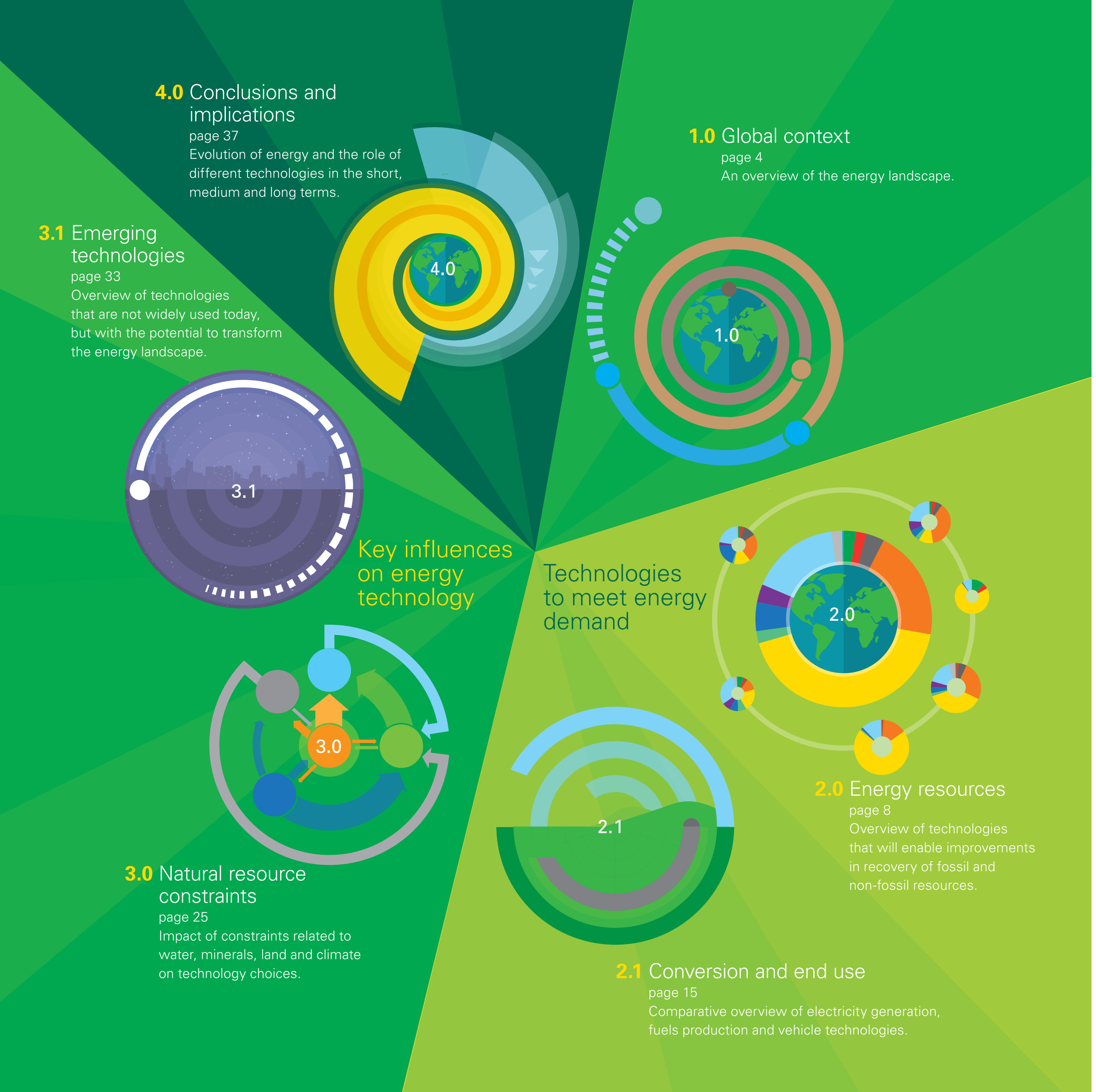
BP Technology Outlook

Technology choices for a secure, affordable
and sustainable energy future

November 2015



Contents

External perspectives

Within this publication there are six opinion pieces authored by a range of industry experts, including IHS Energy, Bloomberg New Energy Finance, Ford Motor Company, Princeton University, Tsinghua University and Masdar Institute of Science and Technology.

The opinion pieces can be found on pages 14, 19, 23, 28, 32 and 36.

About this publication

This publication sets out how technological developments could shape and influence the way we identify sources of energy and extract, convert, store and ultimately consume them over the next 35 years.

Using insights from BP's data and analysis, it maps out a path that can deliver energy supplies that are secure, affordable and environmentally sustainable. While we provide an overview of technologies across the energy system, we present more detail on oil-and gas-related energy technologies. We look at each major region in the world, focusing on North America as a specific example. When analyzing costs, we use data from the period when oil prices were around $100 per barrel, and show how technology could reduce costs relative to this benchmark. Clearly, other deflationary forces are at play in the lower-oil-price environment – and these can and should be differentiated from the technology signal in this publication.

The analysis is, of course, based on what we know today. In that sense it can only ever be a snapshot of new and emerging technologies – some, such as carbon capture and storage, are still in their infancy; others, such as solar photovoltaic (PV), are developing quickly. We must also acknowledge the impact that breakthroughs in other sectors, such as data analytics, will have in helping us to meet global energy demand in the most effective way. This trend of convergence between sectors is already making an impact.

Naturally, the future is uncertain. This analysis looks at today's trends and the implications those trends may have for future governments, businesses and wider society.

Introduction

We live in a world of rapid change where developments in technology can transform societies, economies and industries. In the corporate world, history tells us that companies that do not anticipate or adapt to new technologies struggle to survive. On the other hand, companies with leading technologies are often the most competitive and successful.

For many years at BP we have regularly assessed energy technology developments, looking back to learn lessons and looking forward to anticipate the trends that will shape our industry and others.

BP Technology Outlook marks the first time we have shared the outcomes of our analysis with the wider world. It sets out how technology could shape our energy landscape over the next 30 to 40 years.

The analysis shows that the world is not running out of resources for its energy needs. Fossil fuels of oil, gas and coal, along with uranium, are plentiful while the alternatives of renewable energies do not deplete by definition. With existing and incremental technology advances, we have abundant and technically accessible resources to meet foreseeable global primary energy demand out to 2050 and beyond. The extent to which each fuel is used depends on many factors. These include technology and policy but also capital. At the time of writing, an abundance of supply and a fall-off in demand growth have driven energy prices down and constrained the funds available for investment. Such price falls compel the industry to develop new technologies to reduce costs; however, the situation reminds us that energy is influenced by the interplay of many different factors.

Technologies such as enhanced oil recovery, advanced seismic imaging, and digitization will have a huge impact on which of the available fossil resources we develop, how, where and when. Innovation will not only help to sustain the supply of hydrocarbons, it will enable renewable resources – most notably solar and wind – to be more competitive, changing the merit order of investment and resource development.

In terms of energy's end use for transport, liquid fuels, including biofuels, are likely to continue as the major source of transport fuel for at least the next 30 years. They will be used more efficiently as vehicles and engines become lighter and smarter. In power generation, as well as increasing contributions from renewables, new opportunities such as a global shift towards natural gas, improved energy efficiency and, ultimately, carbon capture and storage technology will help us to move towards a lower-carbon future. Meanwhile, further falls in the costs of renewables and developments in areas such as battery storage and smart energy systems will widen options in an already competitive market.

Society's challenge is how to balance mitigating climate change while at the same time providing the energy security and affordability that drives socio-economic development. The energy industry can assist in the transition to a more sustainable economy if policy frameworks are developed to promote investment in lower-carbon technology.

Our aim for this publication, similar to *BP Energy Outlook 2035*, and *BP Statistical Review of World Energy 2015*, is to make a valuable contribution to the debate about how best to shape a secure, affordable and sustainable energy future. I hope you find it interesting and useful.

Bob Dudley
Group Chief Executive
November 2015

Key insights

What the analysis shows

Energy resources are plentiful

Energy resources are more than sufficient to meet future, long-term demand.

Technology has great potential to increase the supply of both fossil and non-fossil fuels, while reducing their costs.

The questions for policymakers are about choosing which resources to prioritize in meeting demand, while limiting emissions and providing energy security.

The power sector offers greatest scope for reducing emissions

Using technology to improve energy efficiency is often economic. Beyond this, there is an immediate cost to reducing emissions, and this is generally lower in power generation than in transportation.

In many regions, a modest carbon price can make new-build natural gas more competitive than existing coal, and gas is cleaner.

At higher carbon prices, wind and solar become more competitive, providing there is backup power capacity. Capturing the carbon from burning gas for power can also become economically viable.

Transport is set to become more efficient

Continued improvement in the efficiency of internal combustion engines (ICE) and vehicles will reduce emissions.

