the energy marketplace.

— Since the beginning of this century, we have seen a rebirth of renewables. Renewable power has become a significant and highly visible business – with revenues totalling US$184 billion in 2012. It is now a global industry. Its growth has been spurred by a mixture of research and development, innovation and government policies – mandates, subsidies and incentives – aimed at promoting its market penetration. This growth has been accompanied by a marked advance in technology and a substantial decline in the costs of wind and solar. Parallel policies have promoted biofuels. All this represents an effort to shift from "ancient sunlight" for our energy to "just in time sunlight."

— Yet the picture is more complicated. Though little recognized, in terms of energy generated the biggest growth since the beginning of the century has been, by far, in coal – nearly twice that of natural gas, nearly three times that of oil, and almost ten times that of renewables. This is the result of high economic growth rates in emerging market countries and the rapidly rising need for power. Many have the expectation that natural gas will increase its share of the energy mix over the next two decades.

— Price and value delivered will be key determinants in shaping the energy mix of the future. That price may be set in the competitive marketplace or may result from a price on carbon and/or government incentives and subsidies.

— A broad-based emphasis on innovation and technology – at a level of intensity never seen before – will likely have a major impact on the energy mix, but probably not until the 2030s, owing to lead times.

— The last half decade has seen an acceleration of government policies aimed at spurring a shift to renewable electricity and the development of the electric car. If the electric car becomes a mass market rather than a niche product, it would erode oil's last bastion – its almost total domination of auto and truck fuel.

— Perceptions of shortages and scarcity of oil and natural gas, so prevalent a few years ago, have receded. The unconventional oil and gas revolution – especially to the degree that it delivers relatively low-cost energy – is likely to extend the competitive position of those two energy sources for much longer than had been anticipated a few years ago.

— The great energy challenge of the future, which will test all sources, is meeting the demand growth of a growing world economy and rising incomes in developing countries. Yet no less urgent is the challenge of meeting the needs of the 1.3 billion people who do not have access to modern energy.

All of this sets the stage for the dialogue that is to follow. This *Energy Vision* is not an advocacy piece. Rather, it seeks to provide a context and framework for understanding the energy mix, how a transition might unfold, and the challenges and questions about the components of the energy mix, both today and tomorrow. We recognize that future developments will bolster some of the judgments in this work and not others. We also know that readers, coming at this from different experiences and points of view, will find points of agreement and disagreement, sometimes strongly felt. We welcome that debate, for our objective is to contribute to an informed and constructive discussion about the energy mix on which the world now depends – and the mix on which it will depend in the future.

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Chapter 1: Introduction

Energy undergirds civilization and has powered the sweeping economic changes that have transformed the world over the last two and a half centuries. But just as the economy has changed, so has the energy mix that fuels it. The development of the modern world has been a story of evolving new uses for energy and constantly growing energy demand. New forms of energy and new technology to harness that energy have been developed over time, shifting the energy balance and expanding the menu of energy sources.

Today there is great focus on the next transition – on the expectation or the possibility of a substantial change in the energy mix. What would be the nature of the changing mix? What would drive it? How fast could it come? Or how long might it take? The answers to these questions will have a profound impact on the global energy system, on producers and consumers alike and on markets everywhere.

In this *Energy Vision,* our aim is to provide a framework for understanding the potential for changes in the energy mix and how an energy transition could unfold. We do so by looking at how energy transitions have unfolded in the past and the factors that brought about these transitions. Rather than attempting to predict the future, we provide a discussion of factors that may drive changes in the energy mix in the coming decades. Although energy efficiency and other demand-side issues are critical to future energy systems, this report focuses on the supply side of the equation – how society will meet its ever-growing energy needs. We addressed energy efficiency in the 2010 *Energy Vision, Towards a More Energy Efficient World,* entirely devoted to that subject.

Figure 1 illustrates historical transitions in the energy mix. But what does "energy transition" mean? The very word "transition" suggests not a swift change from one reality to another, but rather a process that unfolds over time and brings more diversity to the energy supply system. Biomass dominated the primary energy mix until the turn of the twentieth century when coal reached a 50% share. At that time, several other fuels also entered the mix including crude oil, natural gas and hydropower. Decades passed before most new fuels gained a significant share, with the exception of nuclear, which rapidly gained a substantial share of global energy in the 1970s and 1980s. With the introduction of more fuels, the overall energy mix has become more diverse. Today the mix continues to evolve, with renewable sources such as wind and solar photovoltaic (PV) experiencing strong growth rates in the last few years.

Past transitions occurred for a confluence of reasons. Over the past 250 years, the dominant fuel in the energy mix transitioned from biomass to coal to oil. In each case, the new fuel was in some way better, faster, cheaper or more suited to its purpose than what came before. In all of these cases, technological innovation brought new uses to fuels that transformed the energy system – coal brought industrialization and facilitated transportation and oil brought a vast increase in mobility, for example. Electrification provided a new and incredibly useful way to deliver and use energy. Again and again, price was critical in driving shifts and spurring energy demand growth.

But since the beginning of this century, two factors have concentrated attention and stimulated debate on a new energy transition. The first is deep concern about climate change and the political and policy traction that this issue has gained. This concern is reflected very clearly in the European Union's 2020 goals and its carbon trading system, explicitly aimed at driving a low-carbon energy transition. It is also reflected in the wide range of mandates, incentives and regulations for low-carbon energy in the United States. The National Renewable Energy Laboratory, part of the US Department of Energy, predicts that 80% of US electricity could be renewable by 2050.[1] And the same reorientation can be found in China's 12th Five Year plan, which calls for

1. National Renewable Energy Laboratory, *Renewable Electricity Future Study,* 2012.

reductions in greenhouse gas (GHG) and other air emissions and an increase in the share of non-fossil fuel primary energy consumption.

The second factor is the shift of the world's centre of gravity toward emerging markets and the accompanying growth in energy demand. In 2000, the developed world used two-thirds of world oil. By 2011 it was split about evenly between developed and developing countries and virtually all growth from here on is expected in emerging market nations. Rising incomes and population growth in developing nations are paramount. Primary energy consumption is expected to mirror the growth in global population, as shown in figure 2.

Across the world, 1.3 billion people still do not have access to modern sources of energy. Bringing an end to energy poverty is an important part of integrating more people and countries into the modern economy, with the rising standard of living that brings. The amount of energy that will be required to achieve these goals – perhaps 30% more two decades from now – creates debate and even anxiety about the ability of conventional energy supplies to meet the needs of economic growth.

In response to these challenges, many policy-makers are looking for the next energy transition to add more low-carbon and renewable sources of energy to the mix. But expectations for transition have to be matched up against present realities. Some 87% of total world primary energy demand is met by three hydrocarbons – oil, coal and natural gas. Add in nuclear and it's over 92%. Wind, solar, geothermal and other non-hydro renewable resources provide just 1.6% of total world energy.[2]

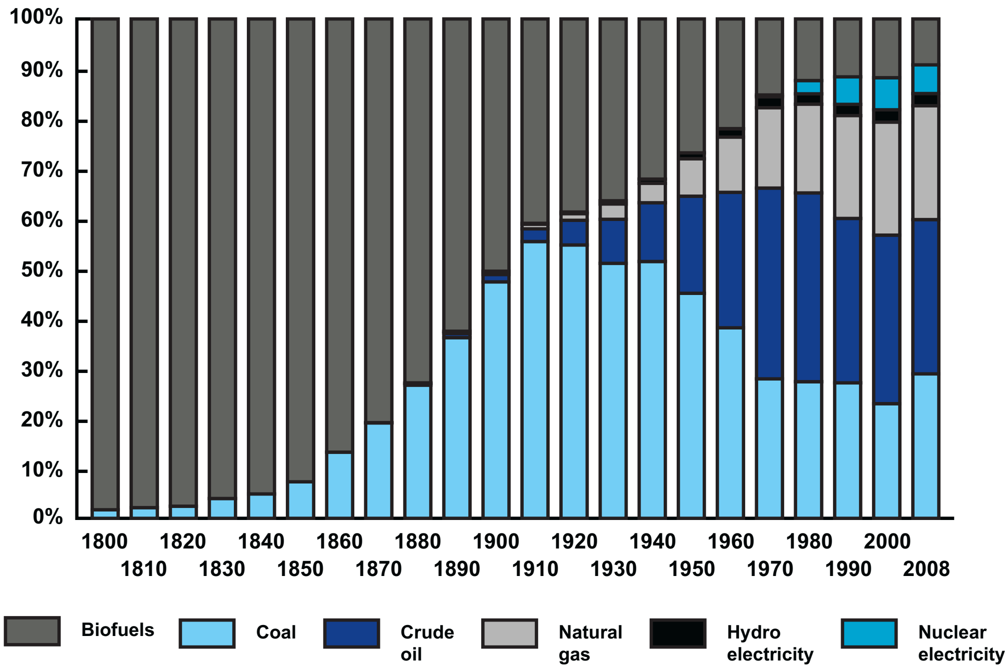
There are two major barriers to any swift transition. The first is scale – the amount of energy currently provided by conventional sources and the size of the embedded infrastructure that has been built over many years. Owing to its immense scale, any transition in the energy system is necessarily slow. Steven Koonin describes this reality in his contribution From Energy Innovation to Energy Transformation, "Energy change is sluggish due to scale, ubiquity, longevity, interdependence and incumbency. Energy infrastructure is long-lived – a single power plant is a multi-billion dollar investment with a lifetime on the order of decades."

The energy mix of 2030 and beyond is thus strongly influenced by decisions made today. Although overall consumption will grow and the share of low-carbon sources will also grow, the energy mix in 2030 will not be too different from what it is today. Beyond 2030, the impact of innovation and research and development, as well as prices and government policies, could have an increasingly large impact in terms of altering the mix. Vaclav Smil, the dean among scholars of the energy mix, writes, "The most important historical lesson is that new resources require extended periods of development."

The second barrier to transition is the energy density of current resources. Moving to wind and solar involves replacing a higher energy density but generally lower-cost source – such as oil or natural gas – with lower energy density substitutes that are generally more expensive. In the case of advanced biofuels, they may be "dropped into" existing systems. But renewable power is likely to require new transmission infrastructure. A more distributed energy supply system in future decades could also pose a competitive challenge to the current structure of the electric power industry.

Figure 1

Share of Fuels in Energy Mix, 1800–2008



Source: *Energy Transitions: History, Requirements, Prospects,* Vaclav Smil, 2010.
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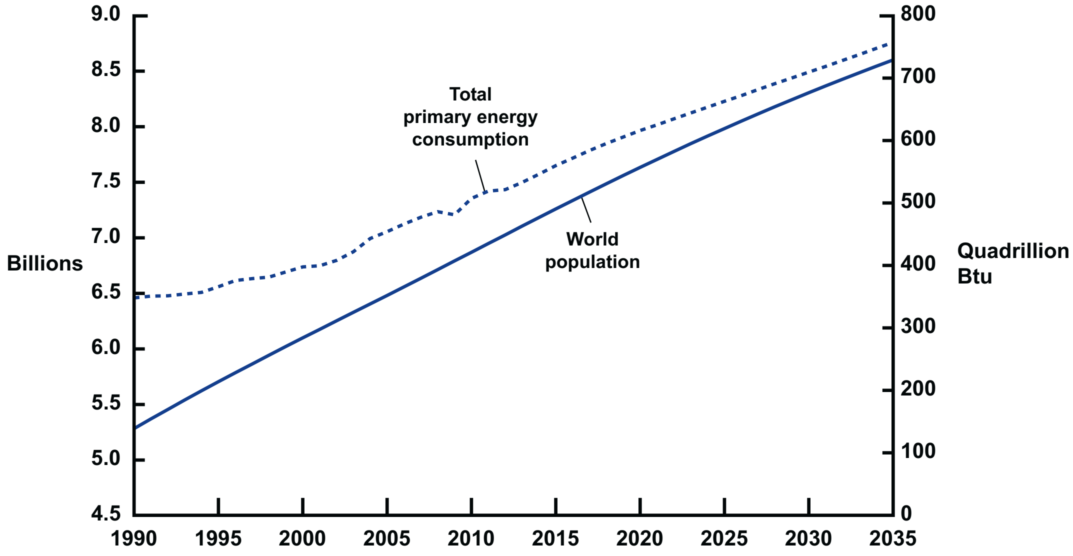
2. BP Statistical Review of World Energy, 2012.

Figure 2

Growth in World Population and Primary Energy Consumption, 1990–2035



Sources: IHS Global Insight, IHS CERA, United Nations, US Bureau of the Census.
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One could well conclude from current discussion that a transition toward low-carbon energy is already gaining steam. Certainly the scale of the renewables industry has grown dramatically, in absolute terms, since the beginning of the century.

In fact, however, the energy picture is more mixed – and may surprise. The biggest transition so far in this century has been towards coal. Since 2000, coal has added nearly ten times more energy to the mix than have renewables. The unconventional oil and gas revolution may change energy supply in ways not even imagined half a decade ago. Rex Tillerson, in his contribution Energy Transitions: Enabling Positive Change for Long-Term Global Prosperity, describes the revolution this way, "High-impact, proven technologies have made these new unconventional sources not just economical, but environmentally responsible. This development of unconventional sources is a reminder that innovative thinking, advanced technologies and long-term planning are critical to meeting the challenges of the future."

Information technology will play a powerful role in shaping the future energy mix. "What the application of steam power was to the 18th century and the industrialization of electromagnetism to the 19th and twentieth centuries, the gusher of data promises to be for the twenty-first. We stand at the dawn of a fundamentally new global energy environment, thanks to the emergence of a fundamentally new global information environment," Ginny Rometty writes in her contribution Data: The Next Natural Resource. She adds, "More and more leaders across all sectors of society are coming to see that the sustainability of our world's finite resources – the sources of energy that underpin modern civilization – depend on harnessing its newest and most infinite resource – an emerging planet of data."

Biotechnology is another potential game-changer. In his contribution Genomic Science Coupled with a Strong Energy Policy Can Change Our Energy Future, J. Craig Venter says that, "Our new ability to rewrite the genetic code when coupled with sound public policies can move us toward a completely renewable carbon fuels and chemical industry."

Perspectives on Energy Transitions

The chapter includes five perspectives on past and future energy transitions.

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From Energy Innovation to Energy Transformation

Steven Koonin

Director, Center for Urban Science and Progress, New York University, USA

There are compelling reasons to improve our energy system – to increase accessibility, affordability and reliability and to reduce environmental impacts. Yet the energy system has historically evolved much more slowly than other technology-dependent sectors. It took eight decades for oil to overtake coal as the US primary energy source, while mp3s replaced CDs and tapes in only three years. If we aspire to improve the energy system, it is important understand both the reasons why our energy system changes so slowly and the motivations of those with the resources to affect true transformation.

Energy change is sluggish as a result of scale, ubiquity, longevity, interdependence and incumbency. Energy infrastructure is expensive and long-lived; a single power plant is a multi-billion dollar investment with a lifetime on the order of decades. Further, the energy sector has a multitude of stakeholders with varied interests (governments, citizens, private industry and NGOs), and its many parts must all function as an integrated system. Last, as is true with any commodity, the consumer cannot distinguish among products from different sources, and so suppliers see incumbency as a considerable advantage.

These factors also underscore the challenges for governments to affect material change in the energy sector. Although many cite the Manhattan Project and "Moon Shot" as potential models for government catalysis of energy transformation, those projects were of singular focus, were funded entirely by the government and had little impact on the daily lives of citizens. For energy transformation, we need not only scientific innovation but also large-scale deployment.

In nations where the government operates the energy system, any energy technology that doesn't violate physical laws can be deployed given sufficient time and capital. But in those nations where free enterprise and market systems dominate, transformation will be achieved only with the participation of private industry and large corporations. Because industry's goal is legal and predictable profit, energy transformation must be either profitable or mandated to occur. To provide meaningful incentives, government must accurately understand the risk/reward perspective of industry.

To make the investments necessary for any particular energy project, industry must balance several decades of return against a multitude of risks, including capital, construction, technology, operations, supply, business model, market and policy. The number of risks, combined with the size of capital required and the commoditization of power and fuels, makes technical conservatism the norm of the large corporations typically involved in the energy supply sector.

Beyond conventional industry, some have suggested venture capital is the appropriate mechanism to engender transformation in the energy sector. While venture capital has both the inclination and the capacity for high-risk, high-reward investment, it does not have the funds or business model required for the scale of deployment – or duration of investment – necessary for true transformation of the energy supply sector.

To shape the energy system, every step a government takes must be framed the way the private sector operates – in terms of risk and reward. Governments can mitigate the risk to investment in new energy technologies through funding innovative research, integrating diverse perspectives and informing effective policy.

Loan guarantees and tax credits reduce capital risk for technologies that are nearly ready for investment by large corporations. Government can also reduce capital risk by investing in applied research and technology development that shrink typical project size, such as small modular fission reactors and distributed generation technologies.

Easing the interface between government-funded research and industry to aid the demonstration of new technology can mitigate technology risk. The US Department of Energy has several projects that blur these lines, including the Energy Frontier Research Centers, Energy Innovation Hubs, and Advanced Research Projects Agency-Energy (known as ARPA-E). Government assets in computer simulation and test beds can also be leveraged to demonstrate new technologies and emphasize lessons learned and international partnering to accelerate technology risk reduction.

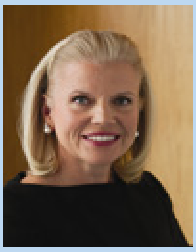
Market and policy risks must be mitigated with effective and predictable policies targeted at energy goals at every level of the government. Regulatory uncertainly increases market risk and limits investment by the private sector.

Transformation of our energy system is both necessary and difficult. To succeed, we must acknowledge that its scale presents unique challenges that require industry participation, and shape government policies according to the risk/reward calculations at the core of the private sector.

Data: The Next Natural Resource

Ginni Rometty

Chairman, President and CEO, IBM, USA



Over the past decade, information technology (IT) has had an ever-increasing impact on how energy resources are developed, produced, distributed and used. But what is coming next promises to outpace our progress thus far and truly change the basic equation of energy supply and demand.

Energy systems have become increasingly instrumented and interconnected, helping to expand the accessible supply of natural resources and bringing new efficiencies to operations. Through the use of sensors and intelligent devices, we are beginning to understand the detailed status of energy operations and the ways in which energy is used by systems and people.

In fact, what we are witnessing is nothing less than the discovery of a vast new natural resource – what some call "Big Data." How big is it? Last year, the amount of information created globally was more than 1.8 zettabytes; by 2016, we expect it to be 75 zettabytes. A "zettabyte" is a 1 followed by 21 zeros, a staggering quantity.

The social and economic impact of this new resource is almost incalculable. What the application of steam power was to the 18th century and the industrialization of electromagnetism to the 19th and twentieth centuries, the gusher of data promises to be for the twenty-first. We stand at the dawn of a fundamentally new global energy environment, thanks to the emergence of a fundamentally new global information environment.

Let me give just a few examples of the progress already under way.

New insights in reservoir management are enabling producers to extend the life of existing oil and gas fields through enhanced recovery techniques, optimized production and improved operations management. Similarly, innovation in 3D and 4D seismic imaging has made it more feasible to unlock resources in previously uncharted areas. The resulting resource expansion is contributing to a revision of long-held assumptions about global reserves of fossil fuels.

In electric power, smart grid technologies that monitor and automate components of the distribution grid are reducing the incidence and duration of outages. In systems from CenterPoint Energy in Texas to the island nation of Malta, along with hundreds of other examples from around the world, smarter energy systems are providing consumers and utilities with better information about how energy is consumed, leading to improved conservation and reduction in peak demand.

Or consider wind power. Choosing turbine locations has been a persistent challenge, but using sources such as geospatial and sensor data, tidal phases and weather modelling, it's now possible to determine which sites will produce the most energy. Once the turbines are operating, utilities can analyse weather conditions rapidly and develop much more accurate microforecasts. Better wind forecasting can improve the generation from wind farms by as much as 20%. These improved weather-driven predictions also can be used to balance the mix of generation resources on the power grid to maximize efficiency.

Most fundamentally, human behaviour drives energy use. Therefore, the key to our energy future lies in capturing the value in multiple streams of data – not just those from our legacy energy systems, but from diverse sources such as traffic patterns, retail behaviour, public safety statistics and social media posts. We will need to make sense of them and apply that to the dynamics of energy production and consumption to support real-time adaptation to the changing factors influencing demand.

We now have before us the possibility of seeing the world's production of energy as a complex global system of interdependent, highly dynamic systems.

An early view of the dramatically different energy systems that are now emerging is available at the Pacific Northwest Smart Grid Demonstration Project in the United States, which is pioneering a "transactive control" capability. It evaluates changing dynamics for cost and delivery of electric power – considering demand from things such as connected household appliances and heating and cooling systems. Instead of planning an hour or a day ahead for when large generation systems should be turned on or off, energy system operators will be able to use cost "signals" automatically sent across the network every five minutes to help balance supply and demand. An earlier pilot of this kind of transactive system realized a 15% reduction in peak loads when consumers were given the chance to reduce their energy bills by 10%. Efficiency on that scale could, by itself, eliminate the need to build a new power plant.