The cost of supplying biofuels will fall, particularly second-generation biofuels made from grasses, wastes and other non-edible agricultural matter.

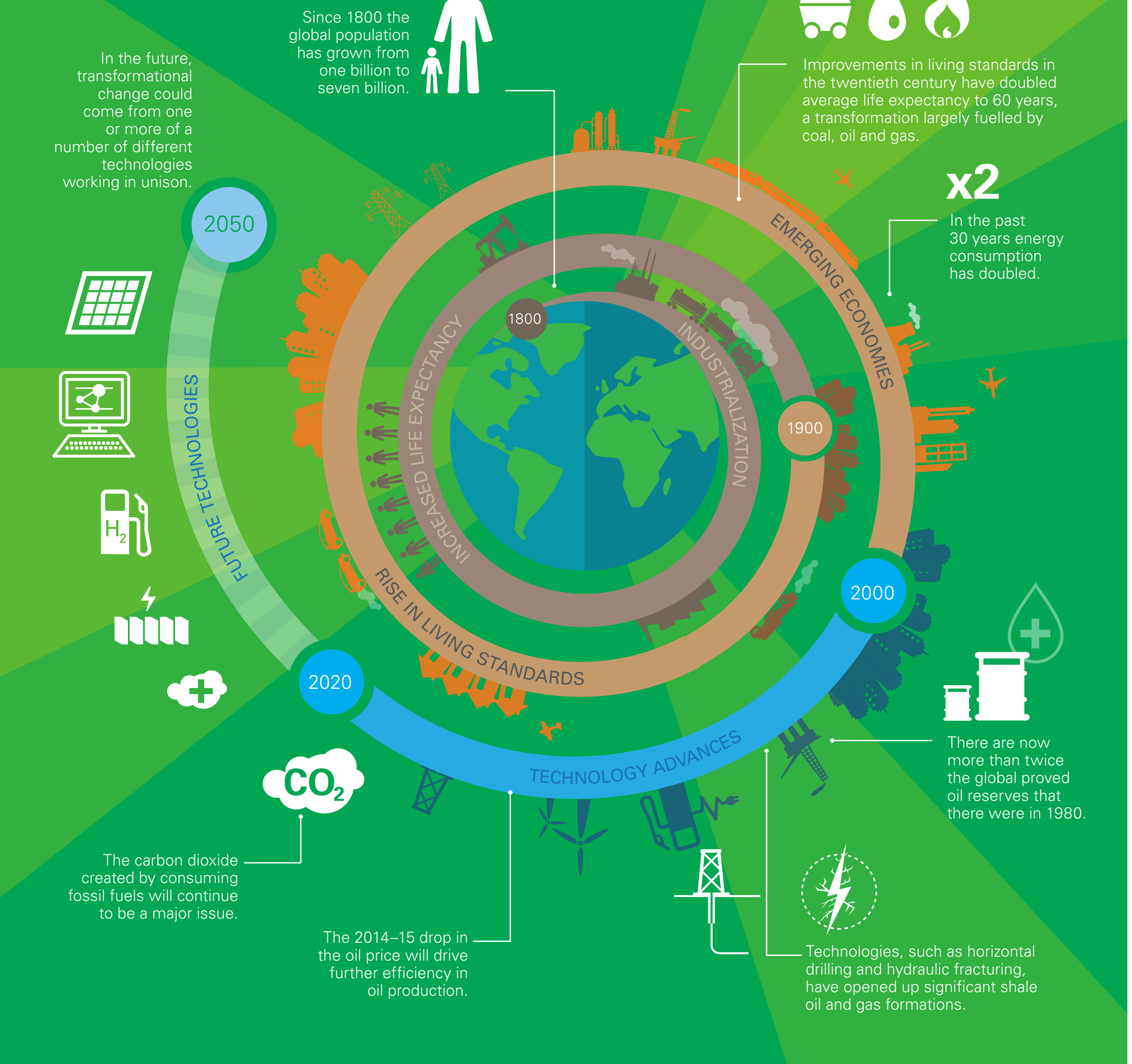
Despite their high energy efficiency, electric vehicles or fuel-cell vehicles still need significant technological advances to compete with ICE vehicles on cost.

Some emerging technologies could prove disruptive

The nature of certain technologies, in areas such as digital systems, bioscience and nanoscience, makes them potentially disruptive to markets, trends and business models.

Developments in advanced materials could lead to extraordinary improvements in the performance of batteries, solar conversion and the use of hydrogen as a fuel; however, these technologies could take decades to be applied globally, because of the capital required.

Digital technology has particular potential to drive far-reaching change because it offers multiple opportunities to make energy supply and consumption safer, more reliable, more efficient and more cost effective.



1.0 Global context

The twenty-first century energy journey

Which technologies will be most significant in the world of energy in the coming decades? In this publication, we review the range of technologies used to find, produce, process and consume energy – and how they might develop. We examine the journey that energy is likely to take and the technologies with the potential to be significant at each stage.

The journey so far

Since 1800 much of the world has industrialized, and the average life expectancy has doubled from 30 to 60 years. It took all of human history for the world's population to reach one billion in 1820; today it is seven billion and is forecast to be eight billion in less than a decade. This transformation has been largely fuelled by coal, oil and gas providing heat, power and mobility, which in turn has helped drive economic growth, create jobs and raise living standards.

The past decade and a half has seen a surge in these trends, driven by demand from emerging economies, led by China and India. Consumption of energy has almost doubled. Although energy has played a major part in lifting millions out of poverty in recent decades, many lack the access to energy taken for granted in advanced economies. For example, more than a billion people still live without electricity.

On the supply side, technology has helped the energy industry discover more oil and gas than society has consumed. Proved oil reserves, for example, now stand at more than twice the level they were at in 1980. Key technologies driving this phenomenon include advances in seismic imaging that enable geologists to pinpoint subsurface reservoirs more accurately, and new techniques to improve oil recovery that prolong production from reservoirs.

Meanwhile, other technologies such as horizontal drilling and hydraulic fracturing have opened up significant shale oil and gas formations. Resources are now plentiful and the concern about oil and gas running out has all but disappeared. The resources are unevenly spread, however, with four countries accounting for more than 50% of proved oil reserves. The same is true for gas[1]. With such disparities between where energy is located and where it is used, net consumer countries often seek to increase their domestic production and limit imports to enable energy security.

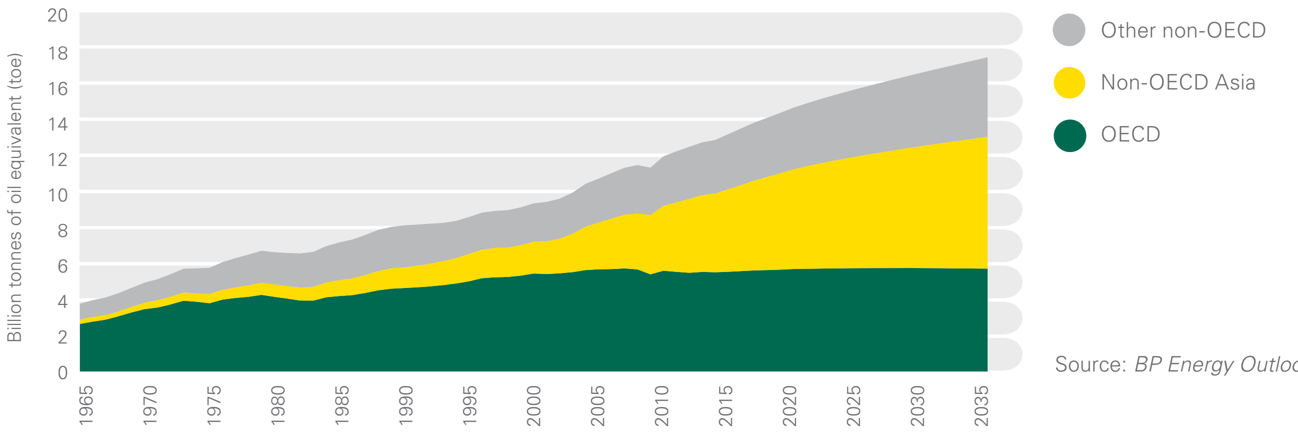
[1] *BP Statistical Review of World Energy 2015.* Four countries control more than 50% of the world's proved oil reserves (Venezuela, Saudi Arabia, Canada and Iran). Four countries control more than 50% of the world's gas reserves (Russian Federation, Iran, Qatar and Turkmenistan).

Yan'an Road and People's Square, Shanghai, China.

Harvesting sugar cane for biofuels in Brazil.