Now imagine how much more dynamic, efficient and societally sensitive such systems could be when enhanced by information about the behaviour, wishes and desired lifestyles of millions of empowered individuals, communities and businesses. Up to now, such challenges were beyond the capacity of existing technology. But that will no longer be the case in just a few years, thanks to a major shift in computing architecture now under way, towards "cognitive" systems.

We won't *programme* these machines. Rather, we will be able to describe to them complex situations and objectives, and explore what the best course of action might be. They will sift through vast amounts of structured and unstructured data, consider its relevance, estimate its probability of being correct – and tell us what they believe to be true, and why. They will be able to understand natural human language. They will ask questions of us, too – refining hypotheses, reconsidering assumptions. Rather than just doing what we've programmed them to do, they will adapt. They will learn.

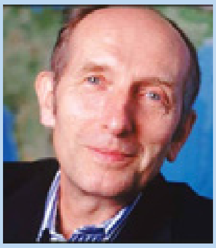
The transition to a new, information-infused global energy reality will not be easy or seamless. It will require a profound reconsideration of how the energy and IT industries operate. We will need new skills and new investments. We will need to collaborate in new ways with each other and across sectors of society. We must address crucial challenges of privacy and security. All of that will require leadership – on a global scale, across many traditional boundaries.

However, with the stakes so high and the potential benefits so compelling, I am optimistic. More and more leaders across all sectors of society are coming to see that the sustainability of our world's finite resources – the sources of energy that underpin modern civilization – depend on harnessing its newest and most infinite resource – an emerging planet of data.

Energy Transitions

Vaclav Smil

Distinguished Professor Emeritus, University of Manitoba, Canada



Energy transitions are not sudden revolutionary advances that follow periods of prolonged stagnation, but rather continuously unfolding processes that gradually change the composition of sources used to generate heat, motion and light. Such transitions also replace dominant prime movers by new converters and introduce better, and invariably more efficient, final uses of energy. Historically, changing sources of primary energy supply generated the most attention, as coal combustion displaced traditional biofuels and was, in turn, augmented by the rising use of hydrocarbons and primary (hydro and nuclear) electricity. And while the recent focus has been on the unfolding transition from fossil fuels to renewable sources of energy (modern biofuels, wind, solar), the most consequential global shift during the coming 20-40 years will be the rise of natural gas to become the world's single most important fuel.

Inventions and diffusion of new prime movers drove most energy transitions: just think what steam engines did for coal and what internal combustion engines (ICEs) have done for hydrocarbons. The overall level of primary energy supply and its composition can be substantially modified by still considerable opportunities for more efficient use of energy: transitions toward universally adopted optimal conversion efficiencies could be as important as harnessing of new energy resources. The pace of unfolding changes will be determined not only by those fundamental factors that have been critical in the past but also by several new considerations arising from unprecedented features of modern energy systems.

The most important historical lesson is that new resources require extended periods of development. The verdict is clear: only small economies endowed with suitable resources can undergo very rapid resource transitions. For example, in the Netherlands natural gas supplied 50% of total primary energy just 12 years after the discovery of the giant Groningen field in 1959. The scale of large economies makes everything more inertial, and global resource transitions unfold across generations. Even though the country is endowed with abundant hydrocarbon resources, it took the United States 25 years to raise the share of oil consumption from 5% to 25%, and for natural gas it took 33 years. After crude oil reached 5% of global primary energy supply, it took another 40 years to rise to 25%, and the comparable period was even longer, 55 years, for natural gas.

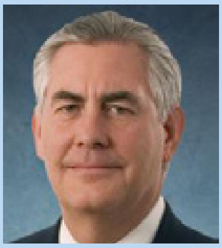
There is no shortage of national, even global, targets for renewable energy deployment (such as 30% of all electricity from wind by 2030, 50% of all energy from non-fossil sources by 2050), but these are, at best, aspirational goals and not realistic aims. Between 2000 and 2010, global output of renewable energies grew by 2% but that of fossil fuels by 2.65%. **During the first decade of the twenty-first century the world has been running into fossil fuels, not away from them, a reality that will not change rapidly.** And while the contributions of wind and solar PV more than tripled during that decade, the world is now more dependent, in both absolute and relative terms, on fossil-fuelled generation than it was in 2000.

Reliable and inexpensive performance will often favour long-established uses. The first diesel engines powered an ocean-going vessel in 1911, but 30 years later when the US Navy needed a large number of transport ships in WW II, it chose to equip them with much-tested oil-fired steam engines rather than with diesels. Similarly, after nearly 130 years of development, gasoline-fuelled ICEs will not rapidly yield their huge market share to electric cars powered by new batteries, and there are no real alternatives to diesels in marine transport and to gas turbines in flight.

Public acceptance and environmental considerations have become critical components in the conquest of new markets. New energy sources and techniques now face unprecedented public scrutiny and must comply with many environmental laws and restrictive regulations. In many countries significant shares of the population were uneasy about nuclear electricity generation even before major accidents undermined public confidence in this rewarding but risky process. Widespread hydraulic fracturing to produce oil and gas and mass-scale underground carbon sequestration are two recent innovations facing such public perception challenges.

High power-density demand will be even more important. Urbanization and industrialization have created unprecedented needs for incessant flows of highly concentrated energies. Since 2008 more than half of the world's population has been living in cities where buildings, factories and transportation and communication networks require high power density of energy supply (particularly of electricity and liquid fuels). In the absence of mass-scale energy storage (on a multi-gigawatt scale, orders of magnitude above our current capabilities) meeting such demand with the intermittent, low power-density flows of renewable energies is a difficult task. A non-fossil future is highly desirable and eventually inevitable, but a civilization built on fossil fuels cannot make that transition easily or speedily.

Energy Transitions: Enabling Positive Change for Long-Term Global Prosperity



Rex Tillerson

Chairman and CEO, ExxonMobil Corporation, USA

One of the great challenges for the energy industry is effectively communicating to the public and policy-makers the tremendous complexity and scale of global energy markets. The energy that is being delivered today is the product of bold vision; continuous technological advancement; and highly disciplined, long-term investment.

Because of this complexity and scale, transitions in global energy markets are measured not in months or even years – but in decades. Such transitions may not occur very often, but when they do, they have a profound and positive impact on countless lives by expanding supplies of the energy that fuels development and progress.

The history of energy over the last century helps put this reality into perspective. Today we are living a historic moment of energy transition – one that promises to power a cleaner, brighter future. But to secure its full benefits now and for future generations, we must make the right policy decisions today.

Evolution of the Energy Mix

At the beginning of the twentieth century, coal and wood provided more than 95% of the world's energy needs. From that moment, it took more than half a century for petroleum – a cleaner and more versatile alternative – to surpass coal as the world's largest energy source. The ongoing pursuit of technological advances enabled this transition.

It took several more decades to develop the technologies and build a new and expanding infrastructure for natural gas, connecting robust supplies of an even cleaner-burning source with major markets, allowing it to begin to play a sizable role in the world's growing energy needs.

Now as we look to the future, we can see new technologies unlocking new supplies of energy that will transform the world. Rather than a wholesale shift in energy sources, this latest transition will be in ***how*** the world's abundant supplies of oil and natural gas are developed, produced and consumed.

In the decades ahead, owing to their scale, affordability and versatility, oil and natural gas are set to continue to provide the majority of the world's energy needs. They will provide close to 60% of the energy used in the global economy through 2040. Oil will remain the most widely used fuel, but we project that natural gas will grow fast enough to overtake coal for the number two position. In fact, measured from 2010 to 2040, demand for natural gas will rise by about 65%.

The single biggest driver of demand will be the need for energy to generate electric power – a sign in itself of increased global prosperity and improved standards of living, as more consumers and businesses have access to secure and reliable supplies of electricity.

The growing role of natural gas will bring tremendous benefits. Natural gas has already proven itself to be a safe, reliable, affordable and efficient means of power generation. It will also bring environmental benefits. A recent report by the US Energy Information Administration noted that US energy-related carbon dioxide emissions were at their lowest levels since 1992, mainly as a result of natural gas replacing coal for electricity generation.

A second major part of the energy transition taking place will be ***where*** that oil and natural gas will come from. The majority of oil and natural gas will continue to come from conventional sources, but much of it will come from more challenged environments such as the ultradeepwater and the arctic.

In addition, the years ahead will be marked by the growing importance of unconventional sources, such as shale, tight rock and oil sands. High-impact, proven technologies have made these new unconventional sources not just economical, but environmentally responsible. This development of unconventional sources is a reminder that innovative thinking, advanced technologies and long-term planning are critical to meeting the challenges of the future.

Key Factors Influence the Energy Mix

Two key participants will largely influence the changes in the global energy mix: industry and government.

Industry must continue to develop and deliver new supplies of energy in a safe, secure and environmentally responsible way. As part of this responsibility, we must remain committed to effective risk management. We must engage in long-term planning. We must invest with discipline and ingenuity. And we must focus relentlessly on operational integrity and best practices – to protect the people and environment wherever we operate.

A second key factor influencing the energy mix will be government. Policy-makers must recognize the importance of sensible policies, not only to allow for but to promote investment, innovation and international cooperation.

Government has a responsibility to provide a stable and fair legal, tax and regulatory framework that supports responsible, long-term energy development. Uncertainty undermines the long-range thinking, investment decisions and mutually beneficial partnerships that allow our industry to excel. Because our industry thinks long term, we need the confidence that the investment environment will not be changed or altered haphazardly or every time commodity prices move through their typical price cycles.

Government has a role that industry cannot replicate or replace. Only governments can open – and keep open – the doors to international trade, competitive markets and cooperation among nations. The more energy policies promote free trade and the free flow of goods, services, and expertise, the more they can help industry diversify our energy mix, support global energy security and maximize the value of energy resources for all.

If we meet our roles and responsibilities together, government and industry can lay the foundation for positive changes in our energy mix and flow – and deliver transformative new supplies of energy in safe, secure and environmentally responsible ways.

Genomic Science Coupled with a Strong Carbon Policy Can Change our Energy Future

J. Craig Venter

Founder and CEO, J. Craig Venter Institute and Synthetic Genomics, USA

Starting with the first domestication of animals and the earliest forms of agriculture, biology has been the principal source of food, medicine and until the last two centuries, even fuel for the world. Today more than ever we need to responsibly manage our energy sources and production. I believe we can do this through a combination of new advances in science coupled with sound public policy.

In the 1700s and well into the 1800s whaling was a huge industry because whale oil was the key ingredient used for lamps, lubrication and soaps. Kerosene from crude oil became readily available by the second half of the 1800s and led to a rapid decline in the use of whale oil. Today, natural gas produced from shale fracking has the potential to decrease the use of petroleum. Natural gas or methane is a great improvement over coal and oil burning because methane is a much cleaner burning fuel. Coal, petroleum and natural gas are all the result of biology from decay and compression of ancient plant and animal life including algae from hundreds of millions of years ago, so it could be argued that they are all by origin biofuels. The problem is that they are not renewable biofuels and their burning results in a net increase in CO_2 accumulation in our atmosphere as well as a variety of toxic byproducts.

The production of fuel from renewable resources has been a goal of science and industry for at least the last 50 years, but the successes have been very minimal. Humans have been fermenting alcohol from sugar for at least 12,000 years, mostly for consumption in beverages, although alcohol was the first fuel used in an internal combustion engine. By 1860, thousands of distilleries made 90 million gallons or more of alcohol per year for lighting, cooking and industry. Alcohol is a poor fuel for producing energy, but is increasingly used as a fuel additive due to federal mandates in the United States and the abundance of sugar in countries like Brazil. While other alcohols as well as methane, butane, propane, etc. have been bio-produced, the yields are still limiting.

Without government mandates and/or a progressive carbon tax, biofuels cannot compete with oil and natural gas due to the simple fact of their current cost of production. In the absence of a carbon tax, existing producers of fossil fuels can and will continuously undercut biofuel prices. The game will change, however, if a realistic accounting of environmental costs is added to today's petroleum and natural gas prices and biofuels will become cost competitive.

Algae provide one option. Algae are fast growing single-cell organisms that most often obtain their energy from photons captured from the sun to drive photosynthetic processes that fix CO_2 into fatty acids for energy storage. Many scientists and engineers have proposed that growing algae could be a great source of renewable hydrocarbon fuels; however, we have seen the same experiment being conducted over and over again during the last few decades, where large open ponds are used to grow algae from which oil is extracted. To date, all have failed to produce a cost-competitive fuel owing to high production costs and low lipid yields. Natural selection has not selected for an algae cell that can naturally produce high amounts of hydrocarbons. This would be equivalent to evolution providing a survival advantage for humans that produce 100 times as much fat. Such a species would not last long in the environment.

Altering the biochemistry of algae cells to produce high yields of oil (10,000 gallons per acre per year) is theoretically possible, even though today's best strains produce only 2-3,000 gallons per acre per year. All existing plants and eukaryotic algae are linked together by a single evolutionary event where a photosynthetic bacterium became the chloroplast of the plants and algae. The chloroplast has its own genome, but also uses the host cell genome. These genomes are the software that determines each and every cellular function. Recent breakthroughs in synthetic genomics provide us with the tools, for the first time in human history, to completely rewrite the software code of the cells and gain control over evolution.

We are using this new power to alter the genetic code in a number of ways to force the cells to produce much more lipid than natural cells would. Recently, we have successfully altered the photosynthetic efficiency of an algae cell to produce three times as much cellular energy per light-absorbing chlorophyll molecule using a novel approach. As algae grow and reach high densities, they block sunlight from hitting all the cells and limit cell growth. With our new engineered strains we reduced the photo-antenna size allowing more light to reach all the cells. We are taking other novel approaches, including adding a completely new synthetic chromosome to the cells to alter their energy production. While none of these approaches on their own will quickly produce a "super-algae", I think that the accumulation of our genetic software changes can produce a game-changing renewable carbon-based energy source from CO_2 and sunlight.

Production of a fuel is not the only way that biology can help change the carbon game. As we switch to natural gas, a great opportunity opens up for carbon capture using biology. Because burning natural gas produces a clean CO_2 stream, the capture of CO_2 from a gas fired power plant using algae is much easier than trying to capture CO_2 from a coal fired plant due to all the toxic by-products from burning coal. Even today's algae can convert CO_2 into food for humans, farm animals and fish farms. As we are demonstrating in our southern California desert algae facility, we can produce high value food chemicals from CO_2 and sunlight.

There is a way forward. Our new ability to rewrite the genetic code when coupled with sound public policies can move us toward a completely renewable carbon fuels and chemical industry.

Energy Transitions: Past and Future

Chapter 2: The Evolution of Combustion – Wood, Coal, Oil and Gas

The first major energy transition was also the longest. More than 400,000 years ago, humanity began using biomass – primarily wood but also crop remnants and animal waste – for fuel. Wood was an intuitive fuel; it was readily available. Biomass retained its dominant role in the energy mix for thousands of years.

The European wood supply began to feel the strain of growing populations as forests were cleared to provide more land for food production. Shortages were acutely felt in Great Britain as early as the thirteenth century, when coal began to be used as a substitute fuel for industrial purposes in urban areas. But public outcry in London over coal smoke and its detrimental health effects eventually led to a Royal Proclamation in 1306 that prohibited the use of coal and demanded a return to wood and charcoal. From 1530 to 1650, the population nearly doubled in Britain, and demand for wood continued to rise as industrial and household consumption began to strain supplies. Wood prices rose as well.

But coal was plentiful; in many places veins were visible at the surface. As firewood costs rose, it became more economical to haul coal toward city centres, which were the most affected by wood shortages. Coal suddenly became a viable energy option. Despite its pollution, coal's economics trumped its nuisance, and London eventually gave up its efforts to curb coal burning as demand for fuel continued to rise.

Coal and the Industrialization of Europe

The iron industry's adoption of coal began the first major energy transition. To make iron, the ore must be heated to its melting point in a process called smelting. Charcoal made from wood had been the primary fuel for this application, but shortages of wood threatened the industry. Early experimentation to smelt iron ore using coal proved unsuccessful, since coal's sulphur content created iron too brittle to use. In 1709 an ironmaster by the name of Abraham Darby in Shropshire discovered a process to turn coal into coke, which releases coal's sulphur as gas. Over the next 50 years, coke would come to replace charcoal in iron smelting. Darby's invention marked the beginning of the coal era.

As surface supplies of coal were depleted, industrial innovations were essential to sustaining its growing role in the energy mix. When Thomas Newcomen invented the first steam engine in 1712, the device played an important role in pumping water for coal extraction. But the engine was inefficient and often uneconomic.

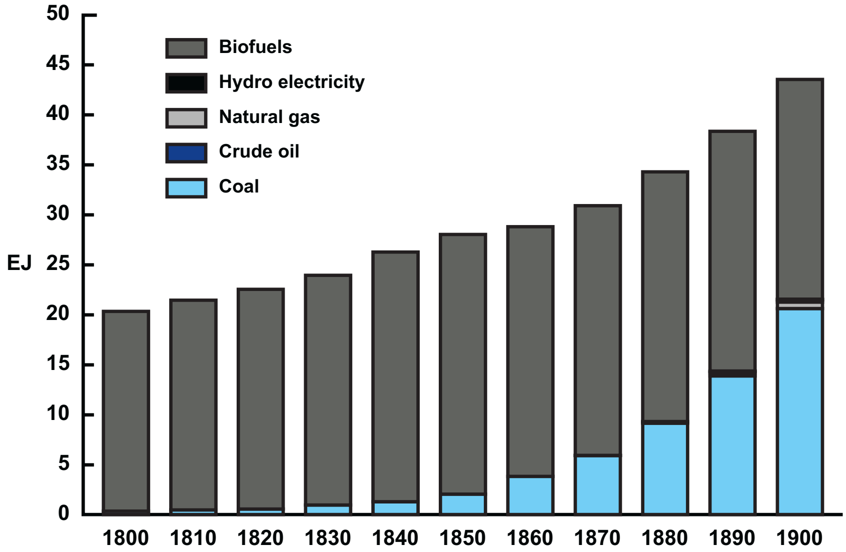
James Watt's improvements to the steam engine in the 1760s and 1770s made it more efficient and coal-powered engines became a viable transportation option, contributing greatly to increased supply and demand for coal. Over the nineteenth century, continued advances in the steam engine enabled it to power the mills and factories of the Industrial Revolution, as well the railways and ships that transported the goods they produced. Coal's energy density made such mechanical transportation feasible. Each kilogram of coal contains more than three times the energy of dry wood. Coal enabled ships and locomotives to go further and faster without increasing the space allotted to fuel storage. Yet transitions can take a long time. Despite these revolutionary uses for coal, it did not reach a 5% share of the total primary fuel supply until 1840; combustion of biomass remained the main source of primary energy, as shown in figure 3.

Beginning in the 1880s, the emerging electricity market brought with it a new and lasting use for coal. The first power plants used steam engines to produce electricity. By 1884 steam engines were replaced by more efficient steam turbines. Over the next century, many improvements were made in thermal generating technology, but coal remained the most widely-used, inexpensive fossil fuel source for power plants.

By the beginning of the twentieth century, coal's share of the primary energy supply had increased dramatically, nearing 50%. Soon thereafter, coal's overall share of primary energy

Figure 3

Energy Mix, 1800–1900



Source: *Energy Transitions: History, Requirements, Prospects,* Vaclav Smil, 2010.
21215-3

began to drop with the advent of oil and natural gas, but coal consumption continued to rise throughout the twentieth century on an absolute basis owing to its large role in electricity generation.

Driving Demand for Oil

The nineteenth century also saw a rise in demand for illumination. Whale oil was one of the highest quality sources of illumination. But strong demand decimated whale schools and whalers were forced to sail farther afield, as far as Cape Horn and the Pacific Ocean. In the 1850s, whale oil prices increased to as much as US$ 2.50 a gallon, or US$ 72 a gallon in today's dollars.

Price provided an incentive to find a substitute. Kerosene refined from oil was one possibility. But supply was the great obstacle. If oil was found in significant quantities, it could be sold cheap enough to capture the illumination market.

This happened in 1859, when "Colonel" Edwin Drake struck oil outside Titusville, Pennsylvania. Oil quickly made its way into the lighting market and its virtues were immediately clear. "As an illuminator the oil is without a figure: It is the light of the age," wrote the author of America's very first handbook on oil, less than a year after Drake's discovery.[1] After Drake's first well was drilled, production quickly rose, with output increasing six fold in the first two years.