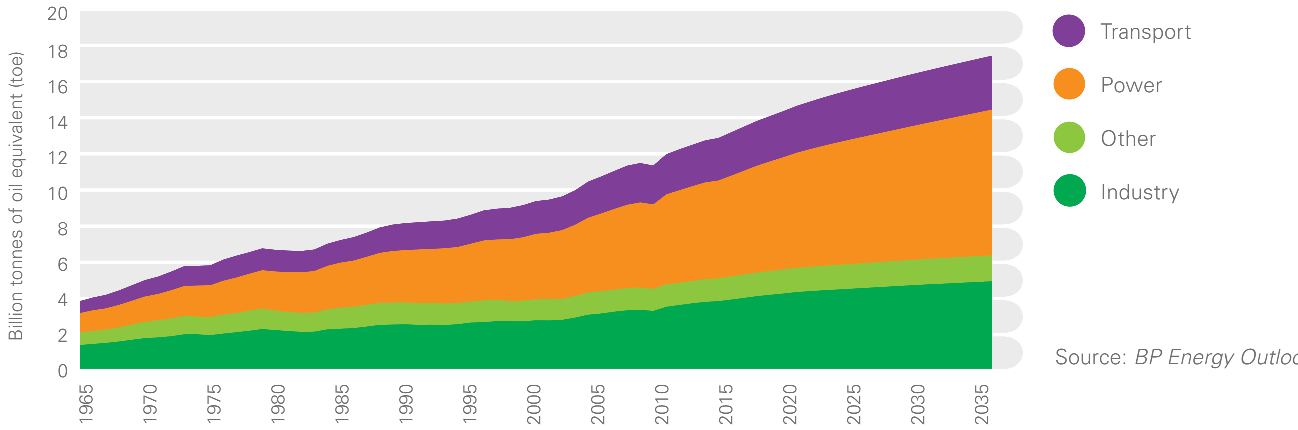
Demand is likely to grow but, with resources being so plentiful, industry will need to adapt and be resilient to lower prices.

Global primary energy consumption by region



Source: *BP Energy Outlook 2035.*

Consumption by final sector



Source: *BP Energy Outlook 2035.*

At the time of writing, the abundance of new supplies, coupled with a slow down in demand growth for energy in developed economies, has led to a dramatic drop in oil prices. Demand is likely to grow but, with resources being so plentiful, industry will need to adapt and be resilient to lower prices.

The past two decades have also highlighted the environmental challenges of using fossil fuels. Greenhouse gas (GHG) emissions have risen in the past two centuries and have been increasing by more than 2% per year in the twenty-first century[1]. Carbon dioxide (CO_2) from fossil-fuel use accounts for around two-thirds of the total[2]. The Intergovernmental Panel on Climate Change (IPCC) states: "Without additional mitigation efforts beyond those in place today, and even with adaptation, warming by the end of the twenty-first century will lead to high to very high risk of severe, widespread and irreversible impacts globally."

The journey ahead

BP Energy Outlook 2035 sets out how we believe the journey will continue, based on a series of projections on current and expected trends in supply, demand, policy and technology. Energy consumption could grow by around 37% in the next two decades. Almost all this growth in energy use – an estimated 96% of it – comes from non-OECD[3] economies, led by China and India. That level of growth in energy use could result in CO_2 emissions increasing by 25% by 2035.

Policymakers face multiple challenges in seeking to set frameworks for energy.

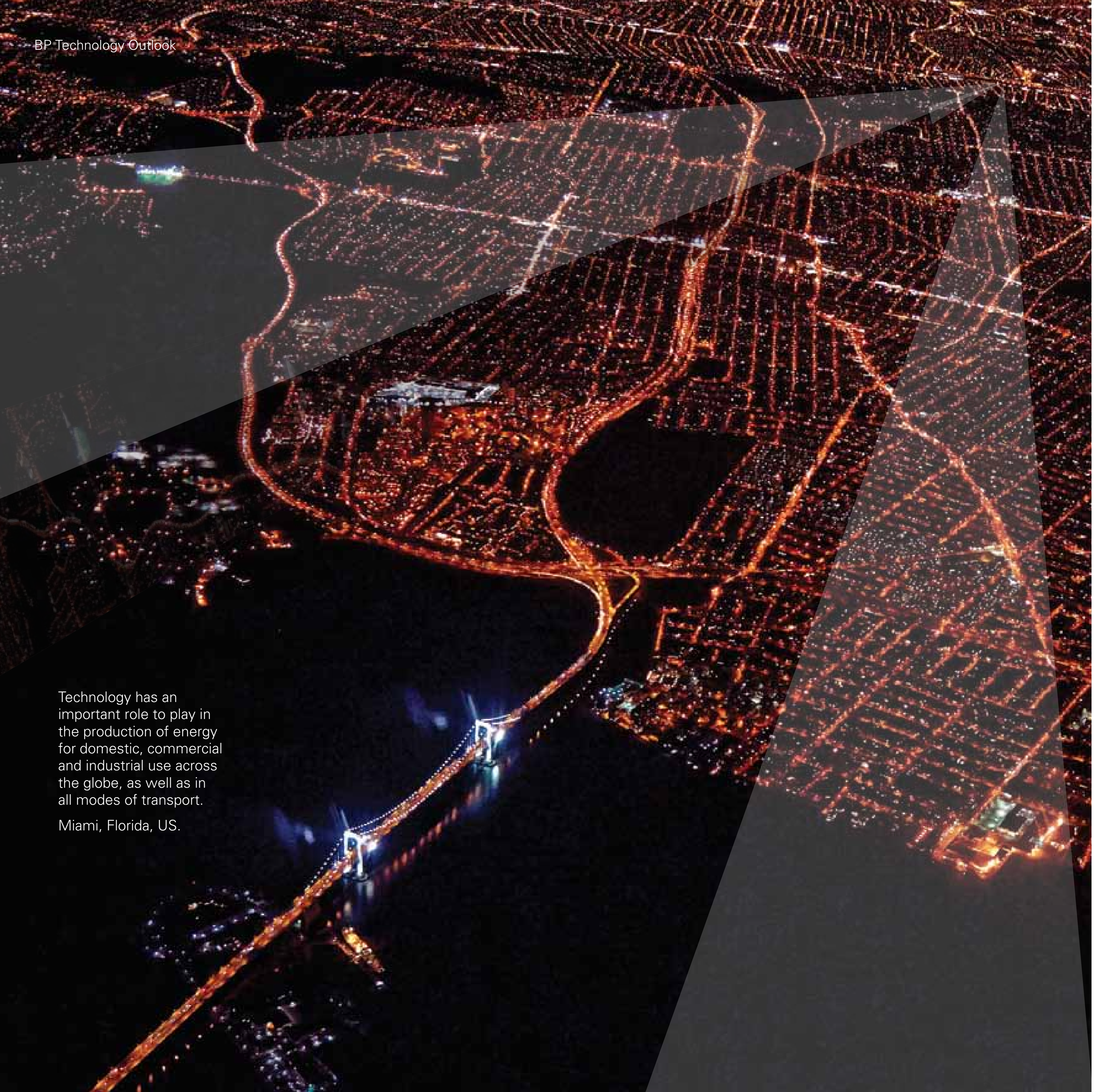
On the one hand, there is a continuing and pressing need to improve access to affordable energy for the billions who need it in places such as Africa and Asia.

On the other hand, there is the environmental imperative of driving a transition to a lower-carbon economy.

This situation is further complicated by the fact that, today, lower- or zero-carbon energy, such as solar, wind, wave, nuclear and sustainable biofuels, are generally more expensive and/or less reliable than fossil fuels. In addition, carbon capture and storage (CCS), a process whereby CO_2 is collected from industrial exhaust streams and injected into underground storage sites, is only now starting to be demonstrated at scale.

Governments around the world have given some support to lower-carbon energy through many measures. These include emissions limits for vehicles and industrial plants, quotas that mandate certain proportions of renewable energy in power or transport, and subsidies such as tax credits and feed-in tariffs to help lower-carbon energy compete with fossil fuels.

[1]IPCC Fifth Assessment Report Summary for Policymakers.
[2]IPCC Fifth Assessment Report WG 3.
[3]Organization for Economic Cooperation and Development (OECD) is a unique forum where the governments of 34 democracies with market economies work with each other, as well as with more than 70 non-member economies, to promote economic growth, prosperity and sustainable development.



Technology has an important role to play in the production of energy for domestic, commercial and industrial use across the globe, as well as in all modes of transport.

Miami, Florida, US.

However, renewables (excluding large-scale hydro electricity and the use of biomass in small-scale heating and cooking) still only make up around 3% of world primary energy. While they are the fastest growing type of energy, they are only expected to reach around 8% by 2035. Responses to the accident at the Fukushima nuclear power plant in Japan in 2011 have slowed down the growth of nuclear power, which currently only accounts for around 4% of global primary energy consumption.

Many governments, businesses, including BP, and experts believe a decisive shift to lower-carbon energy can best be driven by putting an effective price on carbon, raising the costs of consuming higher-carbon-content energy, and tilting the economic balance in favour of lower-carbon options.