Kerosene was also shipped to Europe in 1861, immediately turning oil into an international business. This prompted a rise in production elsewhere, including the Russian Empire, where output rose tenfold between 1879 and 1888 to rival US production. Kerosene became a globally traded product. It is striking, and little remembered, that John D. Rockefeller became the richest man in the world as an illumination merchant.

1. Daniel Yergin, *The Prize: The Epic Quest for Oil, Money, and Power,* Free Press, 2008.

Oil prevailed over coal in its energy density, adaptability and ease of transport. Yet by 1900, despite the wealth it had generated, oil's share of global primary energy remained marginal at 1.5% globally, compared to wood's 51% and coal's 47% share, as shown in figure 4.[2] Oil's big breakthroughs were yet to come.

By the late nineteenth century, oil's main market, illumination, was threatened by the development of the light bulb by Thomas Edison in the United States and Joseph Swan in England. Electricity was clean, offered superior light and required no attention from its user. But just as the lighting market was about to slip away, a new market would open that would facilitate the transition to oil.

Oil Dominates Transportation

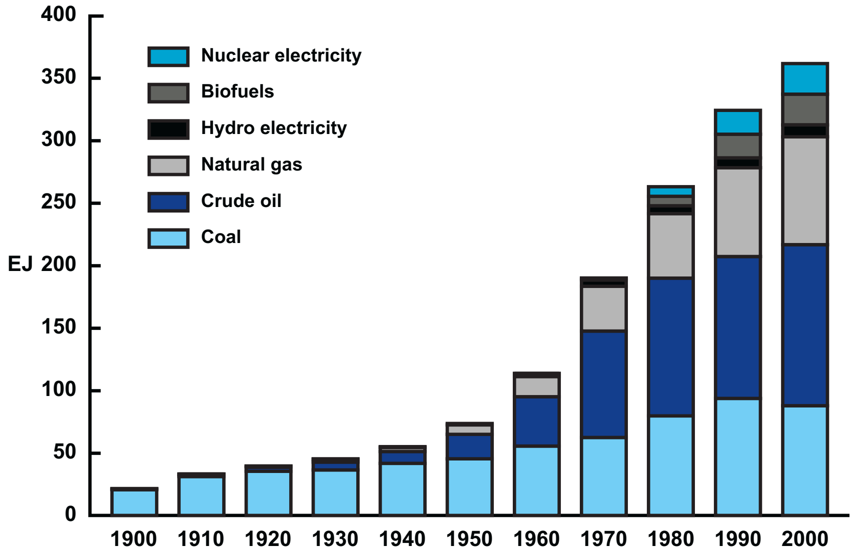
The internal combustion engine entered the market as a competitor to the steam engine in 1876, but several decades passed before its development and adoption realized a scale large enough to impact oil demand. That scale came in 1908 when Henry Ford introduced the Model-T automobile. Two years later, in 1910, Thomas Edison predicted, "More electricity will be sold for electric vehicles than light." On the contrary, the internal combustion engine would be the clear winner. Gasoline became the fuel of choice owing to its versatility, energy-density, reliability and ability to be easily stored and transported.

The Model-T also began a revolution toward automobile ownership and personal mobility. Until the advent of the automobile, gasoline had been a by-product of the kerosene refining process that could barely be sold. However, the automobile turned gasoline into an increasingly valuable product. In addition to gasoline, a second major new market for petroleum developed with the growing use of fuel oil in the boilers of factories, trains and ships. The advantages of oil over coal as a fuel were evident – speed, flexibility and no

2. *Energy Transitions: History, Requirements, Prospects,* Vaclav Smil, 2010.

Figure 4

Energy Mix, 1900–2000



Source: *Energy Transitions: History, Requirements, Prospects,* Vaclav Smil, 2010.
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need for labour to shovel coal. On the eve of the First World War, Winston Churchill, Britain's First Lord of the Admiralty, made the decision to convert the Royal Navy from coal to oil.

But car ownership was the main driving force behind demand for oil in the early twentieth century, particularly in the United States. In 1929, more than three-quarters of the world's automobiles were American owned. After World War II, car ownership became a global phenomenon. In 1945 worldwide car ownership was 64 million; by 1972 that number topped 280 million vehicles.

Along with rising demand, increased supply played a role in strengthening oil's place in the energy mix. A crucial discovery occurred at Spindletop in Texas in 1901, making Texas a major oil producer. In 1908, the same year that Ford released his car, oil was found in Persia (later Iran). In 1938, oil was discovered in Saudi Arabia and Kuwait. Over many decades, the oil market became intertwined with national strategies and global politics. Its advent also brought about major change in the energy mix. In 1964, 105 years after Colonel Drake's discovery, oil finally overtook coal as the world's number one source of energy.

The switch to oil seemed inexorable. For both environmental and price reasons, utilities in the United States, Europe and Japan replaced coal with oil as a power generation fuel. Owing to the huge build-up of supply from the Middle East, oil was cheap. But that changed with the 1973 October War and the resulting oil embargo. Oil prices quickly quadrupled, delivering a major economic shock to the global economy and the economies of oil-importing countries. For oil-exporting countries, rising oil prices meant a rapid increase in income and acceleration of modernization.

After the embargoes, concerns about future oil price shocks or supply disruptions led to policies in the industrial countries aimed at pushing oil out of most sectors other than transportation. "Energy diversification" became a bulwark of Japanese energy policy. France made a wholesale transition to nuclear power. In addition, fears of dwindling oil supplies, or later "peak oil", began to feed anxieties about overall global stability. High oil prices provided a stimulus for fuel-switching, including a major swing back to coal, and acceleration in nuclear power and innovation.

However, after a collapse in oil prices in the mid-1980s, oil demand resumed its growth. Since 2000 growth has been concentrated in the emerging market countries.

Oil's superiority as a transportation fuel means that substitution in this sector is much more difficult. In addition, any shift would require changes to the massive infrastructure in place to support the world's automotive and trucking sector. Although alternative fuels are available in the market, oil still accounts for 87% of transport fuel.[3] Oil has remained the most widely used source of primary energy since overtaking coal in 1964. In 2011 oil held a 32% share of primary energy consumption.

Natural Gas: The Flexible Fuel

The first shallow natural gas well was dug in Fredonia, New York in 1821, but it took half a century before natural gas gained a significant foothold in the energy mix.

A market for gas began to develop in the second half of the nineteenth century after the discovery of oil and gas in western Pennsylvania. Iron and steel works in Pittsburgh began using natural gas for industrial heating, finding its stable combustion temperature advantageous for industrial processing. Natural gas also entered the household and commercial heating markets at this time, providing a cleaner alternative to coal, whose smoke polluted the city of Pittsburgh. The invention of the Bunsen burner in 1855

3. IHS CERA.

encouraged more widespread use, since it controlled the mixing of gas and air to create an adjustable, hot and non-luminous flame that provided a safe way to burn gas for cooking and heating.

Although oil came to dominate the energy mix through the transportation sector, natural gas took a more circuitous route into the energy mix, owing to the complexities and costs related to its use and transport. The properties of natural gas initially made it a difficult fuel choice. Costly pipelines are needed to transport gas. Without an effective way to reach markets, gas was often wasted – allowed to burn or vent into the atmosphere when discovered alongside oil or simply left in the ground undeveloped.

After World War II, enhanced metallurgy improved pipeline construction. Large-diameter, high pressure pipelines with compressors to propel the gas were developed to carry large volumes of gas over long distances. In the early 1950s, a transcontinental pipeline system developed in the United States. Gas became a more important fuel in Europe with the development of Po Valley supplies in Italy, the discovery of the Groningen field in the Netherlands in 1959 and North Sea gas in the 1960s. Beginning in the 1970s, gas became a continental fuel in Europe with the building of the pipeline system that connected gas supplies in the Soviet Union with markets in Western Europe. With new supplies, even more uses for natural gas developed. Its clean combustion and flexibility made it sought after in many sectors, including in the power sector.

Liquefied natural gas (LNG) made global trade in natural gas possible. LNG is natural gas that is compressed and liquefied at -260°F, allowing it to be transported via tanker, re-gasified and then sent along pipelines to consumers. However, LNG systems are very expensive and need long-term commitment and stability for investment to take place. The first oceanic shipment of LNG took place in 1957, from Louisiana in the United States to England. However, LNG developed primarily as an Asian trade in its first decades, driven by Japan's quest for energy diversification. A truly global LNG market only took off in the last decade.

Chapter 3:
Electrification – A New Way to Deliver Energy

The rise of electricity in the twentieth century signalled a change in the way the world related to energy. It is not a resource that is harvested – like wood, coal or oil – but instead a method of delivering and using energy. Electricity is easy to consume, very efficient and extremely flexible, both in terms of how it can be used and how it is produced. It can be generated from a variety of sources, including traditional fossil fuels, nuclear reactions and the energy contained in moving water and wind or sunshine.

The commercialization of electricity began in the late nineteenth century, primarily to support widespread use of electric light. The first commercial electric generators were built in London in 1881 and in the United States in 1882, both powered by coal. Inventions of other new technologies created demand for electricity beyond its role in illumination. The electric induction motor, invented by Nikola Tesla in 1888, made it possible to covert electricity into mechanical energy with high efficiency and control. Within decades electric motors revolutionized industrial production and utilization of electricity in households. They transformed day-to-day life for many people, introducing conveniences such as washing machines, refrigerators and vacuum cleaners.

All of these new uses greatly increased electricity demand throughout the twentieth century. Electrification of industrial manufacturing was complete in the United States by the 1930s and in Europe by the 1950s. This marked a major shift in how primary energy was used, signalling a transition from direct consumption of fossil fuels, especially coal, to a system in which a large share of fossil fuels was used to generate electricity.

The fuel mix used to generate electricity is determined by the geography and the constraints and resource endowments of a particular region. The electricity generation mix can vary greatly from country to country. In the United States, coal's share has declined from 48% in 2007 to about 36% of all power generation today. But natural gas is expanding, rising from a 19% share in 2005 to 31% today.[1] In Europe, nuclear, coal and natural gas hold roughly a 25% share each. Japan's electricity mix, uncertain today and subject to great debate, historically has had a similar mix to Europe. China, on the other hand, generates nearly 80% of its electricity from coal; hydropower is the next largest fuel source at 16%.

Rise of Electricity: Big Hydro and Growth of Demand

At the same time coal-fired power plants were being built, efforts were simultaneously underway to generate electricity using hydropower. Moving water had been used for years to provide mechanical energy, but the first small-scale hydroelectric scheme was developed in England in 1878 and the first hydroelectric plant began operation on the Fox River in Appleton, Wisconsin in 1882. Growing demand and technological advancements, including the development of the electric generator and improvements to the hydraulic turbine, encouraged the growth of hydro projects. Thus, the energy mix expanded again, with the first non combustion-based fuel source implemented on a broad scale.

The number of hydropower stations increased as electricity demand quickly ramped up. By 1910, over 500 small hydropower stations were generating electricity worldwide.[2] Both the Soviet Union and the United States were early adopters of large hydropower technology. "Communism equals Soviet power plus electrification," became one of the slogans of the new Soviet Union. Acting on that slogan, the Soviet government began an electricity expansion campaign that included large hydroelectric stations.

1. Monthly Energy Review, US Energy Information Administration (EIA), November 2012.
2. Vaclav Smil, *Energy Transitions: History, Requirements, Prospects*, Praeger, 2010.

In the United States in the 1930s, New Deal economic programmes enacted in response to the Great Depression stimulated electricity consumption, the construction of thousands of miles of power lines and the extension of electricity access to rural America. To meet growing electricity demand, colossal hydro stations were built, including the 1.4 gigawatt (GW) Hoover Dam, which was the largest dam in the world when it was built in 1936. It was quickly surpassed by the Grand Coulee Dam, built in 1942, at over 6 GW. By 1940, hydroelectricity accounted for 40% of power generation in the United States and three quarters of electricity in the Western United States came from hydropower stations.

In the second half of the twentieth century, hydropower quickly developed around the world. Today, the share of hydropower in the electricity mix in countries with large resource endowments is as high as 95% in Norway, 80% in Brazil and 68% in Venezuela. China is now the world's largest producer of hydroelectricity, including the largest hydropower station at Three Gorges Dam, with a generating capacity of 22.5 GW.

For more than 20 years, hydropower has maintained a 2% share of primary energy consumption. Hydro is unlikely to gain substantial market share in the future, except for a few places with untapped potential.

The Rise of Nuclear Power

Although new technologies are generally adopted slowly, nuclear power was deployed in the United States, France and Japan on an accelerated timeline. The advent of nuclear power introduced a potentially vast new energy source for electricity generation. Such promise led to swift development of nuclear power plants worldwide.

Technological innovations based on US nuclear submarines –and borrowed specifically from an aircraft carrier that was never built – became the backbone on which today's light water reactor was developed. In 1954, the Soviet Union unveiled the first nuclear reactor for public power. It was a tiny unit, but it was two years ahead of the first commercial deployment in Britain (Calder Hall Station in 1956) and three years before the first full scale US nuclear power station was built in Shippingport, Pennsylvania in 1957.

Rapid electricity demand growth after World War II contributed to expansion of the nuclear fleet in the United States, with several dozen plants ordered within just a few years. In 1954, the head of the US Atomic Energy Commission predicted that within 15 years, nuclear power would deliver "electrical energy too cheap to meter."[3] Capacity rose from less than 0.5 GW in 1960 to 50 GW in the late 1970s, and then to slightly less than 100 GW in the late 1980s, providing about 18% of US electricity.

Nuclear power was expected to sustain this growth pattern and eventually claim a large share of electric generation. But by the 1980s, the tides began to shift and growth slowed as concerns about cost over-runs, safety and nuclear weapons proliferation became more pronounced. Storage, recycling and disposal of spent fuel also presented challenges for countries employing nuclear energy. The accident at Three Mile Island in Pennsylvania in 1979 and the disaster at Chernobyl in Ukraine in 1986 dealt additional blows to the industry.

3. Daniel Yergin, *The Quest: Energy, Security, and the Remaking of the Modern World,* Penguin Press, 2012.

Amid pushback following these accidents, many countries scaled back or abandoned their nuclear power agendas – a completed plant in Austria never went into operation. But two countries in particular – France and Japan – pushed forward contrary to the international trend. Both continued to invest in nuclear power in the wake of the oil embargos, viewing the technology as the main way to decrease fuel imports for electricity generation.

By the late 1980s, France had installed 48 nuclear reactors with a capacity of nearly 50 GW. Currently holding 63 GW of nuclear capacity, France derives 78% of its electricity from nuclear power and is the world's largest net exporter of electricity, providing power to other countries in Europe.

The Power of Natural Gas

The flexibility of natural gas makes it an attractive energy source in many different sectors. However, demand for power generation will be the key driver of global natural gas consumption over the next two decades. Global growth in electricity demand from non-OECD countries will loom large. Compared to coal, natural gas offers a lower carbon fuel for electricity generation, bringing about demand growth even in mature markets.

Expected demand growth for natural gas varies among countries. As a result of growing abundance and low price in the United States, natural gas is rapidly displacing coal in electricity generation. However, gas imports are costly elsewhere, including in Europe and Japan, and high prices will influence the extent to which natural gas is used in electricity generation in those regions. According to the IEA, at its lowest price in 2012 US gas traded for one fifth the price of European imports and one eighth the price of imports in Japan.[4]

Coal's Renaissance

After coal's long history in the energy mix, it remains the largest contributor to electricity generation. In 2012 coal powered 40% of the world's electricity generation. Concerns about GHG emissions from coal-fired power plants have reduced its use in certain regions, including Europe and the United States. But coal is the fastest growing primary energy source today and the second largest overall source after oil. It held a 30% share of world primary energy consumption in 2011 – strikingly, its highest share since 1969.

Modern coal plants (super critical and ultra-super critical) are more efficient than older plants, and thus use less coal and produce fewer GHG emissions per unit of power. But coal's GHG emissions are still higher than those from modern natural gas plants. Pollution control technology on modern coal plants can also greatly reduce emissions of air pollutants, including particulate matter, sulphur oxides and nitrogen oxides.

Burgeoning population and energy demand, especially delivered as electricity, in non-OECD countries has spurred increased use of coal. Coal is playing an important role in the industrialization of developing countries since it is abundant, cost competitive and available in many parts of the world. Coal's place in the future global energy mix largely hinges on China and India. Today China accounts for roughly half of global coal consumption; India accounts for nearly 8% of global coal consumption. Although demand

4. IEA, World Energy Outlook, 2012.

growth is decelerating due to the global recession, China is expected to account for 67% of growth in global coal consumption through the year 2030. India is expected to account for the other 33% of growth during the same period.[5]

5. BP Energy Outlook 2030, January 2012.

Chapter 4:
Today's Energy Mix – Constancy and Change

World energy consumption has increased 27% since 2000, with some modest shifts in the mix since then. Coal's share changed the most, increasing from 23% in 2000 to 28% today. Oil was 36% in 2000; today, it is 32%. Renewables have doubled, from 0.6% to 1.1%.

Yet the simple shares mask dynamic changes. The first change is in the engine of demand growth. As late as 2000, energy demand was concentrated in the developed world, which consumed almost two-thirds of total oil. Today oil consumption is split almost evenly between developed and developing countries. In the future, virtually all the growth in oil – and total energy – will be in the emerging nations as their incomes and populations increase, while demand will be largely flat or even declining in developed nations.

In 2000, renewables were primarily represented in the electricity mix by hydropower. Hydropower is still the dominant renewable source, but the years since 2000 have brought a "rebirth of renewables."[1] Today, renewables are a growing global business. In 2012, renewable electric power was a US$ a 184 billion industry. Led by wind, the share of non-hydro renewables in the global power generation mix rose from 1.4% in 2000 to 4% in 2011.[2]

Wind was the largest contributor to renewables growth during this period, averaging 35 GW of annual additions since 2008. Solar has also grown rapidly, but from a much smaller base. Solar averaged 15 GW of annual additions over the last five years and accounted for more than half of renewable energy investments in 2011. Substantial solar capacity additions in coming years likely will be based on opportunities in emerging economies. Biofuels have achieved penetration into overall liquid fuels. According to EIA, global production of biofuels grew more than six-fold between 2000 and 2011 – from more than 315,000 barrels per day to nearly 1.9 million barrels per day.[3]

Nuclear energy supplies 12% of world electricity today. Prior to 2011, nuclear energy was considered a viable, carbon-free option for meeting increasing demand for power. Following the Fukushima disaster, the outlook has changed, owing to concerns about safety. However, this is not deterring certain nations with high growth in electricity demand such as China and India.

Meanwhile, natural gas has become a global fuel. As shown in figure 5, global LNG trade doubled from 2000 to 2010. IEA expects it to increase another 50% by 2020. A sustained global market allowed for financing and long-term contracts that encouraged investment in the costly infrastructure needed for LNG trade.

Natural gas seems slated to become an increasingly important fuel in the future. Today, natural gas holds a 21% share of the primary energy mix. The share of gas varies widely across geographies – from as much as 47% in the Middle East to as little as 10% in the Asia Pacific region. Consumption has tripled over the past thirty years worldwide, and according to IEA, demand could grow another 50% by 2035. Observes Rex Tillerson, "Oil will remain the most widely used fuel, but we project that natural gas will grow fast enough to overtake coal for the number two position. In fact, measured from the year 2010 to 2040, demand for natural gas will rise by about 65%."

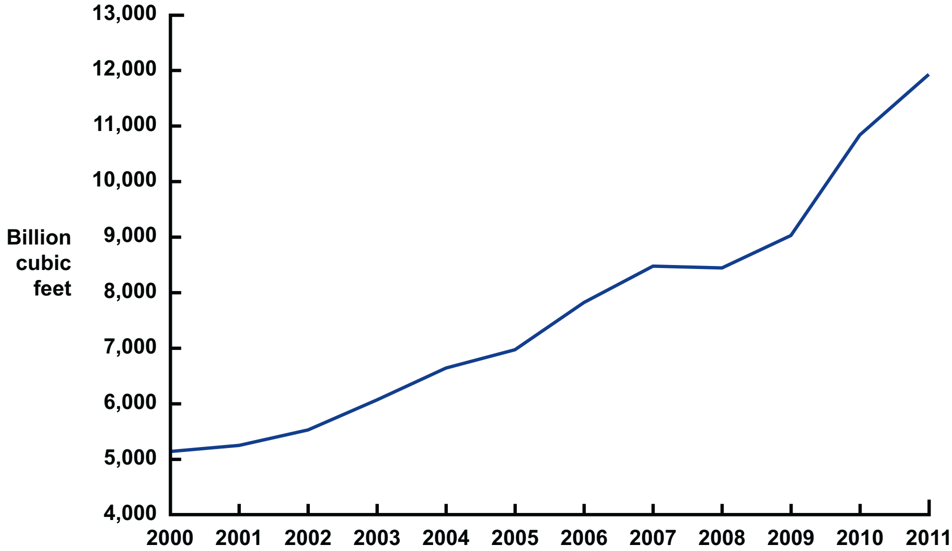
Its flexibility makes natural gas a desirable fuel for many applications. As shown in figure 6, it holds a significant share in many sectors, though it does not dominate any particular one. Primary uses include space and water heating in residential and commercial applications, fuel and feedstock for industrial processes and power generation. In OECD countries with mature gas distribution networks, the most robust growth is expected to come from power generation.

1. Daniel Yergin, *The Quest: Energy, Security, and the Remaking of the Modern World,* Penguin Press, 2012.
2. IHS Emerging Energy Research.

3. IEA, International Energy Statistics.

Figure 5

Global LNG Trade, 2000–11



Sources: IEA, EIA, IHS CERA.
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In the United States, there is a growing expectation that inexpensive natural gas will spur a "manufacturing renaissance".

In emerging markets, growth in natural gas use will span all sectors as more customers become linked to gas infrastructure. However, the power sector will still account for a significant portion of its rise in the energy mix. IEA anticipates that India's power sector will triple in size by 2035, with gas expected to be the second largest source of electricity generation after coal. China's Twelfth Five-Year Plan (2011-2015) points to significant gas-fired power additions as a means of achieving GHG emission reduction goals, with a plan to increase the share of natural gas in China's energy mix from 4% to 10% by 2020. Likewise, demand for natural gas and power will continue to grow in the Middle East and North Africa as living standards rise and as a result of increasingly urbanized and growing young populations.

Despite strong growth in lower-carbon alternatives, coal had by far the largest growth on an energy basis since 2000 – nearly twice that of natural gas, nearly three times that of oil and almost ten times that of renewables.[4] This growth can be attributed to demand in the emerging markets, which rely heavily on coal to power their electric generation.

Growing Supply for Oil and Gas

A new dynamic in the energy mix comes from additional supplies of oil and gas, potentially expanding the horizon for these fuels. As John Watson explains in his contribution, twenty-first Century Energy: Opportunities and Responsibilities, "Advances in conventional and unconventional technologies are allowing us to safely and responsibly recover more oil and natural gas from our mature fields, while opening new frontiers in areas such as deep water, arctic, tight oil and natural gas from shale – new energy resources unimaginable just a few years ago." World proved oil reserves increased 31% from 2000 to 2011; proved reserves of natural gas increased 35% over the same period.[5]

Discoveries are bringing new resource areas into the mix. Very large new supplies have been identified on- and off-shore East Africa – in Mozambique, Tanzania, Uganda and Kenya – making those countries potentially large suppliers of oil and natural gas in the next decade. Expectations continue to grow about the scale of recoverable natural gas in the Israeli and Cypriot sectors of the Levantine basin in the Eastern Mediterranean.

Ginny Rometty describes some of the technological advancements that continue to make oil and gas production more economic. "New insights in reservoir management are enabling producers to extend the life of existing oil and gas fields through enhanced recovery techniques, optimized production and improved operations management. Similarly, innovation in 3D and 4D seismic imaging has made it more feasible to unlock resources in previously uncharted areas. The resulting resource expansion is contributing to a revision of long-held assumptions about global reserves of fossil fuels."

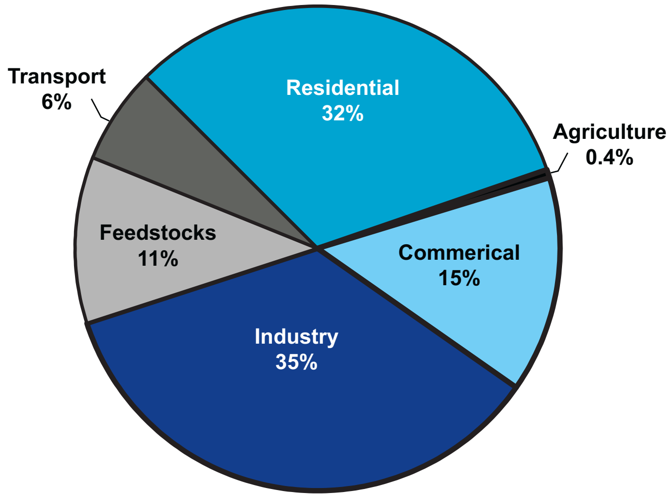
Hydrocarbon development is also happening in areas where production was once thought to be uneconomic, such as the deep waters of the Gulf of Mexico and the "pre-salt" in Brazil, changing the outlook on future energy supplies. Technology has brought dramatic increases in Canadian oil sands production. At 1.7 million barrels per day, production is equivalent to Libyan output prior to its civil war, and is expected to rise to more than 3 million barrels per day by 2020.

The "revolution in unconventional gas and oil" in North America is having a dramatic impact on markets and expectations for future supplies. The combination of two

4. BP Statistical Review of World Energy, 2012.

5. BP Statistical Review of World Energy, 2012.

Figure 6
Share of Global Natural Gas Consumption by Sector, 2011



Source: IHS CERA.
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technologies, hydraulic fracturing and horizontal drilling, became crucial to unlocking the potential for shale gas and tight oil. Relatively high natural gas prices in the United States in the last decade provided incentive to rapidly deploy these new techniques. Shale gas has risen from 2% of supply in the United States a decade ago to 37% today. The United States now produces more natural gas than Russia.

Over the last decade tight oil production has risen from 200,000 barrels per day to more than two million. US oil production has risen 25% since 2008 and is expected to increase another 30% by 2020. The IEA now predicts that North America could become a net exporter of oil and gas by 2030.[6]

Globally, unconventional resources have vast potential. Lessons learned in North America are likely to be applied around the world. China's resource potential is possibly larger than that in the United States and resource estimates in Europe rival those in North America. Parts of South America and Mexico are thought to have considerable unconventional resources.

Despite the promise of the increasing role of unconventional oil and gas in the energy mix, several issues around production may alter longer term outlooks. Although opportunity exists worldwide, challenges such as mineral rights ownerships, infrastructure, labour constraints, pricing and regulatory requirements will influence the development potential of these resources. Environmental concerns related to production may also impede the development of some resources. Disposal of wastewater is a key concern, along with a range of other issues related to land disturbance, dust, noise and equipment exhaust emissions.

"During the first decade of the twenty-first century the world has been running into fossil fuels, not away from them, a reality that will not change rapidly," says Vaclav Smil, summarizing today's energy mix. "And while the contributions of wind and photovoltaics more than tripled during that decade, the world is now more dependent, in both absolute and relative terms, on fossil-fuelled generation than it was in 2000."

What will the mix look like two decades from now? In his contribution Energy Transitions, Christof Rühl points to the prospect that there will be no dominant fuel. "Not only are oil, coal and gas likely to remain the most important fuels over the next 20 years; their market shares are likely to roughly equalize, at 25% to 30% each. This would be the first time that the world has not been dominated by one single fuel."

Perspectives on Today's Energy Mix

The chapter includes two perspectives on today's energy mix.

Christof Rühl, Group Chief Economist and Vice President, BP, United Kingdom

John Watson, Chairman and CEO, Chevron Corporation, USA

6. IEA, World Energy Outlook, 2012.

Energy Transitions

Christof Rühl

Group Chief Economist and Vice President, BP, United Kingdom

The forces of globalization are taking us into a world in which, for the first time, no single fuel will dominate the energy mix. An increasingly globalized energy system has been with us since the beginning of industrialization. Its size, fuel composition and reach have evolved greatly. So what can past transitions tell us about the future of the global energy system and, in particular, about the prospects of a lower-carbon mix?

Historically, population and income growth have been the most powerful driving forces behind energy demand. Since 1900, population has more than quadrupled, real income increased by a factor of 25 and energy consumption by a factor of 23. The next 20 years are likely to see continued economic integration and growth of low and medium income economies, along with a population increase of 1.4 billion. The most fundamental relationship in energy economics appears robust – more people with more income will mean rising production and consumption of energy.

Today, oil, coal and natural gas account for almost 90% of the global energy mix. Absent disruptive technological change, the energy system is likely to remain fossil fuel-based for many years to come: The energy sector is capital intensive and has long lead times and gestation periods. Even with continued high growth in renewables their share in primary energy consumption 20 years from now will be below 10%, simply because of today's low starting point.

Fuel transitions are subject to a complicated web of technological, economic and political forces. In the past, transitions were often heralded by disruptive technological change. The first wave of industrialization was based almost entirely on a truly disruptive technology, the steam engine, and on coal. Coal replaced wood as the world's dominant fuel. The next major transitions came with electricity and the internal combustion engine. Oil replaced coal in transport. And while coal remains the principal fuel in power generation, it is gradually being replaced first by natural gas and now by renewables.

Disruptive technological change is impossible to predict, but tracing the behaviour of energy intensity over time provides a glimpse into the future. Energy intensity is defined as the amount of energy needed to produce one unit of GDP. It is a broad proxy for energy efficiency, well suited to allow comparisons over long periods of time and across countries.

Mimicking economic development, energy intensity in almost any country follows a typical pattern. As countries industrialize, people and production move from less energy-intensive agriculture to more energy-intensive industrial production, and energy intensity rises. As production later shifts towards services and lighter manufacturing, energy intensity gently declines again.

The peaks vary across countries, owing to technological improvements (countries that industrialize later do so with more efficient technology), resource endowments (countries that have fewer resources tend to use high-priced energy more efficiently), and the system under which industrialization occurs. Countries that industrialized under central planning built a much less energy-efficient capital stock compared to economies that industrialized under market conditions.

Energy-intensity improvements accelerated as soon as the cold war ended and globalization took off in earnest. More importantly, a striking process of convergence is still accelerating across countries, as those with the least-efficient industrial structure had huge gains to realize when catching up with more technologically advanced economies. As a result, global energy intensity today is at a 100-year low, while the differences across countries are the smallest since the beginning of the industrial revolution.

The forces of globalization that brought about this rapid convergence are also shaping the future composition of global energy. Globalization means that it has become possible to trade any fuel across almost any border, greatly enhancing the prospect that fuels are allocated to their most efficient application. Globalization allows the diffusion of technology across borders to proceed at unprecedented speed, helping to ensure that fuels compete on true cost. Globalization also brings standardization, ensuring efficiency gains and unprecedented flexibility in energy production and consumption.

A number of trends are already discernable. Power generation will continue to rise in importance, as industrialization and the switch towards services proceeds. Power will be an area of renewable energy growth but also one of considerable competition across fuels. Transport will remain focused on efficiency improvements and much less exposed to interfuel competition. Oil will continue losing market share as it becomes specialized in transport. Natural gas will increase market share owing to increasing affordability, availability and tradability, and because it is a cleaner substitute for coal in power generation. Coal's share, on the other hand, continues to follow the pace of industrialization in Asia and perhaps Africa, and carbon policies in the OECD.

The big picture is again one of convergence, this time across fuels. Not only are oil, coal and gas likely to remain the most important fuels over the next 20 years; their market shares are likely to roughly equalize, at 25% to 30% each. This would be the first time that the world has not been dominated by one single fuel.

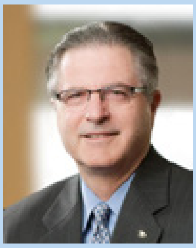
Where does this leave renewables? Here, a problem appears. Renewables by and large need subsidization to compete. As long as this is the case, their ability to acquire durable market share will be impaired.

Europe provides an example. Subsidies are being cut in many countries, not for lack of support but rather for too much success. Renewable growth has been so fast that the required subsidization creates a fiscal problem. Behind the dilemma stands a simple rule: As long as the rate of expansion exceeds the rate of efficiency improvements for any subsidized fuel relative to others, subsidy payments need to increase.

The long-term task is thus improving the productivity of renewables relative to fossil fuels. There are many ways to do this, but subsidization may not be one of them. Lessons from the history of fossil fuels are fairly unambiguous: Markets, free prices and competition are the prerequisites to generate technological innovation. How to replicate these conditions for a subsidized sector is less clear, but it looks as if this is the challenge in securing a larger share for renewables in the long term.

Absent another round of disruptive but unpredictable technological change, that is.

Twenty-First Century Energy: Opportunities and Responsibilities



John Watson

Chairman and CEO, Chevron Corporation, USA

Over the past 150 years, we have seen the greatest advancements in living standards in the history of the world. Light, heat, mobility, mechanized agriculture, industrialization, biotech and cloud computing have all improved the lives of billions. The development of abundant, affordable energy has enabled all of these advancements.

In the twenty-first century, affordable energy will continue to be a cornerstone of sustained economic growth and the rise of a global middle class. For our industry, this represents a tremendous opportunity – and a big responsibility.

If history is any predictor, the opportunity is within our reach. We are well positioned to develop all the energy, in its many different forms, that the world will need. Advances in conventional and unconventional technologies are allowing us to safely and responsibly recover more oil and natural gas from our mature fields, while opening new frontiers in areas such as deep water, arctic, tight oil and natural gas from shale – new energy resources unimaginable just a few years ago.

Thirty years ago, in fact, geology students were taught there was no potential for hydrocarbons to accumulate in commercial quantities in subsalt, deep water or shale. Yet advances in technology, geophysics, geology and engineering proved that conventional wisdom was wrong, opening up the possibilities of tapping these rich frontiers. And today subsalt, deep water and shale are the industry's three premier zones of growth. The result is that while concern about resource scarcity had been gaining some traction over the past 30 years, during that period the world's proved reserves of oil and natural gas increased 130%, to the equivalent of 2.5 trillion barrels of oil.

And it wasn't more than a few years ago, with the United States depending on foreign oil imports for 60% of its total supply, that the nation's energy security was viewed by many to be at risk. Today, the United States sees a different future, partially driven by the innovative application of existing drilling technologies. This new outlook was supported in November when the IEA forecast that within 10 years, the United States will become the world's largest oil producer, and within 20 years, North America could become a net oil exporter.

In this case, the technologies enabling transformational changes are horizontal drilling and hydraulic fracturing applied to shale, a rock formerly known as a reservoir seal but never a reservoir.

Yet despite the abundance of fossil fuels and advances in their recovery, they alone won't be enough to meet expected long-term demand growth. We're going to need it all – safe and reliable supplies of fossil fuels, nuclear energy and renewables.

As the world's population continues to expand along with the use of energy, we also face a collective responsibility to manage the environmental impacts of energy production and consumption as well as the economic growth that energy empowers.

Once again, technology will help us do that.

For example: We're commercializing our vast reserves of natural gas, which emits the lowest amount of carbon dioxide of any fossil fuel. In Australia, our Gorgon LNG project will produce cleaner energy for at least 40 years.

In our Marcellus operations in Pennsylvania, we're producing cleaner-burning natural gas from shale. We also are working with industry to raise safety performance and support the disclosure of chemical additives used in the hydraulic fracturing process. We strive to recycle 100% of our flowback and produced water while continuing to research ways to further minimize fresh water use in these operations.

And in Coalinga, California, we launched a solar-enhanced oil-recovery project. We're using the solar energy produced by nearly 8,000 mirrors to produce steam needed to increase recovery of our heavy oil reserves, while lowering our carbon footprint.

A final important element in growing the energy portfolio is energy efficiency. Experts estimate that globally one-third of primary energy demand – roughly 160 quadrillion BTUs – is lost in energy production, transformation, transmission and distribution. This is a huge prize that should command our attention. Our greatest efficiency and conservation gains won't be cultural or exercises in self-sacrifice. They will be technological, including innovations in building, manufacturing, transportation and other sectors.

Ours is a problem-solving industry, demonstrated by how consistently we've developed and applied technology to deliver affordable, reliable energy. Over the long term, technology will remain critical to meeting the world's need for energy.

Of course, technology and resources are only part of the energy equation. Meeting the scale of the world's energy needs in the twenty-first century also will require policies that promote access, free trade, responsible taxation, rule of law and other fundamentals of healthy economies.

All of us – industry, political leaders, policy-makers and nongovernmental organizations – will need to work collaboratively to create a broad pathway for the development of affordable energy and the sustained economic growth that energy will help promote.

Chapter 5:
The Next Big Energy Transition?

Over the past 100 years, growing access to modern forms of energy, mostly fossil fuels, has accompanied human progress. But perspectives change. Concerns about the environmental impacts of fossil fuel production, processing and consumption have brought about regulation to reduce smog, air pollution, acid rain and ozone depletion. More recently, climate change and a focus on reducing GHG emissions have taken centre stage for public policy.

The challenge of reducing GHG emissions is compounded by the need to bring modern energy services to the 1.3 billion people who lack access today. People around the world aspire to the high standard of living found in the industrialized countries. Improving standards of living for growing populations in the developing world while still reducing GHG emissions is doubly challenging.

The result is a new focus and debate on the prospect of a new energy transition, decreasing reliance on the fossil fuels that made modern society possible and increasing the supply of lower carbon alternatives. But what alternative fuels can power the world's future? And when? The answers to these questions will be played out over many years. But consideration of the different roles and advantages of today's primary fuel sources can help us frame the possibilities.

Most forecasts of the energy future share one defining characteristic: they assume that the energy technologies available or emerging today are the ones that will primarily be used tomorrow. In the short term this is certainly true. Given the size and complexity of the energy industry, the mix of energy supply cannot change overnight. Technologies in development now may take decades to become significant contributors to the energy mix. However, according to Prashant Ruia in his contribution Technology Transforming the Energy Industry, "Technology has created a wealth of opportunities in the energy business that have already transformed our industry. The future will bring changes of even greater magnitude than those in the past." One must look ahead to 2030 or further to see the greatest possibility for substantial change.

Science or Science Fiction – or Somewhere in Between?

In 1989 two American chemists announced a breakthrough that promised to revolutionize the future of energy. They claimed to have produced "cold fusion" – or nuclear fusion at room temperature – in their lab in Utah. But when their results could not be replicated by independent researchers the claim was dismissed as a fluke or a hoax. Such experiences have led the energy community to be cautious about the likelihood of a "black swan event" that could drastically change the future energy mix. And yet the tight oil deposits of North Dakota were once similarly dismissed as unviable. Today they have catapulted North Dakota to the number two oil-producing state in the United States.

So how does one separate the science fiction from the future solution? Unfortunately, there is no easy answer to this question, but the likelihood of breakthroughs is very real. Nuclear energy went from a pure concept to a large-scale energy source in little more than three decades. So one must not ignore the possibility that potential energy sources that today exist only in the realm of the imagination or basic research could enter the energy mix in a real and powerful way within our lifetimes. Any time one is thinking far into the future, one must expect the unexpected.

Low-Carbon Electricity

Electricity generation is the largest source of energy-related GHG emissions. Owing to its versatility and convenience, electricity tends to make up a larger share of energy consumption as societies become wealthier, meaning that its importance will continue to grow in the developing world. IEA projects that 64% of global electricity generation will take place in non-OECD countries by 2035, compared to roughly 50% in 2010.[1] Decreasing the GHG emissions from this sector will be central to the overall goal of reducing anthropogenic GHG emissions. Christof Rühl points out that, "Power generation will continue to rise in importance, as industrialisation and the switch toward services proceeds. Power will be an area of renewable energy growth, but also one of considerable competition across fuels."

A number of technological paths are possible to provide low-carbon electricity to a growing world. One option is to increase generation from sources that are zero-carbon in their power output, with renewables and nuclear as the leading candidates. Capturing the carbon dioxide (CO_2) emissions from fossil fuel generation is a second option, allowing fossil fuels to continue playing a role in a low-carbon electricity future. Relative costs – a combination of technology costs, fuel costs, back-up costs and additional costs (like carbon prices) that policy may impose – will determine which technologies predominate in future electricity generation.

Renewable Electricity Sources: The Promise and the Challenge

Renewable energy accounted for approximately half of the electricity generating capacity added globally in 2011, but a smaller fraction of actual generation. Those additions were primarily in wind and solar. Despite this rapid growth in renewables, hydropower is the only renewable source to make up a substantial portion of today's power system, with a 16% share of global electricity production and an 80% share of global renewable electricity production. Hydroelectric capacity is expected to expand 30% by 2020.[2]

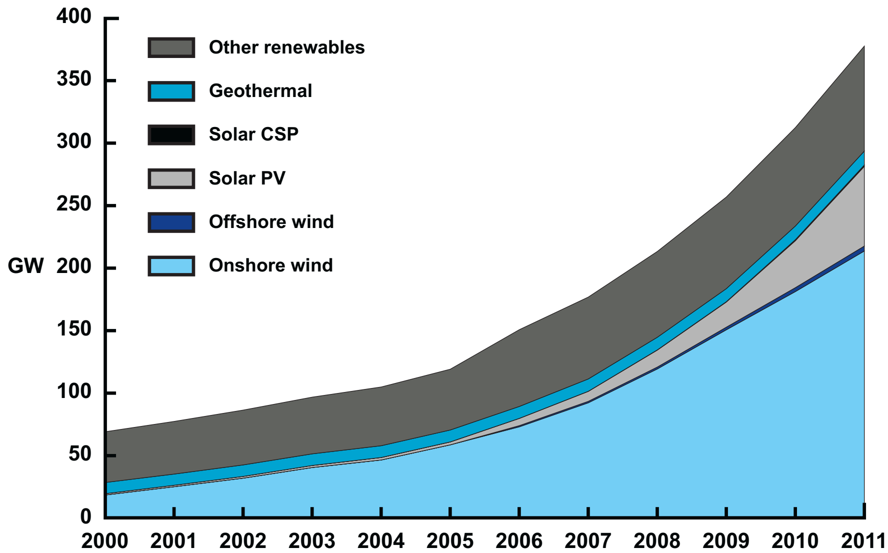
Wind and solar are the sources of renewable electricity that are capturing the imagination of many today. Development of both as modern technologies began in the 1970s in the wake of the Arab oil embargo. They went into a difficult period, known as "the valley of death", at the end of the twentieth century. However, the new century saw increasingly strong growth.