The role of technology

Technology underpins all these energy sources and therefore has an important role to play in the energy future.

In Chapter 2, we examine current and future energy technology options, covering production, conversion and consumption. We also look at the scale and nature of natural energy resources.

In Chapter 3, we consider the forces that may influence the directions taken by energy technology in the future. Firstly, we cover constraints relating to natural resources, including potential areas of scarcity, such as water and minerals, and the impact of carbon in the atmosphere as a driver of climate change. Secondly, we review emerging technologies that are not widely used today and assess the potential influence these may have in the future.

In Chapter 4, we draw some conclusions from the way energy has evolved to date and the role different technologies might play in delivering more energy to more people at lower cost in the future. We also assess how the growth in demand can be met while meeting GHG-emission-reduction targets and moving to a lower-carbon energy system.

Three priorities, therefore, recur throughout this publication:

- **Energy security and growing demand** – given increasing demand and concerns around energy security, technologies for efficiently capturing and utilizing primary energy resources will remain important.
- **Affordability** – pressure on the industry to keep delivering energy competitively means that technologies enabling energy to be produced and consumed at a lower cost are in demand.
- **Lower-carbon energy** – the risk of climate change means that technologies limiting and, in time, reducing GHG emissions by increasing the efficiency of fossil-energy consumption, or enabling switching to a lower-carbon energy, will be a major feature of the journey ahead.

These objectives are not ranked in order. It is for governments, regions and ultimately consumers to decide which needs are most pressing and how the balance between these imperatives can be best achieved.

Technologies to meet energy demand

As energy demand grows in the coming decades, securing access to resources will continue to be essential. Through technology, we will be increasingly able to recover more from known resources and make those that currently face technical and cost challenges more affordable.

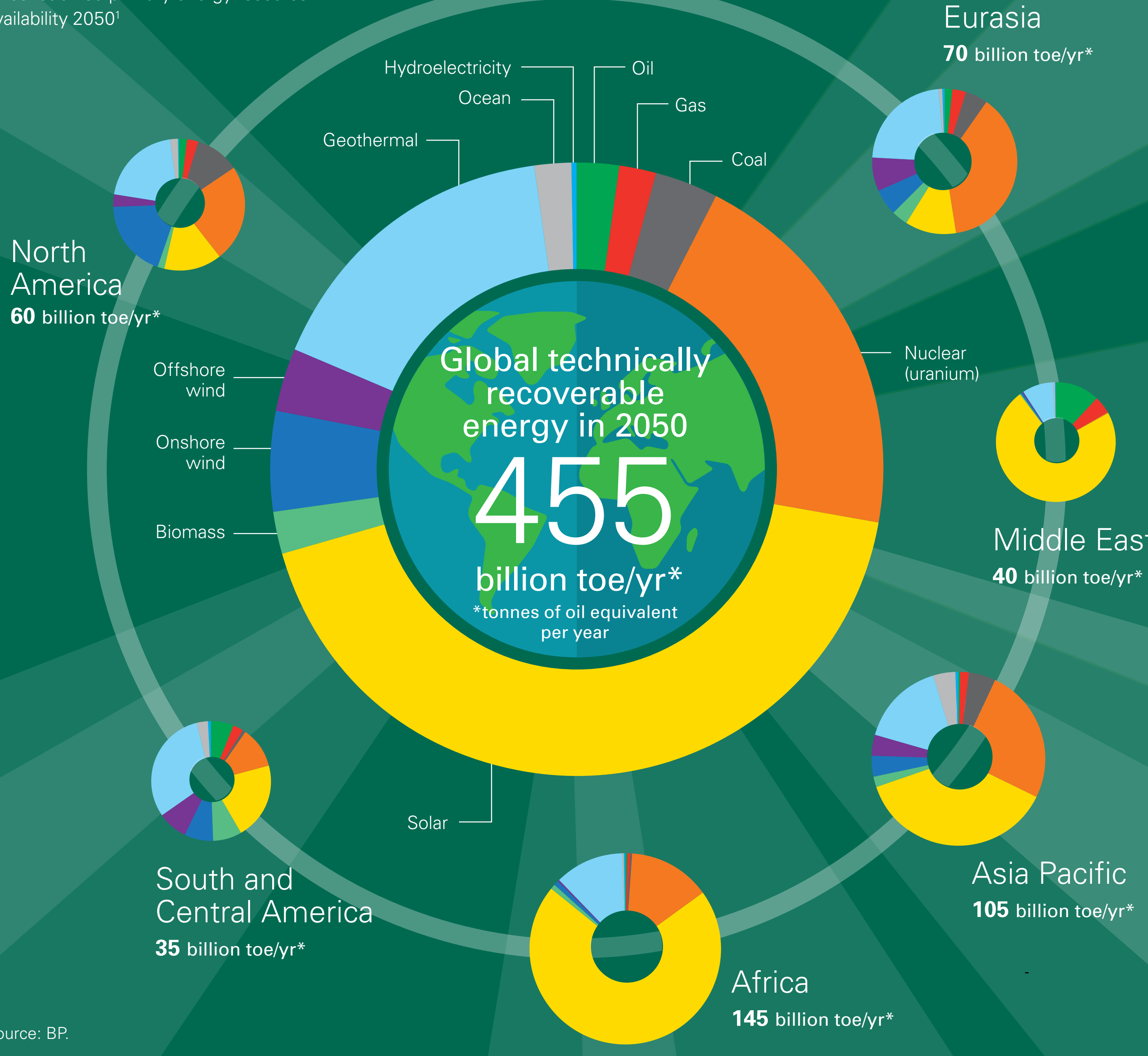
Technology can provide many possible routes through an uncertain energy future and can help to meet the projected growth in global energy demand.

Dubai in the mist, United Arab Emirates.

Energy resources are plentiful

Technology advances are helping to produce resources to meet the world's projected future energy demand many times over.

Unconstrained primary energy resource availability 2050[1]



Source: BP.

2.0 Energy resources

As energy demand grows in the coming decades, securing access to new resources will continue to be essential. Technology will increasingly enable us to recover more from known resources and make those that currently face technical and cost challenges more affordable.

- Oil
- Gas
- Coal
- Nuclear (uranium)
- Solar
- Biomass
- Onshore wind
- Offshore wind
- Geothermal
- Ocean (e.g. wave, tidal, thermal)
- Hydroelectricity

[1] This represents the energy resource potential per year based on the availability of the underlying source of energy, including locally sourced uranium for nuclear, without reference to economic viability. Fossil and uranium resources have been annualized over a 50-year period for comparison with renewables.

[2] *Energy Technology Perspectives 2014*, IEA.

The International Energy Agency (IEA) forecasts that by 2050 the world's annual demand for energy will have risen from today's level of nearly 13 billion tonnes of oil equivalent (toe) to between around 16 to 22 billion toe[2]. How close the outcome is to the lower level depends on progress in using energy more efficiently and therefore using less of it in total. Although demand is strong, our analysis shows that there are plentiful energy resources available to meet it, both conventional fossil-fuel energy and renewable and alternative forms.

Indeed, several resources including wind and solar could meet that demand on their own if they were backed up by conventional sources of energy to counteract the challenges posed by intermittency, or supported by wide-scale energy storage. At issue though, is the practicality of providing energy to consumers when and where it is needed, at a price that is affordable and at a scale that is acceptable. It will be for communities and policymakers to judge the practicality as well as the social and environmental acceptability of taking such steps.

We must also acknowledge that some resource bases, such as wave and ocean thermal energy, while showing promise, are still in their infancy. Here too, technology will play a vital role in their progress.

In the meantime, as these lower-carbon technologies develop – largely by becoming cheaper and more efficient – the challenge is to identify, access and convert fossil-fuel resources more efficiently as we transition to a lower-carbon future.

We present an overview of lower-carbon resources later, but start by considering the future impact of technology on oil and gas resources.