Wind generation is the fastest growing source of renewable electricity, as shown in figure 7. Capacity grew an average of 26% per year from 2000 to 2011.[3] So many turbines have been deployed on such a large scale that this technology may no longer be considered "alternative." According to IEA, one quarter of renewable electricity will come from wind by 2035, and in the OECD wind power will account for half the total incremental generation between 2010 and 2035.

Solar currently accounts for a much smaller portion of power generation capacity. Solar made up 1.2% of global generating capacity in 2011, and an even smaller share of power generation – 0.07% in North America and 0.9% in Europe. Nonetheless, in a short period of time, solar has gone from a niche technology to a multi-gigawatt global industry. According to IEA, global solar PV capacity increased from 1 GW in 2000 to 67 GW in 2011. And in the last year alone, capacity increased by 30 GW, or approximately 75%. The European Union accounted for three quarters of those capacity additions.

Figure 7

Global Renewable Capacity Additions, 2000–11



Sources: IEA, EIA, Utility Data Institute and IHS CERA.
Note: Other renewables includes biomass and ocean power.
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1. IEA, World Energy Outlook, 2012.

2. IHS Emerging Energy Research.
3. IHS Emerging Energy Research.

Solar PV, which directly converts sunlight into electric current, is the dominant technology in use today. The technology began in the late 1950s powering satellites, and then moved into remote applications where the very high cost to bring in grid power made solar PV economic. Europe, with Germany at the forefront, led the way in solar PV installation and manufacturing in the early 2000s, but Asia Pacific is now poised to be a growth area. China is expected to leverage its powerful supply base and government financing to add 30 GW of solar PV capacity between 2010 and 2025.

An important advantage of solar PV is its modularity, meaning that solar panels can be installed for applications ranging from a single house to large utility-scale arrays. Distributed – or onsite – solar generation is becoming increasingly attractive as the cost of PV cells comes down. In industrial nations consumers are taking advantage of a variety of programmes meant to spur PV installation at homes and businesses. In developing countries, solar PV can provide backup for unreliable power sources or service remote areas, replacing more expensive diesel generation.

Concentrated solar power (CSP) uses mirrors or lenses to concentrate the sun's energy to heat a fluid and produce steam, which is then used to generate power. These plants are utility scale, ranging in size from 50 to 200 megawatt (MW). New solar technologies are also under development to more efficiently harness the sun's energy, from photovoltaic materials that can be applied to buildings like paint to solar cells meant to mimic the photosynthesis process of plants.

Other potential sources of renewable energy are promising, but in their infancy. Harnessing energy from wind generated ocean waves or from the daily fluctuation of tides are possibilities, as is producing energy from the thermal differential between ocean surface and deep waters. The role these and other new technologies may play is impossible to know at this point.

Challenges: Cost of Renewables Plays a Role Moving Forward

Cost competitiveness is vital for wind and solar to gain market share over other power generation sources. Steady technology improvements have brought costs down substantially in recent years. Competitiveness certainly depends on the cost of technology, but also on policy decisions such as subsidies or carbon prices and on the prices of fossil fuels. Lower cost natural gas is an unexpected and major challenge to renewables in North America.

The wind industry has seen significant cost declines in the past three decades. Darlene Snow, in her contribution The Appropriate Use of Wind in Electricity Portfolios, notes that, "The cost of energy from wind power in areas with good wind resources, according to the US Department of Energy, has decreased from more than US$ 0.55 per kilowatt-hour (kWh) in 1980 (in current US dollars) to less than US$ 0.06 per kWh today."

Turbine capacity is an important factor in the cost of wind energy. Larger turbines typically have a lower cost per unit of installed capacity than smaller ones, and wind turbine capacities have grown ten-fold over the last twenty years. Nonetheless, the logistics of moving large turbine parts and the extreme forces that very large turbines would have to endure are likely to prevent wind turbines from getting much bigger than they are today. Technology improvements are now focused on improving blade design, power electronics and overall efficiency and developing lighter, tougher materials.

Offshore wind resources are a new frontier as a source of renewable electricity. Higher and more constant wind speeds make offshore development very attractive. Larger turbines might also be possible offshore. However, costs for offshore wind are two to three times those for onshore wind, and the technical difficulties are multiplied by the harsh environment. The cost of offshore wind projects will need to come down substantially for them to become a competitive generation source. Otherwise, they will depend heavily on government incentives or carbon pricing.

However, solar PV is quickly becoming more competitive. The cost of solar PV panels has plummeted by 65% since 2010, as shown in figure 8. However, these recent price decreases mostly occurred as a result of decreasing component costs, reduced labour costs and decreasing margins as a result of growing competition and manufacturing capacity, especially in China. The industry is now suffering from over-capacity. Future cost declines will be more difficult to achieve and may need to come through technology improvements and efficiency gains in manufacturing.

As Michael Stoppard and Susanne Hounsell describe in their contribution Germany's "Energy Turnaround", "Germany has become the laboratory for the large-scale development of renewable power in a major economy. The success of this endeavor will depend on the ability of the German power system to accommodate increasing shares of intermittent renewable power and the ability of German consumers to pay for renewable power subsidies."

Nuclear Renaissance or Retreat?

Nuclear energy supplies 12% of world electricity today. Due to its large scale and carbon free characteristics, nuclear will likely play an important role in many countries in coming years, allowing them to diversify their energy mix, meet growing demand for power, enhance energy security goals and combat climate change. Until the beginning of 2011, there was much discussion about a "nuclear renaissance."

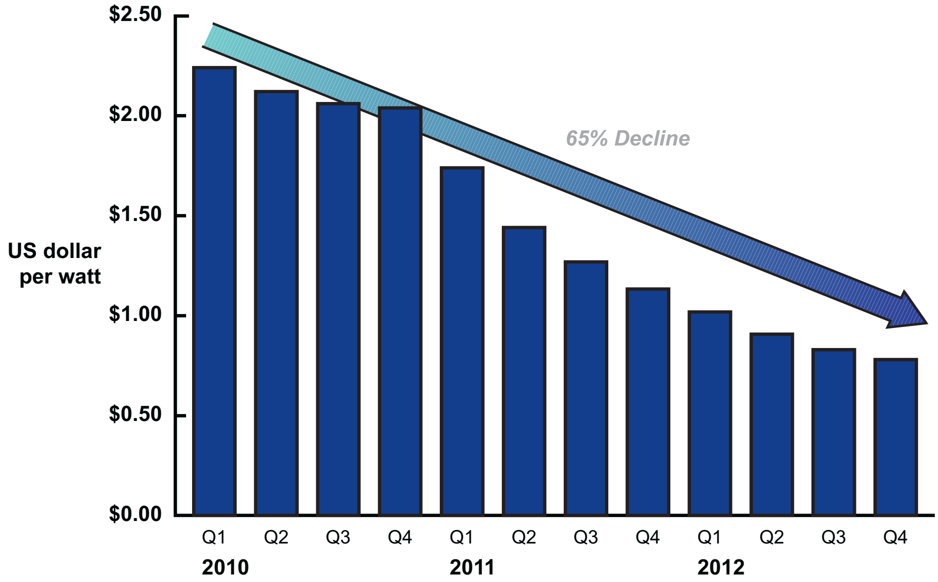
But the disaster in Japan at Fukushima in March 2011 heightened concerns about the safety of nuclear power and shifted the energy policies of many countries. Prior to 2011, nuclear power plants supplied roughly 25% of electricity in Germany. Five nuclear reactors in Switzerland that generate 40% of the country's electricity are slated to be phased out by 2034. Prior to the disaster, Japan had planned that nuclear power would eventually account for 50% of electricity generated, but after an intense national debate, the question is now whether nuclear power will be phased out entirely or remain at a reduced level.

Despite moves away from nuclear in Japan and in parts of Europe, the coming decade will bring the biggest nuclear power expansion the world has seen since the 1970s and 1980s. Strong demand for electricity and GHG emissions reduction goals will continue to drive demand in non-OECD countries, as shown in figure 9. According to EIA, from 2010 to 2035, nuclear power capacity is expected to increase by a net 109 GW in China, 41 GW in India and 28 GW in Russia.[4]

4. EIA, 2012 Annual Energy Outlook.

Figure 8

Average Selling Price for PV Components, 2010–12



Source: IHS Emerging Energy Research.
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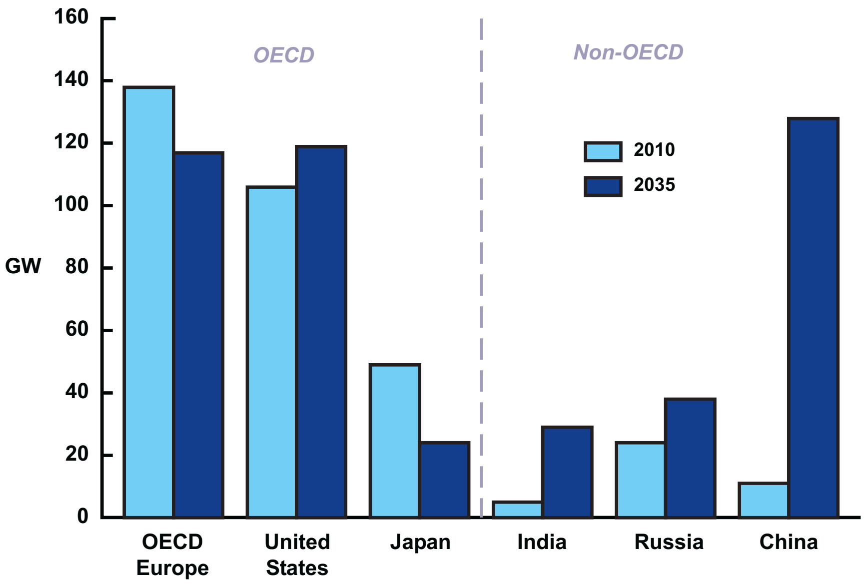
Figure 9

Installed Nuclear Capacity in Select OECD and Non-OECD Countries, 2010 and 2035



Sources: EIA and IEA.
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A complex of four new reactors is being built in the United Arab Emirates. As Mohamed Al Hammadi points out in his contribution Increasing Energy Sustainability and Security Is Possible Today, “Arab nations are embracing nuclear energy as a key component of their energy portfolios. The UAE aims to bring the region’s first plant online in 2017.” Two new reactors are being built in the United States.

New units are being built with passive safety features to limit potential operator error during emergencies. In addition, researchers and companies are testing modular reactors that allow standardization of design and construction to streamline costs and manage time delays. In his contribution Increasing Energy Diversity, Oleg Deripaska points out some of the advantages of advanced nuclear reactor designs. “Modern reactors will be cheaper to run, cheaper to build and are developing a safety record which cannot be matched… Their technologically built-in safety systems remove problems associated with operational errors and equipment failure. Their working lives will be much longer than past reactors thanks to advances in fuel technology, coolants and metal alloys.”

Researchers are beginning to focus on small modular reactors (SMR) that are fabricated in factories and moved to sites. However, it is still very early days for this new technology. A new report from a US Secretary of Energy Advisory Board states that SMR could play an important role in delivering “cost competitive” electricity generation and in meeting “stringent” regulatory standards. But the report adds, “Developing that SMR industry will be both costly and financially risky” and government “will likely have to play a significant financial role.”[5]

Fossil Fuels and Carbon Capture

Of the important fuels in the electricity portfolio today, coal faces the biggest challenges in reducing its carbon footprint. According to the IEA, the global coal–fired power plant fleet produces more than 8.5 gigatonnes of CO_2 each year, one-quarter of the world’s CO_2 emissions caused by human activity.

As shown in figure 10, combustion of natural gas produces the least emissions of GHGs and other air pollutants among fossil fuels – approximately 50% fewer GHGs than coal. Natural gas power plants can be built more quickly and cheaply than coal plants; newer gas plants are more efficient when ramping production up and down, bringing flexibility to power systems.

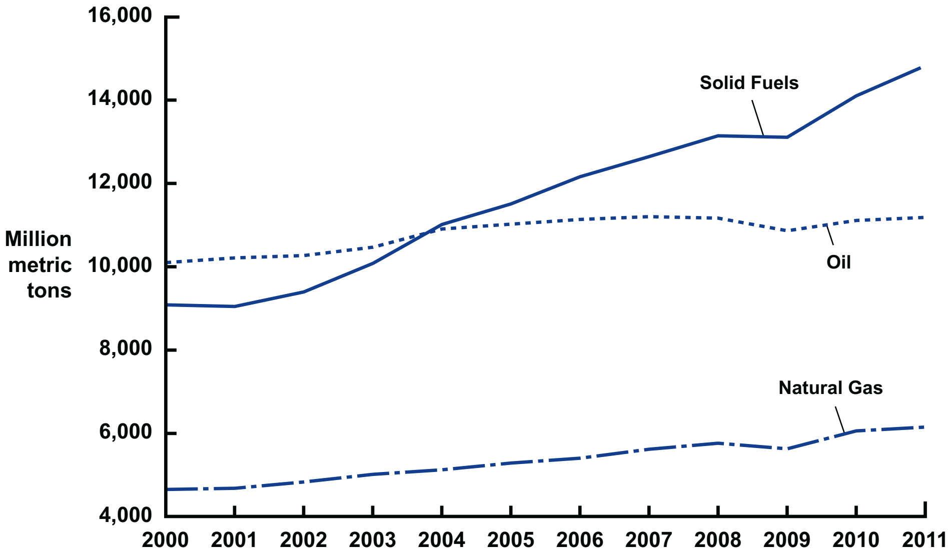
Natural gas plants can clearly contribute to reducing GHG emissions from the power sector and back up intermittent renewable sources of power. Nonetheless, a debate is underway today about the role of natural gas in a low-carbon future. Natural gas can back out coal from electric generation, provide a lower-carbon alternative to new coal generation and back up intermittent renewable generation. But if the goal is minimizing or eliminating GHG emissions, natural gas power is only a partial solution.

Carbon capture and sequestration (CCS) is a potential option to keep fossil fuels in the electricity generation mix while still reducing GHG emissions. CCS is most often focused on reducing emissions from coal, but CCS could also be used in combination with natural gas generation. Per unit of power produced, natural gas would require 40% less CO_2 storage volume than coal, reducing a significant barrier to CCS implementation.

All CCS technologies reduce the thermal efficiency of a power plant, meaning that a greater amount of fossil fuel will

Figure 10

Global CO_2 Emissions from Fossil Fuels, 2000–11



Sources: IEA, IHS CERA.
21215-10

5. US Secretary of Energy Advisory Board, Subcommittee on Small Nuclear Reactors, 2 November 2012.

be needed to produce the same amount of electricity. This "parasitic load" means that the cost of fuel and the amount of pollution and other externalities associated with the fuel are higher per unit of power produced for plants with CCS. Technology improvements can reduce parasitic load, but the laws of thermodynamics dictate that it will never go to zero. As in most things, there is no free lunch in carbon capture.

CCS projects in operation today are at the pilot phase. It remains to be seen if CCS is feasible on a large scale – in terms of technology, economics and public acceptance. Technological advances are needed to make CCS more efficient and less costly; today, adding CCS can double the cost of a power plant. CCS will not be economically feasible without subsidies or a significant price on carbon. Selling captured CO_2 for other purposes, mostly for enhanced oil recovery, is often mentioned as a potential offset for the cost of CCS. However, use in enhanced oil recovery is very site specific and is unlikely to make a project economic alone. Carbon capture at scale would involve very large engineering projects, raising challenges not only about cost, but also about the management of stored CO_2 and public acceptance.

Transportation – Competitors to Oil?

Oil has dominated the transportation sector for almost a century, since Ford's Model T and the internal combustion engine entered the scene. Gasoline, diesel and jet fuel have physical qualities that make them excellent transportation fuels. They are energy dense, easily transportable and readily available around the world. Another form of energy to match oil's ability to fuel the transportation sector has yet to be developed. The vast global infrastructure in place to produce, refine and distribute oil poses a barrier for new transport fuels, but the positive physical characteristics of the fuel may be even more difficult to match.

Today there is greater support and advocacy for alternative fuels than ever before. Yet over the next 15 to 20 years, the transportation sector will continue to drive oil demand growth, particularly in non-OECD countries. Rapidly growing economies and populations will fuel demand for both personal and commercial transportation. From now until 2035, the number of personal vehicles on the road is expected reach 1.9 billion, double the size of the global fleet today.[6] As illustrated in figure 11, regions with growing gasoline consumption include Asia Pacific and Latin America. By 2030, consumption is expected to increase 43% and 36%, respectively, from 2010 levels.

Although non-OECD markets will continue to stimulate oil consumption, fuel consumption in established markets such as North America and Europe has already levelled off and will continue to decrease through 2030, also shown in figure 11. Continuing increases in fuel efficiency standards, a growing share of hybrids and other advanced vehicles in the fleet as well as ageing populations will dampen transport fuel demand in the OECD world.

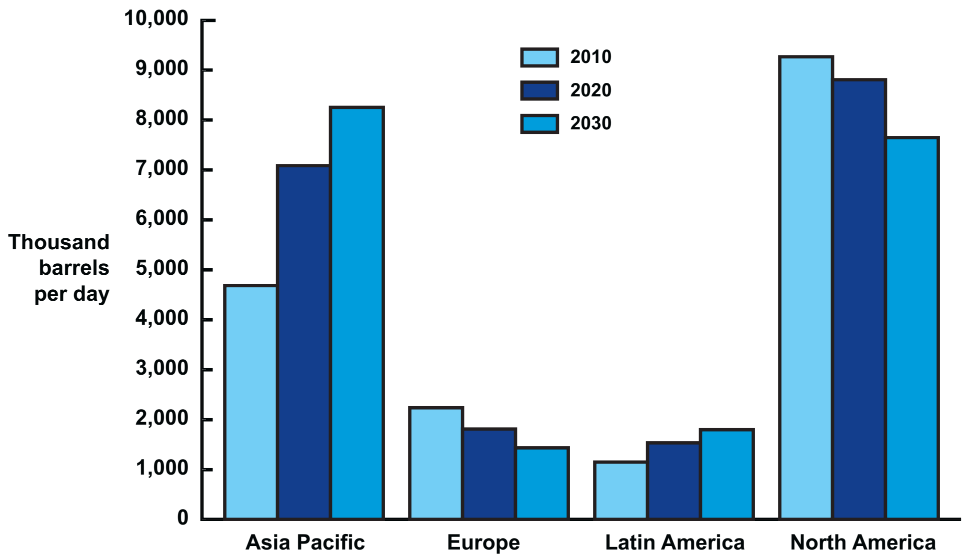
In addition to oil's positive attributes as a transportation fuel, new technologies for oil extraction are continually bringing about additional supply. The world is unlikely to leave the age of oil because of scarcity, but because new fuels with lower GHG emissions gain the ability to compete with oil in the transport sector in terms of price and effectiveness.

Biofuels

Biofuels offer a relatively simple replacement for oil in the transportation sector, since they do not require wholesale changes to vehicles or fuelling infrastructure. However, the

Figure 11

Gasoline Fuel Consumption by Region



Sources: IHS CERA.
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6. IHS CERA, 2012.

scale of the transportation sector and availability of land and feedstocks limit biofuels' role as substitute fuels. Even in countries such as the United States that lead the world in biofuels production, only 10% of gasoline demand by volume (7% by energy content) was met by biofuels in 2012. Brazil boasts a competitive market based on ethanol produced from sugarcane that is more efficient and economic to produce. However, very few countries in the world can replicate the success in Brazil, which delivers 21% of total transportation fuel demand through biofuels, since sugarcane production requires annual rainfall not available in most parts of the world.

Most of the biofuels on the market today are made from food products – corn, sugarcane or oil crops. The key to producing larger volumes of more sustainable biofuel is using feedstocks other than food crops to avoid food versus fuel competition. Research is underway on a number of potentially game-changing products: cellulosic ethanol, biocrude, genetic modification to improve yields of energy crops and synthetic genomics. All of these technologies have the potential to produce lower-cost, more sustainable biofuels that do not compete with food supply.

Additionally, to meet GHG emissions reduction goals, biofuels must have lower life-cycle GHG emissions than the petroleum fuels they would replace. The CO_2 captured by plants as they grow offsets the emissions from biofuel combustion. However, the emissions generated from the production of fertilizers and other agricultural chemicals, growing and harvesting feedstocks and refining biofuel products add up, leading to debate about the carbon footprint of biofuels. Additionally, accounting for emissions that may occur as land use changes from its previous state (forest, pasture or other agriculture) to biofuel feedstock production is a controversial question with no clear answer.

Craig Venter describes the potential of genetically-engineered algae to provide low-carbon biofuel. "Altering the biochemistry of algae cells to produce high yields of oil (10,000 gallons per acre per year) is theoretically possible, even though today's best strains produce only 2-3,000 gallons per acre per year." He continues, "I think that the accumulation of our genetic software changes can produce a game-changing renewable carbon-based energy source from CO_2 and sunlight."

Electric Vehicles

Electric and hybrid electric vehicles have received more attention over the past few years, but they are still a tiny fraction of new vehicles sold. Some automakers are strong supporters, but the major support is coming from governments in the form of regulation and incentives, particularly in the United States, China and Japan. However, there are differences in emphasis among these programmes. In the United States, climate appears to be the most important reason. For China and Japan, international competitiveness looms large. For China in particular, the electric car would also be a way to manage rapidly growing oil imports as a result of a burgeoning auto fleet and a possible avenue to leapfrog towards the front of the global auto industry.

Electric vehicles powered by low-carbon electricity could be game changers in the world's drive to reduce GHG emissions. (That would assume, however, that a substantial amount of electricity has shifted to low-carbon generation.) However, cost and utility are the main factors inhibiting demand growth. Driving range of today's all-electric vehicles is limited to typically 100-150 kilometres and recharge time is usually measured in hours, compared to roughly five minutes to refuel a gasoline vehicle.

Electric motors have performance advantages over their internal combustion counterparts, including more efficient operation, high torque and continuous variability, meaning that they do not need a traditional transmission. But technology to carry energy on the vehicle is way behind. Batteries are the crucial challenge for electric-powered transportation. Batteries currently available have energy density – meaning the amount of energy they can hold per unit of weight – roughly two orders of magnitude smaller than those of liquid fuels. Electric operation is nearly impossible today for aviation or long-haul trucking, applications where the energy density of the fuel is crucial. A great leap in battery technology is needed to make electric vehicles widely competitive.

Despite the challenges, government policies around the world are encouraging electric vehicles. Levi Tillemann describes one such programme in his contribution EVs Everywhere by 2025, "One of the major focuses at the US Department of Energy (DOE) is overcoming the barriers to widespread EV adoption. The DOE's 'EV Everywhere' initiative brings together stakeholders ranging from research labs, to automakers, to EV deployment communities to tip the scales in favour of electrification." Norway, considered a world leader in the market for electric vehicles, provides incentives that include exemptions from sales and VAT taxes, free road tolls and access to free parking and bus lanes. However, electric cars still only account for 2.5% of new car sales in Norway.

China is now the world's largest automobile market. According to the government's New Energy Vehicle Industry Development Plan (2012-2020), China projected that 500,000 electric vehicles will be sold by 2015 and five million will be sold by 2020. The Chinese government has identified the EV market as one of seven "key strategic emerging industries" and has announced EV incentives that will amount to one hundred billion yuan (US$ 15.7 billion) over the next 10 years through sales tax exemptions and consumer subsidies. At this point, however, electric vehicle sales are lower than had been projected. An estimated 12,000 electric vehicles were sold in China in 2012.

Other Vehicle Fuels: Natural Gas and Hydrogen

While policy focus has been on hybrids and electric vehicles in many OECD countries and China, natural gas vehicles (NGVs) have been the primary alternative to petroleum in several countries with large natural gas resources. More than 60% of all natural gas vehicles on the road today are in just four countries – Iran, Pakistan, Argentina and Brazil.

As the dynamics of global gas markets change, natural gas vehicles are becoming more attractive in some new markets. For example, North America is experiencing a substantial price gap between natural gas prices and those for gasoline and diesel that is expected to remain well into the future. Nonetheless, higher prices for natural gas vehicles, limited driving range and consumer acceptance of alternative technologies continue to hinder market growth. Increased fuel efficiency in gasoline and diesel vehicles raises another competitive challenge. Infrastructure also poses a barrier to greater adoption, since refuelling infrastructure for compressed natural gas can be a costly undertaking for fuelling stations, which have limited guarantee of a consumer base.

Commercial fleets hold better promise in overcoming infrastructure challenges, given that they can make use of centralized refuelling infrastructure. Additionally, in North America, long haul trucking fuelled by LNG looks particularly good from an economic perspective, since very high annual mileage (more than 190,000 kilometres per year) can result in significant fuel cost savings. Much, of course, depends on the cost of natural gas relative to oil. In the United States, potential fuel savings can offset the incremental vehicle cost (US$ 40,000–US$ 75,000) in a little over three years. LNG could also become a major fuel for trucks in other areas as well if economics support it.

Hydrogen fuel cell vehicles (FCVs) present another option. These vehicles run on electricity produced on-board by converting the hydrogen fuel and oxygen in the air to water vapour. The fuel cells themselves are still very expensive and today the most viable process for manufacturing hydrogen fuel is from natural gas, meaning that these vehicles still run on fossil fuel. Producing hydrogen using nuclear or renewable power to split water molecules could transform hydrogen vehicles into a nearly zero-emission option, but such technology is prohibitively expensive today. Infrastructure investment would also be needed, as in the case of NGVs and EVs, since a fleet of such vehicles would require hydrogen fuelling stations. Substantial investment and breakthroughs in technology will be necessary before commercialization of hydrogen FCVs occurs.

The future role of all types of alternative vehicles in the transportation mix will depend on their economics as well as their GHG emissions. The kind of infrastructure and fleet changes needed to bring about their widespread use are unlikely to occur without strong policy support, and policy support is unlikely, at least in some countries, unless these technologies can deliver on the promise of emissions reductions. On the measure of emissions, electric vehicles are the clear winner. As show in figure 12, a natural gas car has about the same per-kilometre emissions as an electric vehicle running on coal-fired power. Electric vehicles running on natural gas-fired power have lower GHG emissions per kilometre than natural gas internal combustion vehicles. The combined efficiency of an electric vehicle drivetrain and a modern combined-cycle gas turbine for power generation more than overcomes the losses that occur in the electricity distribution system. Clearly an electric vehicle running on zero-carbon renewable power has the lowest emissions of all. But, as in so much else, relative price will also be determinant. Costs will include not only the battery and vehicle itself, but also the infrastructure to support it.

In his contribution Electric Vehicles: Fantasy or Panacea? Daniel Sperling describes a potential future for transportation that uses very little oil. “By 2050, it is plausible that in many regions of the world almost all new cars and light trucks will be operating nearly exclusively on electricity and/or hydrogen. Pure battery EVs, downsized for local use, might dominate in city centres. Plug-in hybrid vehicles, using natural gas, biofuels or gasoline for their small combustion engines, will likely compete with hydrogen FCVs for larger light duty cars and small and medium duty trucks.”

Moore’s Law for Batteries?

Many consumer electronic devices seem to become smaller and more powerful every year, with advancement in semiconductor technology allowing this rapid improvement. The cofounder of Intel put forward “Moore’s Law” in the mid-1960s, a rule of thumb that postulates that the level of chip complexity that can be manufactured for minimal cost is an exponential function, doubling every 18 to 24 months. This “law” has held true in the semiconductor industry for decades. Could such a rapid improvement in technology apply to batteries as well? And if so, when?

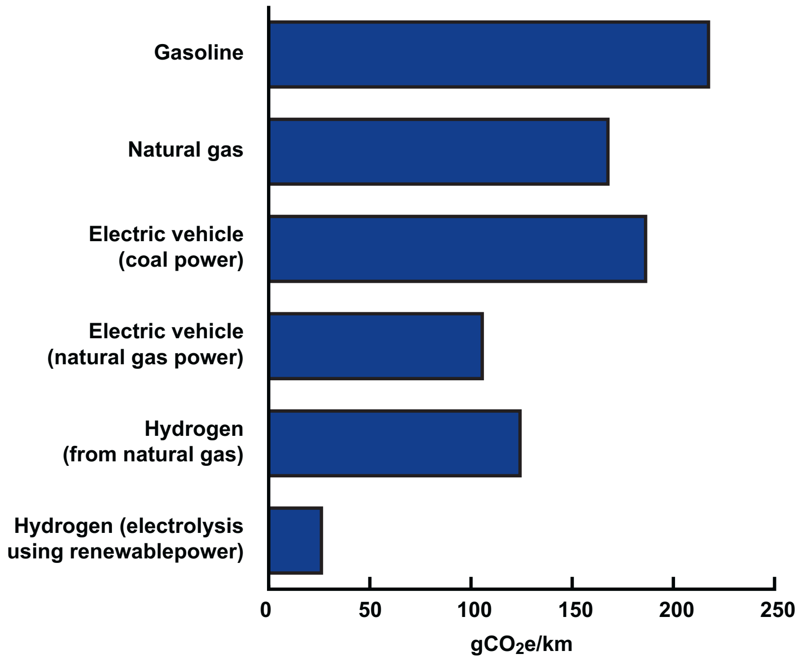
The development of high-purity silicon made the exponential development of semiconductor technology possible. Discovery and development of the fundamental technology set the groundwork for Moore’s prediction to become reality. On the other hand, battery technology today has yet to achieve the critical milestones that brought about semiconductors’ rapid development. For batteries, these milestones include discovery of the optimum battery chemistry and demonstration of manufacturing processes.

The search for the optimum materials for batteries has progressed over time, transitioning from lead-acid to nickel metal hydride to lithium ion. Since the late 1980s, battery chemistry research and development has focused on fundamental materials that yield higher power and energy density, safety, reliability and long life. The last few years have seen much more intense research on batteries. Lithium ion is the focal point today for research and development owing to its high energy density. Several lithium ion battery chemistries and physical designs are considered state of the art today, but it is not clear whether any of these will achieve the ultimate performance needed for broad application in vehicles.

The discovery and development of a battery chemistry that improves on current constraints will be a key milestone for electric vehicles. Ideally, this raw material would be more widely available than lithium, easier to purify to the level needed for mass production, pose a lower thermal management risk, and have the performance characteristics needed to achieve market success in electric vehicles. If and when this breakthrough occurs, long development cycles for vehicles mean that it could still take 15 or more years to mature before being fully integrated into the automotive industry. And even if an ideal battery chemistry arises, there are still no guarantees of the kind of exponential improvement that the electronic industry has enjoyed.

Figure 12

GHG Emissions per Kilometre Driven



Sources: IHS CERA, US Department of Energy.
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Perspectives on the Possible Direction of a Future Energy Transition

The chapter includes seven perspectives on the possible direction of a future energy transition.

Mohamed Al Hammadi, Chief Executive Officer, Emirates Nuclear Energy Corporation, United Arab Emirates

Oleg Deripaska, President, En+ Group, Russia

Prashant Ruia, Group Chief Executive, Essar Group, India

Darlene Snow, Executive Director, Wind Energy Foundation, USA

Daniel Sperling, Professor of Civil Engineering and Environmental Science and Policy, Director, Institute of Transportation Studies, University of California, Davis, USA

Michael Stoppard, Managing Director, IHS CERA, United Kingdom

Levi Tillemann, Special Adviser for Policy and International Affairs, US Department of Energy, USA

Increasing Energy Sustainability and Security Is Possible Today

Mohamed Al Hammadi

Chief Executive Officer, Emirates Nuclear Energy Corporation, United Arab Emirates

As the global population races to nine billion by 2050, awareness grows regarding the need for more energy, more sustainable means to generate it and greater energy security.

There is consensus that all available forms of energy will be needed to meet future demand and that each country must assess the most viable means to deliver safe, reliable and commercially feasible electricity to power its economic and social growth. However, many countries around the world remain undecided about their long-term energy policies and portfolios. As a result, the energy policies of many countries are reaching critical points: what we achieve (or fail to achieve) in the upcoming decades will impact how the global economy functions and how well societies thrive.

Research has shown that achieving substantial reductions in greenhouse gas emissions while retooling the planet's coal-based energy system will take the better part of a century. Increasingly, scientists worldwide are calling for rapid deployment of low-carbon technologies to balance energy policies, increase energy security and achieve sustainability targets. Inaction and unsustainable practices will no longer pass for energy policy.

We can reduce emissions and increase energy security while bringing the benefits of affordable, clean, reliable energy to the planet's growing population. This goal is achievable now with the rapid embrace of existing, large-scale emissions-free energy. For the United Arab Emirates (UAE) and other responsible nations, nuclear energy plays a central role in this effort.

Energy conservation, improvements in renewable technologies and cleaner burning fossil fuels are all important to cutting emissions and building a more sustainable energy future. Governments must lead the way in the implementation of robust policies that promote greater efficiency in energy generation, transmission and consumption without significant increases in cost per kilowatt.

Improvements in renewable technologies and cleaner-burning fossil fuels are gathering great momentum. However, these new technologies and improvements still require decades to obtain regulatory approvals, improve commercial performance and achieve efficient large-scale operations.

The World Energy Council projects that the world will still rely on fossil fuels for more than 60% of its energy in 2035. Investing in wind, solar and emerging renewable technologies makes sense if those efforts are coupled with large-scale efforts to begin reducing emissions with proven and safe technology. Including nuclear energy in a country's energy portfolio to complement fossil fuels and renewables meets this requirement.

For those who believe that the accident at Fukushima relegated nuclear energy to an ancillary role in the world's energy future, the facts demonstrate otherwise. Investment in nuclear energy is growing. The International Atomic Energy Agency projects that even in a low-growth scenario, world nuclear energy capacity will grow 25% by 2030. In the agency's high-growth scenario, nuclear energy capacity doubles to 740 gigawatts by 2030. Currently, more than 60 reactors are under construction in 13 nations. In countries such as the UAE, a dialogue between nuclear stakeholders and the public is helping tear down the myths associated with nuclear energy and increase acceptance.

The majority of nuclear energy programme growth is happening in Asia. China and the Republic of Korea are rapidly expanding their nuclear energy programmes and are emerging as major players in the export and development of new nuclear capacity. Russia, other Eastern European nations, the United States and India are all building new plants. Arab nations are embracing nuclear energy as a key component of their energy portfolios. The UAE aims to bring the region's first plant online in 2017.

To implement a responsible and transparent nuclear energy programme, the UAE adopted international best practice and long-term energy policy planning through its Policy on the Evaluation and Potential Development of Peaceful Nuclear Energy, published in April 2008. In it, the UAE adheres to a series of fundamental commitments: operational transparency; the highest standards of non-proliferation, safety and security; collaboration with international institutions and responsible nations; and sustainability. To demonstrate adherence to these commitments, the UAE published its Federal Nuclear Law Proliferation in October 2009, prohibiting proliferation and reprocessing within the country.

Base-load nuclear energy can help countries around the world reach their sustainability targets in a safe and commercially viable manner. According to the 2011 World Energy Council Energy Sustainability Index, the top five most energy-sustainable countries all operate nuclear energy programmes; their nuclear power plants met an average of 38.1% of their electricity demand. More importantly, countries with nuclear energy programmes achieve better standards of energy security and social equity.

The nuclear industry has the proven technology to become a crucial contributor of abundant and low-carbon power, and it continues to advance in both technology and cost savings. Today, Generation III+ designs are trending towards a set of preapproved, standard designs that are more commercially viable than their predecessors and provide far more robust safety features. Colocated or even remote modular fabrication of major components and systems allows for significant efficiencies in capital cost and addresses a growing preference among owner-operators for fixed-price, turnkey contracts for nuclear construction.

Further advancements in nuclear technology, such as Generation IV reactors or small modular technology, will increase the flexibility of nuclear technology: from smaller reactors capable of running for 40 to 60 years without refuelling to new reactors that can burn spent fuel.

Nuclear energy provides an immediate solution for sustainable, commercially viable and safe production of electricity using proven technology with over 15,000 cumulative years of operational experience. It will continue to be an option on the table of energy policy-makers that want to improve energy security, social equity and sustainability results for responsible nations across the world.

Increasing Energy Diversity

Oleg Deripaska

President, En+ Group, Russia

The world is facing a number of crucial challenges, including the increasingly pressing need to address energy security and climate change. When the global economy recovers, we will find that the challenges of powering our homes, businesses and economies in a secure and sustainable way have not disappeared.

Global primary energy demand is forecast to increase by over 30% between now and 2035. Non-OECD countries will account for 93% of this projected increase. The world's population will grow by some 3.4 billion between now and 2050. Continued development among major emerging economies means they will need even more power to fuel their growing industries. This increasing demand is set against a backdrop of sustained and profound fears about global warming, with the scientific community warning us that we are running out of time to prevent irreversible changes to our climate.

Given this situation I believe there should be no "no-go" areas in seeking to address these issues and that nuclear energy must be part of the solution. Since its arrival as an energy source more than 50 years ago, nuclear energy has yet to live up to its potential. Some of the reasons for this have been scientific, while others have been the result of tragic catastrophes, such as Chernobyl and more recently Fukushima. The events at Fukushima were dreadful and a repeat must be avoided. What we all take away from that disaster, however, must not be a knee-jerk reaction to oppose all nuclear energy. The issue of safety should become paramount, as these incidents demonstrated in such a dramatic way.

If we are serious about meeting the challenges of energy security and climate change, we cannot allow the ambition of doubling nuclear capacity by 2030 to fall by the wayside. Nuclear power is not the only answer. We need to make investments across the board to obtain more energy from other low-carbon sources. But we need to be realistic about what these can offer; no renewable source yet has the capacity to generate the amount of power needed to replace large fossil fuel plants.

Technology should play the most important role. Significant nuclear technology advancements in recent years can and should increase nuclear's share of primary energy over the coming decades. The small and medium-sized reactors now in development could help meet energy needs and boost development in remote areas of the world. Russia is actively pursuing the newest nuclear technologies, including small and medium lead-bismuth fast reactors. Our company EuroSibEnergo and state-owned Rosatom JV are expected to start large-scale production of generating units in 2019.

These new reactors improve on everything we already know about reliable, safe and value-for-money power generation. Modern reactors will be cheaper to run and build, and are developing a safety record that cannot be matched. Their built-in safety systems remove problems associated with operational errors and equipment failure. Their working lives will be much longer than past reactors thanks to advances in fuel technology, coolants and metal alloys. Factor in the reduced carbon emissions and these will present a viable alternative to "old" fossil fuel plants.

We will only reap the benefits of nuclear energy if we lift the barriers that constrain its expansion. More bilateral and international effort is needed to introduce the nuclear industry to new countries and, in particular, the energy-poor in the developing world. If we fail to do so, these nations will rely on old technology powered by increasingly expensive, highly polluting fossil fuels. Currently plans for new reactors are concentrated in those countries that already have a civilian nuclear programme. Unless we help new countries join the "club", nuclear power will not help to tackle global poverty and support sustainable development.

To expand the reach of nuclear generation, we must ensure that the right safeguards and counter-proliferation measures are in place. We should think innovatively about how this can be achieved while also ensuring knowledge sharing and training. We should work swiftly to agree to and implement measures that would guarantee supply for nuclear states that agree not to pursue enrichment and reprocessing activities of their own. Such a scheme could run alongside steps to standardize technology, equipment, handling and transportation rules for nuclear material.

Apart from nuclear power, the importance of other renewable sources should not be underestimated. Among them, hydropower has the greatest proven potential. Russian rivers could generate over 800 terawatt-hours per annum, over three-fourths of total power consumption in Russia last year. However, only 20% of Russia's potential hydropower has been realized. This renewable and environmentally friendly power source also offers a number of economic and social benefits, such as providing reserves of water for municipal, irrigation and industrial water supply systems; enabling navigation and fish-breeding; and regulation of fluvial flow to mitigate adverse effects of high water and floods.

Internationally, countries have increasingly developed their hydro potential to bring diversity to their energy sources. Despite its large reserves of natural gas, Norway relies almost 100% on hydropower. En+ and China's largest public hydroelectricity producer, China Yangtze Power Co., established a joint venture in 2011 to develop projects in Eastern Siberia with total installed capacity of up to 10 GW.

Governments should make new nuclear power projects central to their economic recovery plans while also considering renewable energy sources, such as hydropower. If we get the conditions right, we can accelerate the expansion of civil nuclear power for the benefit of our economies and our environment, while increasing energy diversity through the development other renewable energy sources.