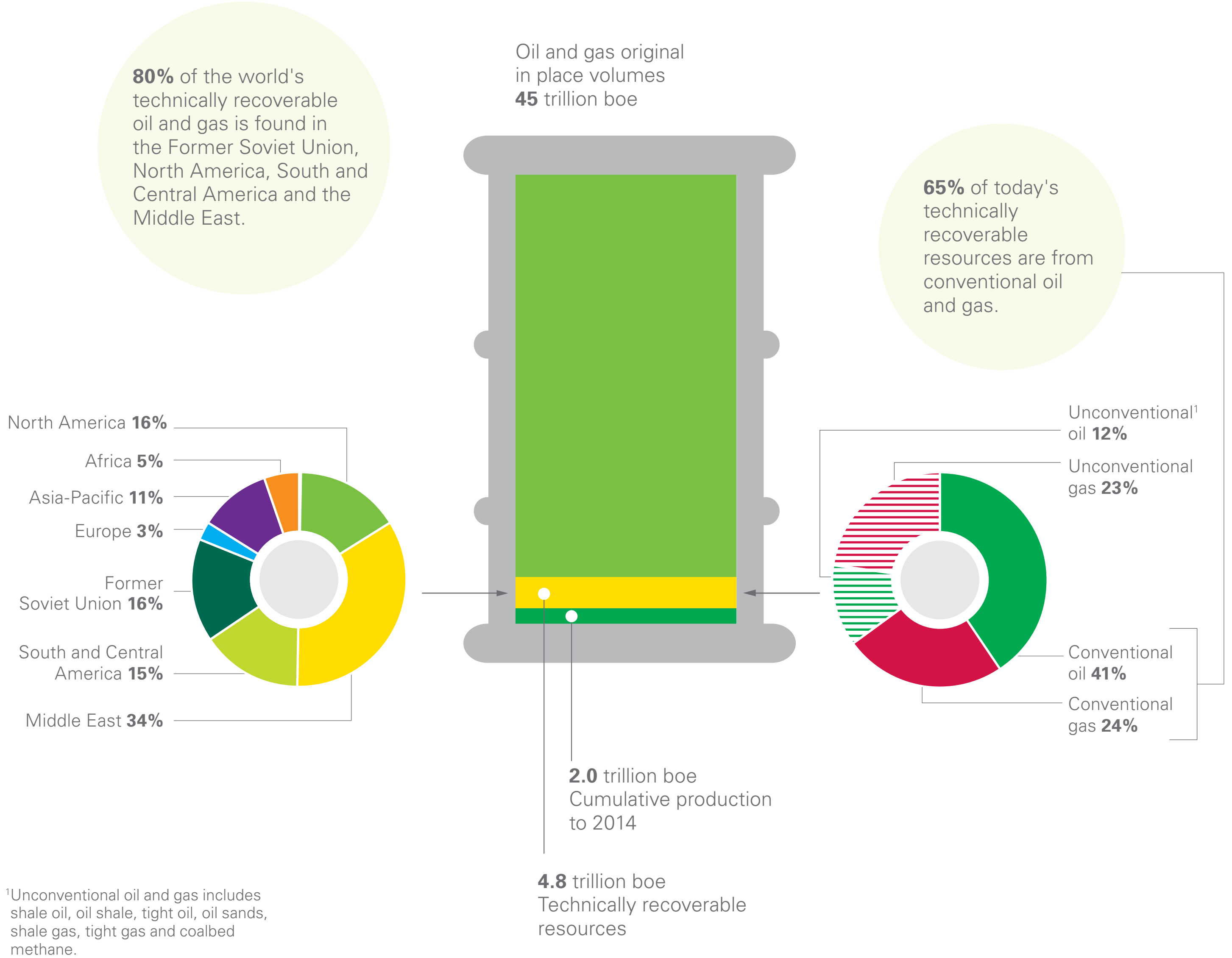
Technology will help unlock future oil and gas resources and reduce costs of extraction

We calculate that around 45 trillion boe of oil and gas were *'originally in place'* of which only 2 trillion boe have been produced to date. Ongoing development of these reservoirs can produce enough to meet anticipated global demand for the foreseeable future.

The availability of resources therefore is less of a challenge than the impact of their consumption on the sustainability of

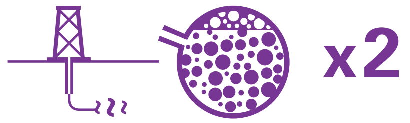
Plentiful volumes of oil and gas

Technically recoverable oil and gas resources from discovered fields, using technology available today, are estimated at **4.8 trillion barrels of oil equivalent** (boe).



[1]Unconventional oil and gas includes shale oil, oil shale, tight oil, oil sands, shale gas, tight gas and coalbed methane.

Source: BP, IHS Energy.



Estimates of shale resources, not only in the US but around the world, have more than doubled the oil and gas *'originally in place'* globally from around **20** to **45 trillion** boe.

the environment. While here we discuss our analysis of the potential scale of recoverable resources, we do so mindful that governments, supported by many businesses and citizens, are increasingly seeking to limit carbon emissions by using less energy and shifting towards lower-carbon fuels. This is likely to have an impact on the proportion of these resources produced, relative to other forms of energy.

A significant volume of fossil fuels will still be used as part of the transition to a more sustainable future energy mix – including the use of natural gas as a substitute for coal – and it is therefore relevant to understand the role of technology in finding, producing and consuming fossil fuels.

The most significant change to the oil and gas resource base in the past decade has been the development of production from shale and 'tight' (or low-permeability) rocks, particularly in the US. Estimates of shale resources, not only in the US but around the world, have more than doubled the total estimated volumes of oil and gas in place globally with development potential.

New technology has been central to enabling the oil and gas industry to find and produce new sources of hydrocarbons. Advances in seismic imaging, for example, have helped reveal previously undiscovered oil and gas fields, particularly in deep water and below formations of salt in the subsurface.

The shale revolution has been made possible largely by developments in directional and horizontal drilling and multi-stage hydraulic fracturing – techniques that have evolved over many years.

The *BP Statistical Review of World Energy 2015* records that there are 2.9 trillion boe (as of 2014) of 'proved reserves'. These are reserves that subsurface information indicates with reasonable certainty can be recovered from known

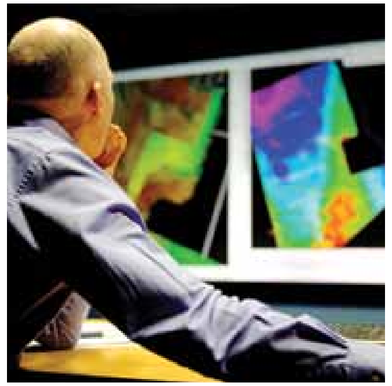
Enhanced oil recovery (EOR)

Once in production, typically only about 10% of the oil in a reservoir flows to the surface under its own pressure. For decades a technique known as waterflooding has been used to push more of the remaining oil out of the reservoir. Using conventional waterflooding the average recovery factor from the reservoir is around 35%, meaning almost two-thirds of the total volume of oil contained in a conventional reservoir is left behind. Clearly, the potential to recover more of the oil left in existing reservoirs represents an enormous opportunity, perhaps even larger than that from anticipated new discoveries.

The effectiveness of waterflooding can be improved by modifying the water injected into the reservoir, either by changing its ionic composition or by adding chemicals, polymers and surfactants. Maximizing recovery can also be achieved by other gas-based EOR technologies, such as CO_2 injection, miscible flooding and vaporization.

Extra-heavy oil and oil sands resources require a different set of techniques and technologies such as steam flooding, in situ combustion or solvent-assisted thermal flooding.

Longer term, breakthroughs in microbial and nano-particle technologies could raise recovery factors even further.



A geologist conducts seismic interpretation on large screens displaying detailed data in the Highly Immersive Visualization Environment in Jordan, Middle East.

Aerial view from a Bristow Super Puma helicopter of a Petroleum Geo-Services Ramform Sterling seismic vessel in the Ceduna Basin, Australia.

Seismic imaging

Seismic imaging technologies underpin exploration deep into the Earth's subsurface. These technologies can be used for oil and gas (and other minerals) resource identification, access, exploration and recovery. The emergence of three-dimensional seismic imaging during the 1990s had a dramatic impact on oil and gas exploration, in some instances raising exploration success rates from 30% to 50%.

Since then, seismic acquisition technologies have advanced and can now illuminate the subsurface from different orientations. Multi- and wide-azimuth surveys, for example, enable surveys to be carried out in different directions over the same area. 4D seismic, which involves repeating the same survey at different times, plays an increasingly important role in helping to determine how reservoirs are changing as oil, gas and water move through the subsurface and are produced to the surface.

These advances have been enabled by rapid increases in cost-effective computational processing capacity and deep algorithmic expertise to process and interpret vast streams of seismic data. As interest in tight oil, shale oil and shale gas grows, advances in imaging technologies that improve our understanding of subsurface factors and identification of 'sweet spots' will be of great value. Understanding reservoir structure, rock and fluid properties is critical to cost-effective, large-scale developments and to maximizing the recovery of unconventional hydrocarbons.

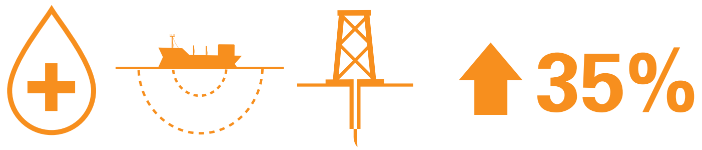
reservoirs under existing economic and operating conditions.