Technology Transforming the Energy Industry

Prashant Ruia

Group Chief Executive, Essar Group, India

Technology has already transformed the energy industry and the world around us. Fifty years ago few would have anticipated seeing things in 3D, far less 4D. Today we do not talk about meters that are read once or twice a year but about smart meters that capture real-time data. Changes are visible throughout our energy systems from the point of creation to final usage. The journey over the next 20 to 30 years can only be more intriguing, as the following examples demonstrate some of the transformational changes envisioned in the upstream, transmission and downstream segments of the energy industry.

Upstream: Subsurface Mapping by Satellite

In the hydrocarbon exploration sector, IT-enabled technology has been at the heart of harnessing resources. Energy companies are today investing in nanotechnology to develop “smart dust” and create sensors that could be released into subsurface pore structures to provide details far superior to current seismic methods.

But imagine a new technology to view the subsurface: frequencies from smart satellites could one day penetrate the earth and provide us with data as good as or better than the seismic we have today over far greater distances. Going beyond the use of satellites to map surface phenomena, IT advances could create a revolution in hydrocarbon development enabling us to probe the earth’s composition deep enough to detect hydrocarbons miles below.

Transmission: Wireless Electricity

Efficient transmission and distribution of electricity to remote locations is a challenge today. According to World Bank statistics, electric power transmission and distribution losses as a percentage of output are six percent in the United States, 24% in India, and as high as 79% in Botswana. If we can find a way to transmit power without wires, the remoteness of a location would not be a hindrance to safe and reliable power provision, and difficult-to-harness energy would not be lost along the way.

Experiments suggest that we can efficiently transmit power wirelessly across several meters by having source and receptors resonating at the same frequency. Efficient transmission over several miles is still to be developed, however. Some futuristic proposals include sending power to the earth using a network of smart satellites that collect solar energy from an orbiting satellite, power a microwave or laser emitter and direct this power wirelessly on demand to collectors.

Downstream: Predictive Demand and Supply

Real-time detection, classification, identification and disaggregation of energy demand signatures are now under way in commercial and residential buildings using simple mobile devices. Such data are being gathered to predict future energy requirements and to institute energy efficiency measures. In the same way, in the next few decades it will be possible to map and predict an individual’s energy footprint and energy consumption patterns in much the same way that companies map consumer behaviours and preferences by monitoring online data or issuing tools like loyalty cards. In fact, the ability to forecast consumption at such a granular level may solve several upstream problems. For example, granular power demand forecasts could create a situation in which load could “determine” or “chase” generation, rather than the other way around, as is the practice today. This would allow the integration of stochastic renewable energy sources into our existing power grids without the need for expensive storage systems.

In the next few decades, individual energy consumption patterns may be further influenced by advances in communication technology that significantly reduce or even negate the need to travel physically. For instance, attending meetings and conferences is an integral part of conducting business and facilitating knowledge transfer in our industry. But if we can reach a point in which 3D virtual rooms can replace physical meeting rooms and replicate a similar level of intimacy, then individual energy consumption trends and carbon footprints can be decidedly reduced.

Technology has created a wealth of opportunities in the energy business that have already transformed our industry. The future will bring changes of even greater magnitude than those in the past. Some of these projections may seem to be a fantasy today, but if we look at the trajectory of growth, development, and innovation in IT over the past decade alone, it would be surprising if all these are not a reality after 2030.

The Appropriate Use of Wind in Electricity Production

Darlene Snow

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As far as wind goes, a lot has changed in the past decade. Taller towers, bigger rotors and a better understanding of the systems integration and control issues have made it possible for a turbine with the same basic bill of materials to produce more than 60% more energy in the 2012 models than in the 2002 models. Technology advancements have led to improved performance, lower costs and accelerated deployment of wind technologies on land and offshore. In the United States, the industry now has 50 GW of real "steel in the ground" experience, including a deeper understanding of what it takes to develop, finance, build and operate wind energy "at scale". Europe has even more, at 96 GW of installed wind power capacity, enough to supply 6% of the EU's electricity.

The industry has seen order of magnitude changes in cost. In the United States, the cost of energy from wind power in areas with good wind resources, according to the US Department of Energy, has decreased from more than US$ 0.55 per kilowatt-hour (kWh) in 1980 (in current US dollars) to less than US$ 0.06 per kWh today.

Around the world, the rated output, rotor diameter and average height of wind turbines have steadily increased over the years. While the average size of turbines varies substantially by country and region, the average turbine installed in 2011 was 1.76 MW, against an average of 1.21 MW for all currently operating turbines worldwide. Today, turbines with rated capacities ranging from 1.5 MW to greater than 6 MW have been installed and are commercially available.

All this adds up to a simple fact: Wind power is now an established mainstream electricity generation source. According to the Global Wind Energy Council, wind plays a role in an increasing number of countries' immediate and longer-term energy plans, experiencing 15 years of average cumulative growth rates of about 28%.

Based on IEA's *World Energy Outlook 2012*, renewables make up an increasing share of primary energy use in all scenarios, thanks to falling costs, CO_2 pricing in some regions and rising fossil fuel prices in the longer term. In IEA's *New Policies Scenario*, electricity generation from renewables nearly triples from 2010 to 2035, reaching 31% of total generation. In 2035, hydropower provides half of renewables-based generation, but wind is almost one-quarter of the renewables mix.

In the United States, the installed wind base has risen nearly five-fold since 2006, from 11.6 GW to over 50 GW at the end of 2012. States like Iowa and South Dakota are experiencing wind penetrations around 20%, approaching those seen in parts of Europe. Before 2006, the highest annual rate of deployment in the United States had been around 2 GW, but since then the industry has shown it is capable of adding ten or more GW per year.

The context for wind development, however, varies greatly among countries. In 2008, natural gas prices in the United States were around US$ 13 per million BTU (MMBtu), while today they are near US$ 3 per MMBtu. At the same time, the "Great Recession" occurred, putting downward pressure on electricity demand – 2009 was the first year in world history that saw a decrease in electricity use. The combination of these two factors – low natural gas prices and a sluggish economy – have slowed wind development.

The wind industry has suffered during the global recession – with growth slowing, non-existent or negative in most of the OECD, where demand for new power generation is slim and the competition is fierce. While China has been the main driver of the wind industry's growth for the last five years – installing 62 GW during that time – significant growth in the Chinese market is not expected again until after 2015. In contrast, Brazil, India, Canada and Mexico are very dynamic markets, although they cannot make up for the lack of growth in the main markets in Europe, the United States and China.

Despite the current market slow down, the basic drivers have not changed. All the fundamentals that have driven the dramatic growth of the wind industry over the past two decades are still there – energy security, electricity price stability, job creation and local economic development, reducing fresh water consumption and pollution and reducing local air pollution and carbon dioxide emissions.

Undeniably, the Fukushima Daiichi nuclear disaster, clean air regulations and hydraulic fracturing of shale gas have rewritten the future of nuclear, coal and gas, respectively. Before these developments, it was easy to envision a future dominated by coal and nuclear. With cheap, abundant natural gas, lower cost wind energy and concerns over climate change, the share of wind and natural gas in electricity portfolios is expected to continue to increase.

In fact, gas and wind work well together: gas generation is very flexible (compared to coal and nuclear). It can quickly ramp up when the wind doesn't blow. It can also back down when the wind does blow and the "fuel" (wind) is free. These very dynamics deliver real benefits to consumers in the form of lower prices and provide the greatest support for moving the electricity mix to a greater dependence on natural gas and wind.

As wind continues to scale up and becomes a major part of generation portfolios, however, a more detailed analysis of costs and benefits will be required, including a better understanding of customer impacts, land use and wildlife impacts, grid integration requirements and costs, jobs through the supply chain, local direct and indirect impacts and GHG and water use impacts.

The challenge for business and policy-makers alike, therefore, is the establishment of a common language and principles to foster a portfolio approach to electricity management that includes both fossil fuels and the appropriate use of renewables. But despite the ups and downs of the global economy, wind will continue its growth.

Electric Vehicles: Fantasy or Panacea?

Daniel Sperling

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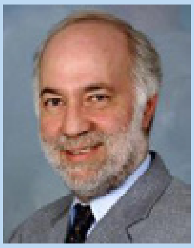

Plug-in EVs are not a new technology. They flourished around the beginning of the previous century but were quickly vanquished by gasoline vehicles. They re-emerged around 1990, triggered by California's zero emission vehicle (ZEV) mandate. But the high cost and low energy density of batteries stymied market expansion. The automotive industry, especially Toyota, Ford and Honda, turned to hybrid electric-gasoline vehicles, which use small electric motors and batteries (1-2 kilowatt-hour [kWh]) to generate and store electricity onboard – but don't plug in.

Nissan, Renault, and GM led a third spurt of interest at the beginning of this decade. Nissan mass-produced its all-electric Leaf (24 kWh battery), GM its plug-in hybrid Volt (16 kWh battery) and Renault a number of all-electric models. These commercial investments responded to a number of aggressive policies. California strengthened its ZEV mandate for the first time since 1990; the United States, Japan, China and other countries offered purchase incentives; and the European Union and United States offered regulatory incentives as part of their aggressive new GHG/fuel economy standards. Japan and many European countries and cities also began building public charging infrastructure.

Several nations have announced ambitious goals in recent years. In 2011, President Barack Obama set a goal to put one million EVs on the road by 2015; China set goals of 540,000 sales by 2015, and Germany 1 million by 2020. Given that barely 100,000 EVs were on the road worldwide at the end of 2012, these goals are unlikely to be met. Are these pronouncements indicative of a massive transition about to unfold, or are they just inflated hopes and hype?

The answer will depend on cost, but also other factors. On the positive side, EVs already offer consumers sharply reduced energy costs (electricity costs are one-fourth to one-half those of gasoline), less maintenance, less noise, zero tailpipe emissions, lower (life-cycle) GHG emissions in most locations, avoidance of trips to fuel stations and a better driving feel (according to most driver surveys).

On the negative side are two important and entangled attributes: higher up-front purchase prices and, with pure battery EVs, short driving distance per charge. Costs and range have everything to do with batteries. Battery costs had been dropping about eight percent per year for two decades, as battery chemistries shifted from lead-acid to nickel-metal hydride to lithium-ion. Since about 2008, the cost of vehicle batteries has dropped much faster, from about US$ 1,000 per kWh to around US$ 500 in 2012, and some forecasts show costs as low as US$ 250 in 2015 owing to better battery management and increasing economies of scale in production.

At projected 2015 costs, the battery costs for the Volt and Leaf would be US$ 4,000 and US$ 6,000, respectively. In the near term, will the advantages of all-electric vehicles offset their cost premium and limited driving range? At what point in the long term will automakers and consumers embrace EVs? And what type of EVs will they embrace?

Technology Choice

Wide technology choice is confounding the future of EVs. It ranges from plug-in hybrids with small batteries such as the plug-in Prius (4.4 kWh) that enable only15 kilometres (km) of all-electric range, to big-battery plug-in hybrids such as the Volt that enable 50 km of electric range, to all-electric mass-market cars with ranges up to about 200 km. Given the breadth, cost and novelty of choices, it is not surprising that the market is evolving slowly. As costs subside and drivers learn about the technologies, sales should increase.

Further complicating matters is another electric vehicle choice: fuel cell vehicles (FCVs). FCVs operate on hydrogen, which is converted on-board to electricity to power the electric motors. FCVs look promising; the US Department of Energy estimates that fuel cell costs could soon be competitive with conventional gasoline engines under mass production. Though still costly because of on-board high pressure storage tanks, FCVs have the advantage of capturing all the benefits of EVs without suffering limited driving range imposed by batteries. If the chicken-and-egg challenge of building a hydrogen gas fuel infrastructure is solved, FCVs could prove appealing. Indeed, surveys of auto executives indicate that FCV sales are expected to exceed EV sales by 2025.

Some mix of EVs and FCVs will almost definitely dominate on-road vehicles – eventually. The only other credible low-carbon alternative for transportation is biofuels, which have their own set of challenges.

As costs drop, consumers gain more familiarity with the new options and marketers become savvier, EV and FCV sales should eventually boom. However, the pace of this transition is uncertain. The transition will accelerate if and when Middle Eastern oil becomes less dependable, oil prices increase and climate change goals are embraced more strongly.

By 2050, it is plausible that in many regions of the world almost all new cars and light trucks will be operating nearly exclusively on electricity and/or hydrogen. Pure battery EVs, downsized for local use, might dominate in city centres. Plug-in hybrid vehicles, using natural gas, biofuels or gasoline for their small combustion engines, will likely compete with hydrogen FCVs for larger light-duty cars and small and medium-duty trucks. For larger long haul trucks, where energy density and weight are more critical, fuel cells will likely compete with biofuels and diesel fuel. And in planes, where energy density is especially critical, biofuels are likely to dominate. Under almost all scenarios, electric motors with energy supplied from batteries and fuel cells will largely supplant combustion engines in new cars and most trucks by 2050.

Germany's "Energy Turnaround"

Michael Stoppard

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Germany has become the laboratory for the large-scale deployment of renewable power in a major economy. It is engaged in a bold venture to transition its electric power system. The process is known as the ***Energiewende*** – meaning literally 'Energy Turnaround' – and is designed to establish a 'sustainable' energy complex beyond fossil fuels and nuclear energy.

In 2000, Germany initiated what has become the global "rebirth of renewables" with its ***Erneuerbare Energien Gesetz*** (the "EEG", Renewable Energy Act), which sought to place Germany at the forefront of renewable capacity deployment. The support framework, largely sheltering renewable capacity deployment from market dynamics through "feed-in" tariffs, was successful in producing renewable capacity additions of about 3.5 GW per year. Onshore wind drove the initial expansion, but falling costs and generous feed-in tariffs brought about an unprecedented boom in solar PV, adding around 22 GW of capacity in the last three years. The focus is now turning toward offshore wind, bolstered by the need to make up for nuclear generation that is destined to be completely shut down by 2022.

In 2011, a decade after the launch of the EEG, renewables were already more than 20% of total domestic generation. Renewable power overtook nuclear as key source of power generation following the shut-down of more than 8 GW of Germany's oldest nuclear capacity, reducing the share of nuclear in Germany's power mix from 25% to 18%. This is only a step on the path to much more ambitious targets – 40% renewable electricity by 2020 and 80% by 2050.

Among the renewable sources of electricity, wind has the largest share at 40%, followed by biomass at 26%. Solar PV holds a 16% share and hydropower 15%, with biogenic sources providing 4%.

Incorporating intermittent resources while maintaining reliable uninterrupted supply has been a challenge. With more than half of renewable power generation now coming from intermittent wind and solar capacity, a significant amount of uncertainty has been introduced into generation profiles and dependability. Thermal generation is covering some of the baseload generation gap left by nuclear. In particular, coal plants have run at full utilization amid low fuel costs – undermining some of the emissions reductions achieved by renewables. Gas capacity has been suffering amid dampened power demand, high fuel costs and pressure from renewables. In response, some gas-fired capacity has been retired or mothballed.

The remaining 12 GW of nuclear capacity will be shut down by 2022, a decision that appears final in light of the political and public consensus on the decision. In the aftermath of the Fukushima nuclear accident, Chancellor Merkel laid out the direction. The accident in Japan "had changed everything in Germany," she said. "We all want to exit nuclear power as soon as possible and make the switch to renewable energy." For the time being, new coal capacity is coming online to compensate for the shut-in nuclear power, with up to 10 GW being added. Nevertheless, the policy objective is still to reach 80% renewables by 2050.

The future success of the ***Energiewende*** will depend critically on two factors. The first is the capability of the German power system to accommodate increasing shares of intermittent renewable generation while maintaining power system stability. Large investment in new transmission capacity – and its timely building – will be required to support achieving the renewables target.

The second is keeping the ***Energiewende*** reasonably affordable for those who are paying for it – the German end consumers. Subsidy estimates for renewable power in Germany for 2012 range between €11 billion and €16 billion. The surcharge to pay for the EEG will reach €53 per megawatt-hour in 2013, more than double the level paid by end consumers in 2010.

Germany has moved very fast to transition its energy system. But current delays to infrastructure developments and surging retail prices will be challenges for achieving the future targets in the time allotted.

Electric Vehicles Everywhere by 2025

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Electric cars are being lauded. Twice in two years, the Chevy Volt has edged out the Porsche 911 for highest customer satisfaction in ***Consumer Reports*** magazine; in 2011 the all-electric Nissan LEAF was named European Car of the Year; and in November 2012 the Tesla Model S was unanimously awarded ***Motor Trend's*** "Car of the Year". Sales, too, are on an upward climb. EVs, including both plug-in hybrids (PHEVs) and all electric vehicles (AEVs) are, in some respects, already equipped to compete with the ICE.

All this portends a fundamental shift in the energy landscape. After a century, transportation is decoupling from its complete reliance on oil.

But there are still considerable challenges to deploying EVs, especially AEVs. Cars are one of the most regulated and technology-intensive industries in the world. Today's vehicles are packed with dozens of computers, intricate emissions systems, even explosives (for air bags). They are constructed with thousands of components – many as complicated as a modern smart phone, iPad or solar cell – that must blend together seamlessly (with complete dependability) over the course of hundreds of thousands of miles and decades of consumer abuse. Building the supply chains, regulatory institutions and competing infrastructure to support a new "EV ecosystem" is an ongoing challenge. After all, almost 100 years have been invested in ecosystems that support the ICE. Still, the underlying drivers of energy security and environmental protection that support electrification are strong.

One of the major focuses at the US Department of Energy (DOE) is overcoming the barriers to widespread EV adoption. The DOE's "EV Everywhere" initiative brings together stakeholders ranging from research labs, to automakers, to EV deployment communities to tip the scales in favour of electrification.

The market in comparative perspective

How are EVs performing in the market today? In a month-to-month comparison, the Chevy Volt is selling almost twice as many cars as the original hybrid Prius did upon its US introduction. Part of the Volt's early success likely stems from the fact that, like the Prius, it uses an ICE to surmount the range limitations of batteries and current lack of charging infrastructure. But the Volt's success also demonstrates consumer demand for electrification.

AEVs, with no supplemental ICE, are a bigger challenge. They have shorter range and batteries that are still expensive and slow to charge. Still, the benefits to full electrification are considerable. Sunlight, coal, biomass, trash and natural gas can all be readily converted into electricity and thus fuel an AEV – not so for an ICE. They have the potential to be cheaper and easier to maintain than either ICEs or PHEVs. But to compete, AEVs need sustained commitment from government, automakers, electric utilities and other stakeholders and a willingness to take risks (and occasionally fail) in pursuit of these ends.

Federal EV policy post-stimulus

The Obama Administration's EV Everywhere initiative builds on programmes that have already invested several billion dollars in grants and loans for new battery and electric drive research, deployment and component manufacturing plants. These enabled the success of EVs like the Tesla and the Volt – as has a federal tax credit of up to US$ 7,500 for EV buyers.

The batteries in today's hybrids and other EVs are the fruits of decades of research – much of that DOE supported. To continue the progress, the DOE is launching a new "innovation hub" for batteries that will fund up to US$ 120 million over five years for energy storage research.

DOE is also promoting a "no regrets" policy of EV infrastructure deployment – encouraging companies to install the ducting and electrical systems in new buildings that will facilitate rapid installation of EV charging stations as the electrified fleet expands. Incorporating these capabilities can lead to substantial benefits and savings for businesses in the long term and improve the experience of future patrons of apartment buildings, shopping malls and garages.

A global challenge

But realizing the vision of EV Everywhere will require collective action by a host of stakeholders around the world. Cities and states have the power to promote deployment in their own communities. California's Air Resources Board leads the nation's most aggressive state-level EV deployment effort with its Zero Emission Vehicle mandate and will be a key player in the global market. Local and state governments can provide EVs with access to high-occupancy vehicle lanes or institute congestion pricing schemes that would allow EVs preferential entry into city centres – as London does today. This can reduce noise, improve local air quality and further incentivize EV deployment.

However, it is important to remember that an EV is not a cell phone or an iPad. The technology hurdles are higher and the scale of the challenge bigger. But a tipping point may have already been reached – uptake of EVs is accelerating. The pace of deployment will likely be heavily dependent on policy, and the DOE goal is to work with American industry, cities and states to put in place the incentives that will support a flourishing US EV market by 2025. By then, millions of EVs could be deployed in the United States – and eventually, everywhere.

Chapter 6:
How Would a Low-Carbon Transition Be Different?

Policy and Price

In this report we have explored the dynamics of past energy transitions, including cost, scarcity of supply, utility and flexibility, technology development and policy. But a potential transition to low-carbon energy sources differs in fundamental ways from energy transitions that have occurred in the past. In previous transitions, technological change was coupled with lower costs, greater efficiency, convenience and new uses, such as personal vehicles. But environmental concerns would be a primary driver for a low-carbon transition, a big change from the past. Additionally, energy demand today is so much larger than it was during previous transitions and there is a vast embedded capital stock for delivering today's energy mix.

Energy prices are always a key factor in energy transitions. Consumers will not willingly pay more for "less", and thus new technologies must be able to compete in the marketplace. The ability of low-carbon energy sources to compete on price will be central to the next energy transition.

The challenge for new technologies is often achieving sufficient economies of scale to effectively compete in the marketplace. This is the classic case for government incentives and subsidies as the "accelerator". By this argument, subsidies to stimulate market demand will promote innovation, enable companies to go up the learning curve, gain economies of scale and ultimately lead to prices that are competitive without government support. Yet what governments give, they can also take away, especially in an era of austerity. In addition to incentives and subsidies, policy can change the relative prices of energy sources by putting a price on carbon directly or through a trading system, or through the shadow pricing of government mandates.

The relative competitiveness of low-carbon energy sources is not uniform and the consumer price of competing resources matters. Solar will be much more competitive in Southern Europe than in Northern Europe. Solar is likely to out compete diesel-generated electricity in an African country, but not coal-generated electricity in the southeastern United States. Solar may be much more productive in the Middle East than in Scandinavia during the summertime; on the other hand, solar in the Middle East may well be competing against extremely inexpensive subsidized electricity.

The point is that the path of prices for new entrants will be a key indicator for the nature and timing of any future transition, but the prices of the incumbent competitors will be no less important.

Scarcity – Maybe Not What Was Thought

Perceived scarcity of fuel, reflected in rising prices, played a central role in the transition from wood to coal and in the transition to kerosene for lighting. But scarcity is less likely to play a role in a low-carbon transition, compared to what was widely thought a few years ago. Although fossil fuels are a limited resource, they are less limited than was the conventional view in the last decade. The world is not running out of oil, natural gas or coal any time soon. There will likely be political limits on access to resources in certain areas. But technological developments in the extraction of these resources are continually bringing new sources into production not possible or economically feasible to recover before. Hydrocarbon prices will continue to fluctuate in the future based on economic and geopolitical events and technological developments, and concerns about supply security will remain.

Although fuel scarcity is not likely to be an important driver, scarcity of other resources, particularly water, may turn out to be an important consideration. Power generation can be very water intensive, with coal and nuclear power at the high end of water use. Dry cooling systems are possible, but they reduce the thermal efficiency of a power plant, particularly in hot and arid areas where water is most scarce. Water is also critical to many methods of producing oil, gas and coal. The most valuable resources in the future may be those that we largely take for granted today.[1]

Energy Density – Turning the System on Its Head

The utility and flexibility of new sources of energy were also strong drivers of past transitions. Coal and oil resources are more concentrated geographically than the fuels they replaced, but their greater energy density allowed production in specific geographic areas and transportation to their point of use. The ability to transport energy-dense fuels facilitated the population shift toward cities. Additionally, trade in energy commodities brought fossil fuels to areas without a local resource endowment.

Most of the low-carbon alternatives available today reverse the trend toward more energy-dense and geographically concentrated energy sources. Wind and solar produce much less electricity per unit of land area than fossil fuel generation. Today's wind farms produce 3 to 10 watts per square metre (m^2) of land area while large hydroelectric dams can produce as much as 20 to 30 watts per m^2. The power per unit of land area for fossil fuel electricity is roughly two orders of magnitude higher, even considering the land area disturbed in extracting the fuel.[2] Additionally, wind and solar resources cannot be transported in their raw form – they must be converted directly into electricity.

A shift toward renewable sources of electricity would require a fundamental shift in the nature of the electricity system. Our current electricity system consists mostly of generation plants built near demand centres, with long distance transmission lines to help balance the system and add flexibility. Raw fuels are often transported long distances to the generation plant, but once the electricity is generated, transportation distances are typically short.

Shifting to renewable sources of power would turn this system on its head. Power plants would have to be built where the resource is, with significant investments in transmission required to get power to where it is needed. The system would shift from one that focuses on transporting the raw material (fossil fuels) toward one that transports the final product (electricity). Considering the wide geographic dispersion of renewable resources (especially solar), the losses that would be incurred during long-distance electricity transport and the fact that some renewable technologies have smaller economies of scale than today's fossil fuel plants, a move away from large centralized electricity generation toward a distributed power generation system is a possibility.

But this change results in a fundamental mismatch between low-density renewable power sources and high density "load centres", otherwise known as cities. As more of the world's population moves to urban areas every year, the challenge of providing power to cities grows. Supplying these cities with low-energy density power may require long-distance transport of power. Distributed renewable technologies, like rooftop solar, hold some promise, but are better suited to smaller buildings. A rooftop solar array can provide a substantial portion of the power needed by a single family home, but will not come close to providing the power required by a large office or apartment building.

The energy density challenge also exists for biomass-based fuels that provide primary energy. Biofuels and biomass are less energy dense than the fossil fuels they could replace – this was an important driver for the transition away from biomass fuels in the past. For biofuels, the differences are relatively small. The energy density of ethanol is about one-third less than the gasoline it displaces and biodiesel is about 12% less energy dense than fossil diesel.

But the real challenge comes into play when one considers the transport of raw materials to produce biofuels. The most energy dense raw materials for biofuel production are often foodstuffs – sugarcane and vegetable oil, for instance. Scientists, encouraged by policy-makers, are working to produce biofuels from non-food feedstocks like agricultural wastes, purpose-grown trees and grasses and algae. But these raw materials have even lower energy density than the foodstuffs that they are intended to replace. The transportation of very low energy density feedstocks to biofuel production plants can have an important impact on the efficiency and economics of biofuel production. As with renewable power, less centralized biofuel production may result, with smaller biorefineries drawing feedstocks from nearby to serve local markets.

For reasons of energy density, a low-carbon future might involve more local production of energy and more distributed energy systems. In a sense, this transition would take the energy system full circle, back towards the local resource gathering that occurred during the days when biomass was the world's primary energy source. The economies of scale that define today's fossil fuel based system do not apply to some renewable sources of energy, meaning that the long lead times and big capital requirements of today's system could change.

A much more distributed system for generating electricity would create challenges for the current business model for electric generation, based on central generation, which goes back more than a century.

"Ancient Sunlight" vs. "Just in Time Sunlight"

A transition toward renewable power could take the world full circle in another way as well. With the exception of splitting atoms for nuclear power, all forms of energy that mankind harnesses are solar energy. The biomass that people used for fuel for millennia came to be because of plants' ability to use photosynthesis to grow. When mankind relied on biomass for energy, a rough balance existed between the amount of energy captured in plants by photosynthesis and the amount that mankind used.

Our fundamental relationship with solar energy changed when fossil fuels came into use during the 18th century. Fossil fuels still have their origins in photosynthesis, but in their case the photosynthesis occurred millions of years ago. Fossil fuels brought about an explosion in energy supply and demand. Humanity was no longer limited by the amount of energy captured by plants, and could rely on a concentrated form of the sun's energy stored over millennia.

Technology now allows us to capture much more of the sun's energy than we could in the days of relying on

1. See the 2009 Energy Vision Update *Thirsty Energy: Water and Energy in the 21st Century.*
2. Vaclav Smil, *Energy Transitions: History, Requirements, Prospects*, Praeger, 2010.

biomass. Sunlight can be captured directly through solar power or derived from weather patterns – wind and rain – that all ultimately derive their energy from the sun. A full reliance on renewable power would, in a certain sense, bring the energy cycle back to its starting place and shift the world from relying on "ancient sunlight" back to "just-in-time sunlight".

The Challenge of Intermittency

Intermittency is an additional challenge to the utility of renewable sources of electricity. Past advances in electricity generation generally focused on steady, reliable sources. Not all renewable sources of electricity are intermittent, but a shift toward wind and solar is a shift away from power that is available whenever it is needed.

Traditional power plants can be run nearly continuously, and many can ramp up and down to follow electricity demand. This is not always the case for renewables. Some resources, such as hydropower dams and geothermal power, are available whenever you need them and can follow load. CSP plants can be designed to store heat in the form of molten salt, allowing them to keep generating for a time when sunlight is low. On the other hand, wind and solar PV are available only when the wind is blowing or the sun is shining.

Intermittent renewables require flexibility in the power generation system. When the system has a large share of intermittent resources, other power sources must adjust not only for the ebb and flow of demand, but also to handle changing weather patterns that impact the availability of renewable power. The greater the percentage of intermittent renewables in the system, the greater the flexibility needed from the entire generating system.

The challenge of intermittency increases the "true cost" of adding more renewable electricity to the grid. Equipment will run at full utilization more often at higher quality sites, producing more power for the same investment. Reducing power generation from fossil fuels when intermittent sources are available is good for reducing GHG emissions, but means that the fossil fuel plants will produce less power to cover their fixed costs. Some fossil fuel plants also run less efficiently when they cycle up and down, adding costs to the power system as a whole. Accounting for these system-wide costs of integrating intermittent renewable resources is a subject that will gain greater attention as the share of renewables grows.

Economic utility scale electricity storage is a potential technological solution to the challenge of intermittency, but such a solution has so far proved elusive. Large hydropower dams provide some element of flexibility and energy storage, and some hydro systems are designed to pump water into a reservoir during times of low demand to be released for power generation at high demand times. However, these systems are very site specific and expensive.

The "holy grail" would be a storage system allowing power to be stored and retrieved at low cost with low losses, in a battery or flywheel or other storage device. Intermittent power sources could then be made steady and reliable – much like fossil fuels are today. Instead of the coal pile or gas pipeline, grid operators could turn to stored power to meet ever-changing demand. The portion of wind and solar PV on the grid could be greater, with much less need for other resources as backup. However, battery packs in today's electric cars have roughly 25 kWh of capacity, compared to the multi-megawatt-hour batteries that would be required for utility-scale power storage. The industry has a long way to go, but the payoff would be enormous. It should be noted, however, that storage would also benefit conventional electric generation, by reducing the need for power plants that only run at times of peak load.

Trade and Globalization May Speed Transition in the Developing World…

Despite the challenges of a large-scale energy transition, some aspects of today's energy market are more conducive to such a transition than in the past. Technology development and diffusion across continents is accelerating. The emphasis on innovation across the energy spectrum is stronger than it has ever been before, and more scientific talent than ever is focused on improving existing technologies and finding new breakthroughs. Robust global markets and trade work to the advantage of new energy technologies. Technologies developed in one place can very quickly be adopted around the world, a very different situation from the time when coal and oil slowly overtook their predecessors.

The pattern of energy demand growth could also aid in transition. Future energy demand growth is expected to come almost entirely from developing countries. Rapidly developing economies have the opportunity to leap-frog to new technologies and build low-carbon infrastructure right away. Such a leap-frog effect occurred in the telecommunication industry in many areas of Africa and Asia, where mobile phone service became available in areas that never had wired service.

In areas where many people lack access to modern energy sources, concern about environmental sustainability often takes a backseat to the immediate concern of providing affordable access to energy. Policies to shift the energy mix to more sustainable sources are more likely to succeed if they also contribute to the overall goal of increasing energy access. The distributed nature of renewable power sources is a natural fit for providing modern energy to areas with minimal infrastructure, but the cost of renewable technologies poses a challenge to such investments.

…While Developed Countries Already Have Embedded Infrastructure

Although the bulk of energy demand growth is occurring in developing countries, the large per-capita energy use and extensive energy infrastructure in the developed world also pose challenges to a shift toward lower-carbon energy sources. Growth provides opportunities to gradually increase the share of low-carbon energy sources. Steady or declining demand means that existing sources of energy must be displaced to shift the energy mix. Significant changes to the energy mix in a climate of steady or decreasing energy demand could mean retiring assets before the end of their design or economic life.

Efficiency: Another Source of Energy?

Efficiency is not a "fuel" per se, so why consider it in a discussion of the future energy mix? As Vaclav Smil explains, "The overall level of primary energy supply and its composition can be substantially modified by still considerable opportunities for more efficient use of energy: transitions toward universally adopted optimal conversion efficiencies could be as important as harnessing of new energy resources."

Efficiency is a means to deal with all three goals of energy policy-makers – inexpensive, secure, low-carbon energy.[3] The most secure and low-carbon form of energy is not using energy at all. Technological innovation is continually allowing consumers and businesses to do more with less in terms of their energy use. The Japanese word ***mottainai***, meaning "too precious to waste" describes the mindset and cultural values in that country toward efficient use of energy.[4] Policy tools are helping overcome barriers to efficiency investments, including availability of capital and knowledge of efficiency choices. High or volatile energy prices and energy taxes, including carbon costs, make efficiency investments more financially attractive to end users.

Technology can also contribute to energy efficiency. For example, smart grid systems can help consumers and utilities better understand electricity demand patterns and even automate some sources of power demand to maximize efficiency. Future advances in information technology and data management could take this revolution even further, according to Ginny Rometty. "Imagine how much more dynamic, efficient and societally sensitive such systems could be when enhanced by information about the behaviour, wishes and desired lifestyles of millions of empowered individuals, communities and businesses. Up to now, such challenges were beyond the capacity of existing technology. But that will no longer be the case in just a few years, thanks to a major shift in computing architecture now under way, towards 'cognitive' systems."

Coupling subsidy reform with efficiency improvement can shift the energy economy, particularly in developing countries. Energy subsidies come in many forms, but subsidizing fossil fuels to reduce consumer prices is common in many areas, especially the Middle East and developing Asia. Subsidy reform is never an easy task from a political perspective, and indeed will often bring angry crowds into the streets. But redirecting subsidies towards low-carbon forms of energy could ease the transition. Subsidizing only a certain level of consumption is another way to ensure that the majority of the subsidy goes into the pockets of those who truly need it. Subsidy reform can reduce wasteful energy use and make investments in energy efficiency and renewable energy more attractive.

Conclusion

When we think about the possibility of the next energy transition, we typically think about how the transition might happen with all other things being equal. More efficient energy use and changes in how we power transport are certainly on the table, but with that comes a tendency to consider a world that looks very much like the one we live in today.

But that's not how energy transitions have occurred in the past. The transitions from wood to coal to oil and the rise of electric power were accompanied by sweeping technological, sociological and economic changes. More concentrated energy sources enabled the industrial revolution and facilitated mass migration to cities. Electricity allowed the rise of appliances in the home and workplace, automating and simplifying many tasks and increasing productivity, and now enabling the digitization of the world.

Understanding the dynamics of energy transitions requires respect for innovation and its unexpected impact, and indeed some imagination about the future. Will the next transition be accompanied by larger changes in way of life? Or will it be mainly a change in how energy is produced and distributed? As to that, time will truly tell.

3. See the 2010 Energy Vision, *Towards a More Energy Efficient World*.
4. Daniel Yergin, *The Quest: Energy, Security, and the Remaking of the Modern World,* Penguin Press, 2012.

Appendix:
World Energy Timeline

Based on Daniel Yergin's *The Quest: Energy, Security, and the Remaking of the Modern World,* Penguin Press, 2012.

400,000 BC	Humans begin using wood for fuel
12th century	English clergyman Herbert builds windmill, declaring, "The free benefit of the wind ought not to be denied to any man."
1712	Thomas Newcomen invents first mechanical steam engine
1775	James Watt patents improvements on steam engine, initiating the 'Age of Steam'
1804	World population reaches 1 billion
1830	First commercial coal powered steam locomotive
1840	Coal reaches 5% share of primary energy market
1859	"Colonel" Edwin Drake drills what is generally accepted as the first oil well in Titusville, Pennsylvania
1873	Baku oil – in present-day Azerbaijan – opened to development
1865	Coal reaches 15% share of primary energy market
1875	Coal reaches 25% share of primary energy market
1881	Lord Kelvin predicts exhaustion of coal resources – "so little of it is left" – and calls for its replacement by wind power
	First hydropower station developed in England
1882	Thomas Edison "throws the switch", lighting up part of Lower Manhattan and demonstrating commercial electric generation
1895	World's largest hydroelectricity generating station at the time completed at Niagara Falls
1900	Coal reaches 50% share of primary energy market, overtaking biomass
1905	Albert Einstein writes five papers while working in the Swiss patent office, including one on the "photovoltaic effect", the basis for solar energy
1908	Ford releases Model T car
1911	First Lord of the Admiralty Winston Churchill calls for converting the British fleet from coal to oil power
1915	Oil reaches 5% share of primary energy market
1920s	95% of homes in Chicago wired for electricity
1927	World population reaches 2 billion
1931	Texas oil prices collapse to 10 cents a barrel during the Great Depression
1930	Natural gas reaches 5% share of primary energy market

1930s	Large hydro stations built in US and USSR
1935	Oil reaches 15% share of primary energy market
1938	Discovery of oil in Saudi Arabia and Kuwait
	Guy Callendar delivers paper linking carbon dioxide and climate change greeted by general disbelief at the Royal Meteorological Society in London
1952	"Killer Fog" envelops London, killing thousands
1954	USS Nautilus, first nuclear submarine, commissioned
	First tiny nuclear reactor for electric power opened in Obninsk in the Soviet Union
	Bell Labs scientists unveil the first silicon solar cell; *New York Times* declares, "Vast Power of the Sun Is Tapped by Battery Using Sand Ingredient"
1955	Oil reaches 25% share of primary energy market
1956	M. King Hubbert presents his theory of "peak oil"
	First commercial nuclear generation at Calder Hall station in the United Kingdom
1957	First shipment of LNG, dispatched from Louisiana, arrives in Britain aboard the *Methane Pioneer*
1959	Discovery of giant Daqing oil field – "Great Celebration" – in northeast China, initiating modern Chinese oil industry
	World population reaches 3 billion
	Giant Groningen natural gas field found in Netherlands
1960	Natural gas reaches 15% share of primary energy market
1965	Samotlar, world's second largest oil field, discovered in West Siberia, Soviet Union
1967	Great Canadian Oil Sands project launched
1969	First oil struck in North Sea
1973	Solarex, founded in Rockville Maryland, produces commercial solar panels
	Organization of Arab Petroleum Exporting Countries (OAPEC) embargoes oil shipments in response to United States' decision to resupply Israel during October War. Oil prices quadruple.
	Gas line lines form across United States
1974	France embraces nuclear power generation
1975	World population reaches 4 billion
	Oil reaches 40% share of primary energy market
1978	Natural gas use in new electric generation banned in the United States
1979	Three Mile Island nuclear plant accident ends new nuclear power development in the United States
	Iranian Revolution leads to Second Oil Shock and Islamic regime
1982	George P. Mitchell starts developing hydraulic fracturing technology for shale gas
1985	Natural gas reaches 25% share of primary energy market
1986	Oil prices collapse owing to declining demand, efficiency gains, switching to coal and growth in "non-OPEC" supplies
	Major nuclear accident at Chernobyl in Soviet Ukraine
1987	World population reaches 5 billion
1988	First Chinese wind farm connected to grid
	Intergovernmental Panel on Climate Change (IPCC) established under United Nations auspices
1990	IPCC First Assessment Report on climate change
	"Feed-in Act" jumpstarts renewable power development in Germany
1994	Toyota engineers introduce idea of "hybrid" drive train
1997	Qatar's first shipment of LNG reaches Japan
	Signing of Kyoto Protocol linked to United Nations Framework Convention on Climate Change
1998	Oil price collapses to approximately US$ 10 per barrel
	Mitchell Energy makes breakthrough in hydraulic fracturing technology with innovation of light sand hydraulic fracturing

1999	World population reaches 6 billion
2000	Toyota Prius hybrid goes on sale in United States
2001	China enters World Trade Organization, reshaping global economy and stimulating new growth in world energy demand
2002	Devon Energy merges with Mitchell Energy – also merging technologies of hydraulic fracturing and horizontal drilling
	Canada's oil reserves upgraded to world's largest owing to technological advances in oil sands production
2003	Demand shock from emerging market economic growth reaches world oil market, initiating price increase
2004	United States effectively mandates ethanol in gasoline by banning MTBE
2005	United States reaches "peak demand" for oil
	Carbon trading begins in European Union
2006	Petrobras makes first pre-salt discovery in off-shore Brazil
2007	US Supreme Court rules that CO_2 is pollutant that "endangers public health and welfare"
2008	Oil price reaches record high of US$ 147.27 per barrel
	Lehman Brothers investment bank fails, creating global financial panic as downturn spreads
	Oil price falls to US$ 32 per barrel
2009	Number of new car sales in China eclipse those in the United States
2010	Tesla Motors – using lithium-ion batteries for its electric Roadster – has initial public offering on the NASDAQ
	Nissan's all electric Leaf goes to market
2011	Japanese tsunami and meltdown at Fukushima Daiichi nuclear power plant create regional disaster, leading to Japanese retreat from nuclear power
	German government announces phase-out of nuclear power by 2022, accelerates renewables
	China overtakes United States as top energy consumer
2012	World population reaches 7 billion
	Shale gas reaches about 37% of total US gas production
	OPEC annual revenues exceed US$1 trillion

Based on Daniel Yergin, *The Quest: Energy, Security, and the Remaking of the Modern World*, Penguin Press, 2012. The full timeline is available at www.danielyergin.com.

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