The technically recoverable oil and gas resource base could be increased by around 1.9 trillion boe to 4.8 trillion boe by applying today's best available technologies to conventional fields and including unconventional resources. The latter require different production methods and extraction technologies and include oil and gas found in shale rock, 'tight' formations and oil sands. Although no technological breakthroughs are required to develop unconventional resources, there are likely to be significant above-ground challenges. These will include government policy, infrastructure, supply chains, public opinion and consumer preferences.

Between now and 2050 technological developments will also drive improvements in field recovery factors. This is particularly the case for unconventional gas and EOR for conventional oil. These factors, when combined with the discovery of new oil and gas resources from exploration, could potentially add another 2.0 and 0.7 trillion boe respectively, over and above the potential from current best available technologies.

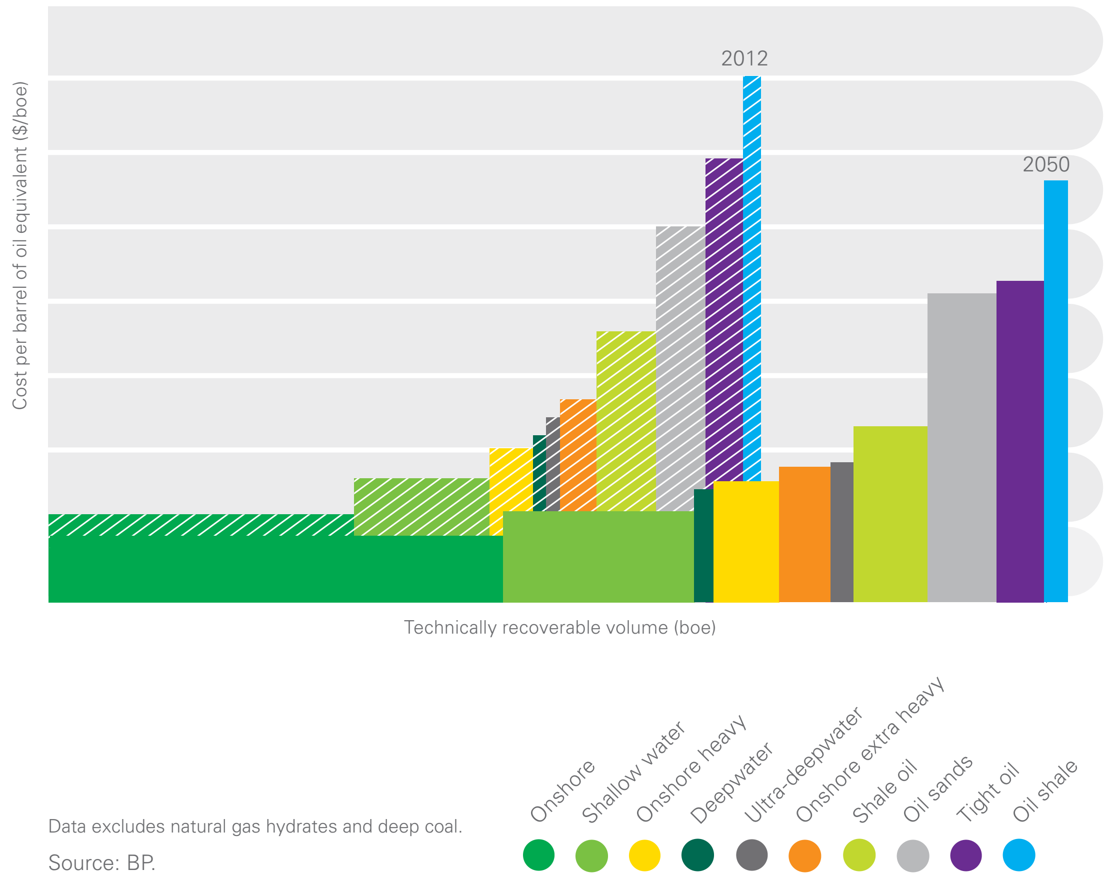
Advanced EOR technology could increase recoverable volumes of light oil by 30%. Developments in imaging, well construction and well intervention technologies will be key to unlocking unconventional oil and gas.

Technology advances will not only extend supply from existing oil and gas resource types, but can also open access



Technologies such as next-generation EOR, seismic imaging, and well construction and intervention could increase recoverable oil and gas resources by **2 trillion boe (~35%)** by 2050.

Technology advances will change the relative cost competitiveness of resource types



Technology improvements to 2050 will enable us to recover more resources than we can today.

Technology innovation will enable us to access resources more cost effectively and they will have a major impact on unconventional resources that today are high cost and complex to recover.

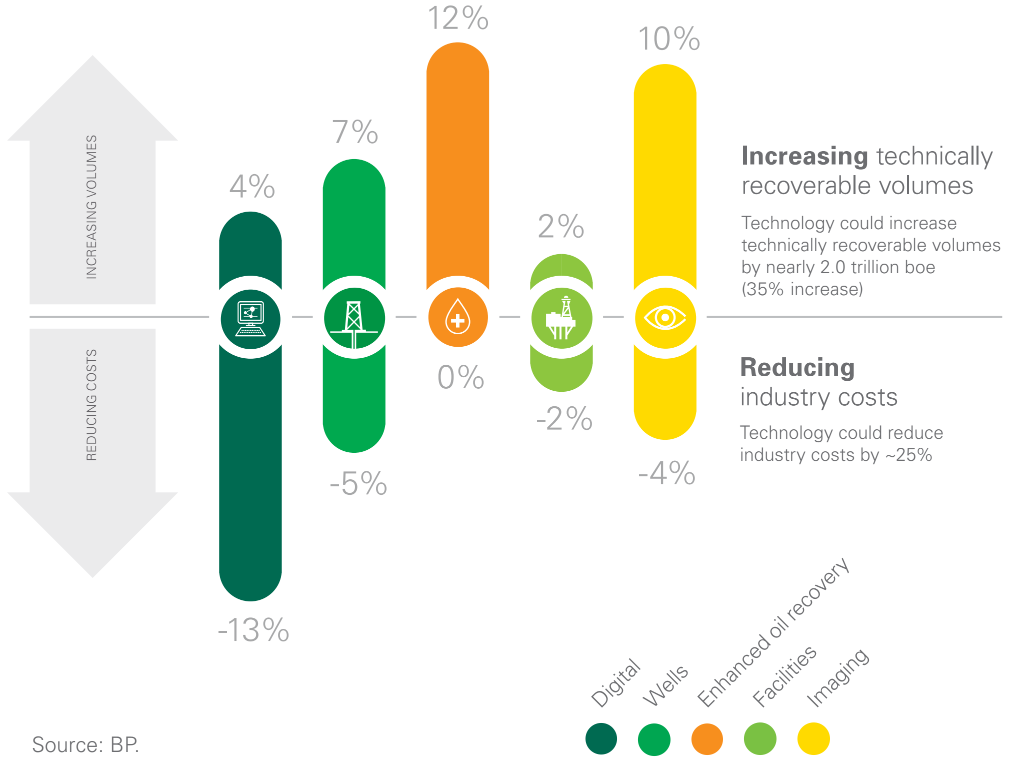
Data excludes natural gas hydrates and deep coal.

Source: BP.

Subsurface imaging, drilling and completions, facilities and digital technologies could all contribute to reducing today's cost of supplying oil and gas resources by as much as **25%** by 2050.

Increased recovery and reduced cost in oil and gas (combined)

Between now and 2050 technology innovation will both increase technically recoverable oil and gas volumes and reduce the cost of extraction. Totals refer to oil and gas combined.



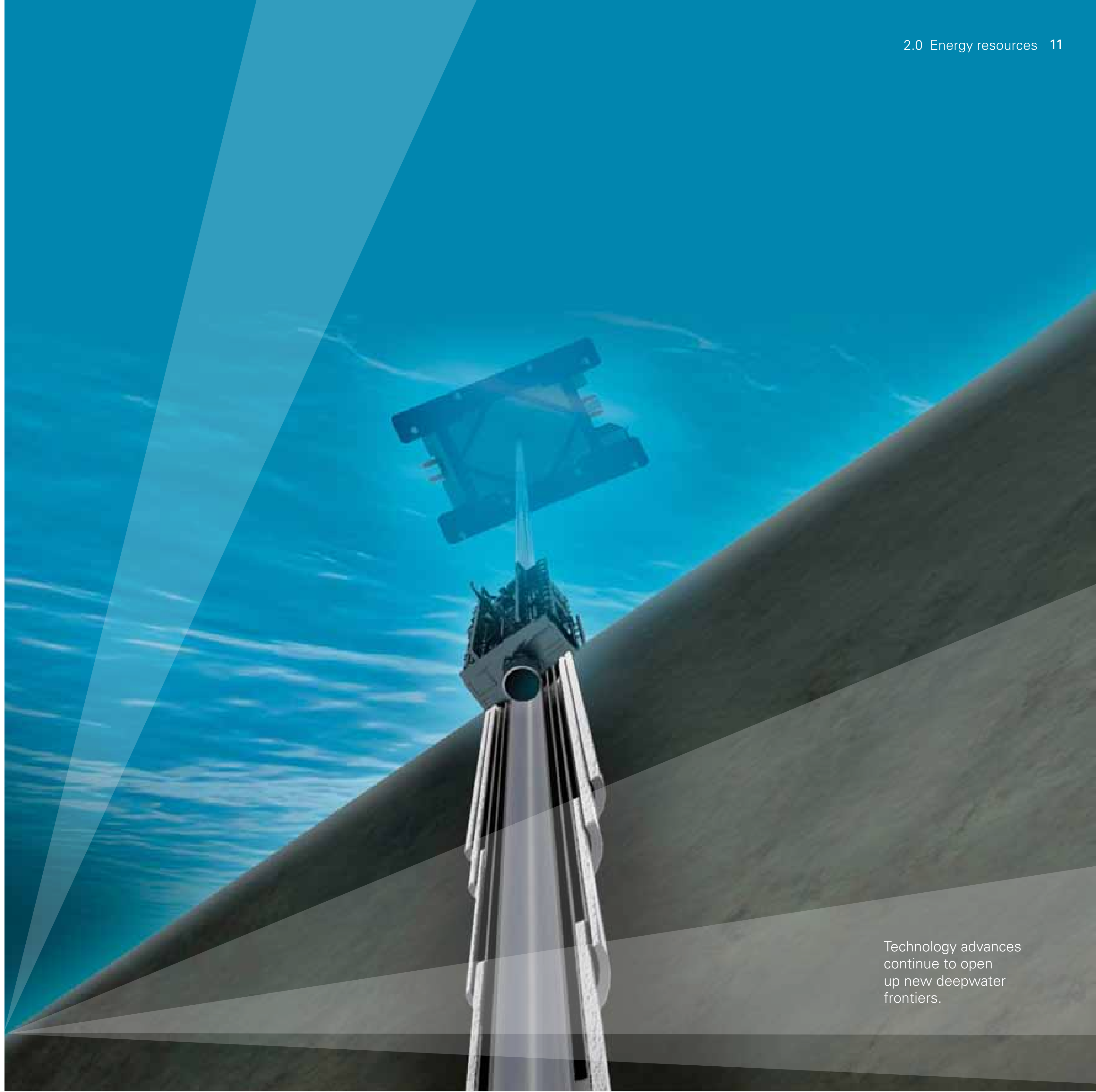
Source: BP.

to resources in geographies previously considered inaccessible, such as ultra-deepwater or the Arctic. As well as the question of whether these resources are needed as part of a future mix, the fundamental challenge the industry faces in addressing these resources is to produce them safely and reliably. Developments in remote sensing, automated operations and data analytics are not only making operations more efficient, but also increasing operational reliability and enhancing safety, especially in higher-risk tasks and locations.

Advances in technology could reduce industry extraction costs[1] by approximately 25% (in real terms) by 2050.

Technology is likely to have the most impact on resources that are difficult to produce or those that are sparsely exploited today such as ultra-deepwater and unconventionals. At a time of lower prices, revenues and capital spending, digital technologies – including sensors,

[1]Undiscounted greenfield life-cycle costs were assessed at 2012 levels and include exploration, access and production capital expenditure, and operating costs, but exclude above-ground costs such as processing, transportation, tax and royalties.



Technology advances continue to open up new deepwater frontiers.

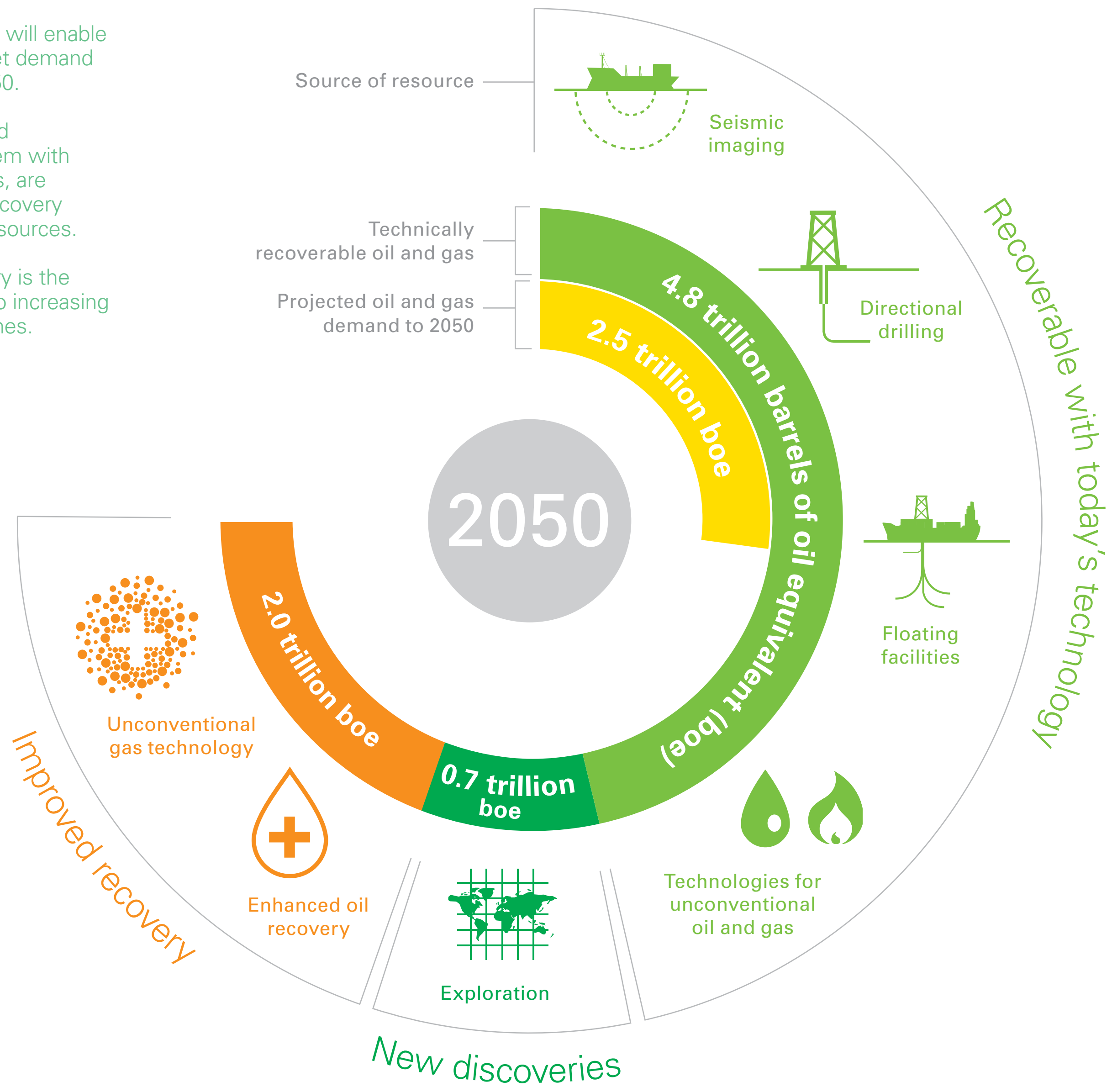
Oil and gas resources are abundant

Advances across a range of technology applications will improve recovery in existing resources and help discover and unlock new resources.

Today's technologies will enable us to more than meet demand for oil and gas to 2050.

Well construction and intervention, in tandem with imaging technologies, are vital for increasing recovery of unconventional resources.

Enhanced oil recovery is the biggest contributor to increasing recoverable oil volumes.



Source: BP.

Digital technologies

Digital technologies – in addition to seismic imaging – will make radical changes to how we find, extract and use energy, providing opportunities for more efficient operations through unparalleled levels of data analysis.

In the oil and gas industry, sensor technologies in equipment such as pumps, wells and appliances are increasingly being used. When connected to data collection mechanisms, they provide real-time information on field activities. Intelligent wells – providing updates on well condition from top to bottom – are now becoming a reality, a development that reduces both non-productive time and cost. Together with the rapid development of data analytics and management techniques, the industry can find oil and gas resources faster and more effectively, and operate refineries and manufacturing plants more efficiently. Digital technologies also provide a route to faster and better decision-making – boosting safety, productivity and efficiency.

data analytics and automated systems – stand out as the leading contributors for reducing costs. These technologies have important roles in enabling and integrating other technologies, and enhancing safety and reliability.

Technology will deliver benefits across a broad range of primary energy resources globally

Technology lies at the heart of accessing and harvesting all forms of primary energy. In the same way that we envisage technological improvements in oil and gas we also expect to see gains made in all other resource types, with nascent technologies in areas such as marine and offshore wind having the most scope for improvement.

After oil, **coal** is the second largest contributor to meeting primary energy demand and, globally, the largest source of fuel for electricity generation; however, it also has the highest carbon content of any primary energy source. Coal is abundant, with North America and Asia Pacific holding nearly 70% of the global resource. It is in the conversion of coal, rather than its extraction, where the greatest opportunities lie for technological advances, particularly with ultra-supercritical and integrated gasification combined-cycle power plants that can reduce the level of carbon emissions per unit of power produced. Being able to access very deep or very complex seams would require incremental, rather than step, changes in technology. Techniques such as underground coal gasification could make resources available that are currently inaccessible, particularly subsea.

Nuclear technology is often seen as an established lower-carbon source of energy for power and heat generation. Identified conventional sources of uranium for nuclear fission are abundant and there has been limited exploration. Although technology is likely to have the most impact in conversion where atoms split to create energy, there is scope for improvement in several aspects of the nuclear supply chain. Exploration for uranium could be enhanced through better field mapping and detection. In fuel processing there is scope for improved milling, conversion, enrichment and fabrication techniques. In addition to

Engineer in control room of nuclear power station, Suffolk, England, UK.

The turbine hall at Russia's largest hydroelectric power station Sayano-Shushenskaya.

mined uranium, reprocessed spent fuel, re-enrichment of depleted uranium and enriched fuels from nuclear stockpiles can also be used in some reactors. There is hope that small modular nuclear could mitigate upfront capital costs, which hamper nuclear economics.

Renewables (primarily biomass, hydro, wind and solar) do not deplete over time, so the requirement to continually discover new resources to replace those consumed does not exist.

While renewables generally have smaller carbon footprints, the delivery of energy from sources such as wind and solar is variable and, in many cases, poorly matched to demand. Renewables are also of lower energy density than fossil fuels and are often located in areas remote from demand sources – significantly increasing end-use cost. In total, renewables of all kinds contributed nearly 15%[1] of total global primary energy demand in 2012.

Biomass is currently the most widely utilized renewable source of primary energy. It is used extensively in low-efficiency stoves for residential cooking and heating in developing countries, as well as for biofuels and sometimes for power generation using more advanced technologies.

Technology can assist by enabling gains in crop yields through biosciences as well as mechanization of agriculture in emerging economies. Advances in fertilizers and pesticides and improved irrigation techniques, coupled with optimization through satellite imaging, will contribute to improving yields. Opportunities also lie downstream in the use of technologies capable of turning cellulosic (i.e. non-food) feedstock into biofuels, thus reducing competition with food crops for land and other natural resources. Increased recycling and/or reuse of waste biomass, such as the production of liquid fuels from waste food oils or biogas from landfills and manure, are possible, but likely to play a limited role.

Following bioenergy, **hydroelectricity** is the most widely accessed renewable source of primary energy. As a resource, it is well understood and technologies to harvest its energy are largely mature. Many of the potential locations where water can sustainably drive turbines at scale have already been exploited. Small increases in its technical potential may come through improved turbine design coupled with better regulation of flow and reduction of head energy losses.

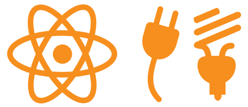
Of the remaining sources of renewable energy, **wind** and **solar** are most prominent today even though they currently make relatively small contributions to the global energy mix. For wind, future improvements are expected to come from increased turbine size, blade length and design, hub heights, tower technologies and gearbox improvements. Offshore innovation, such as advances in structure design, floating platforms and foundations to support larger-scale towers, could open access to wind resources at water depths greater than 200 metres.

Solar is the most abundant of all energy resources, with future potential driven by various capture and conversion technologies at different stages of development. PV and solar thermal are the most widely deployed today, with increases in future technical potential largely expected to come from multi-junction solar cells able to harvest a greater range of the light spectrum and solar thermal to operate at higher working temperatures.

In general, wind and solar face challenges with regard to their intermittent nature – a feature that could have a destabilizing effect on electricity networks. Deployment in tandem with storage technologies could eliminate these issues but at the expense of higher costs and lower efficiencies.

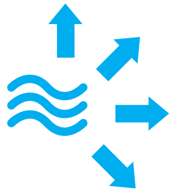
[1]Source: *IEA World Energy Outlook 2014.*

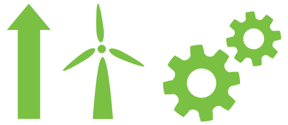
Nuclear technology is often seen as an established lower-carbon source of energy for power and heat generation.



Biomass is currently the most widely utilized renewable source of primary energy.

Following bioenergy, **hydroelectricity** is the most widely accessed renewable source of primary energy.





For **wind**, future improvements are expected to come from turbine size, blade length and design, hub heights, tower technologies and gearbox improvements.

Solar is the most abundant of all energy resources, with future potential driven by various capture and conversion technologies at different stages of development.

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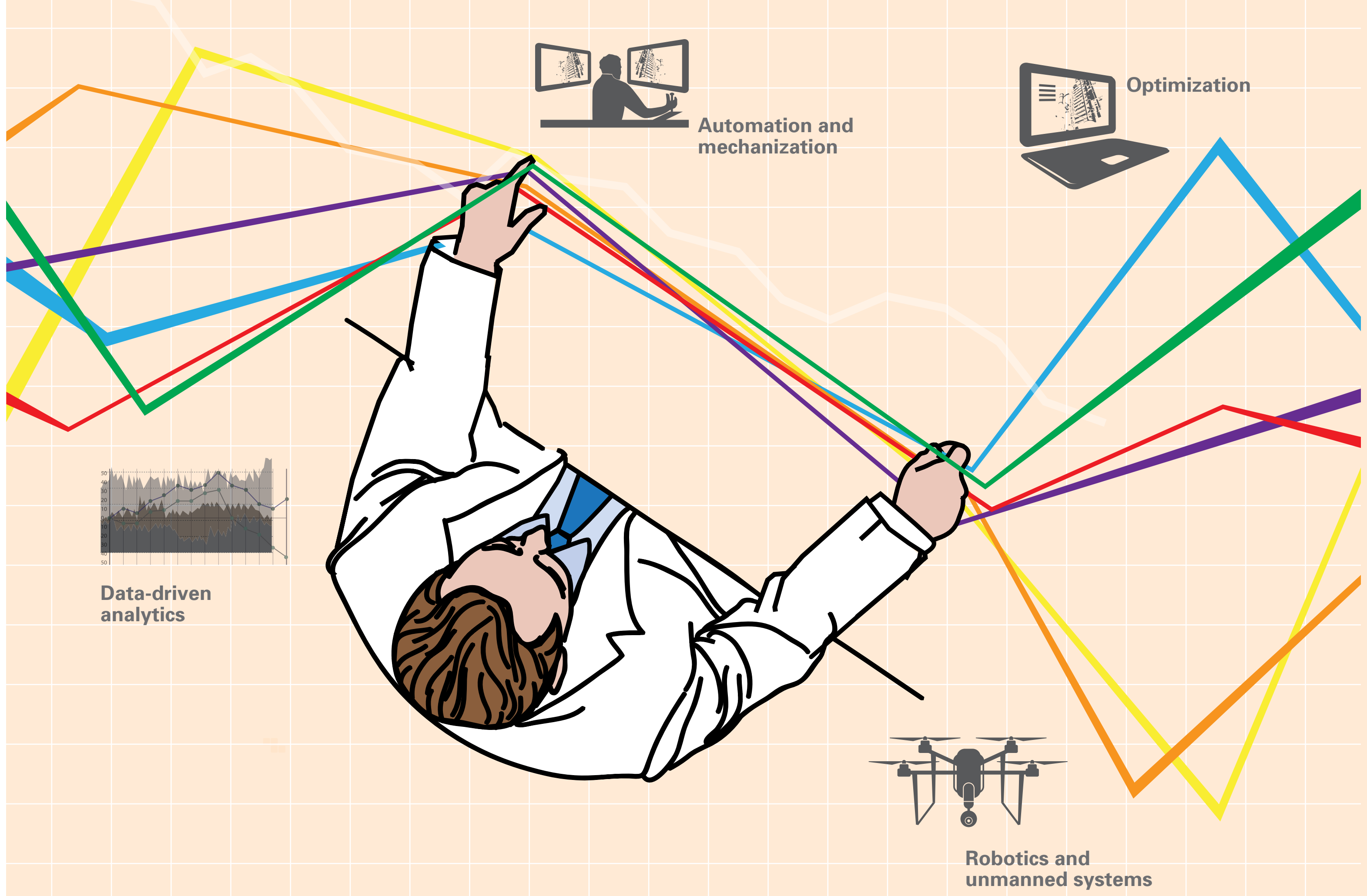


External perspective

Prioritizing technologies through the oil and gas price cycles

Oil and gas technology development is a long game. Producers must commit to unwavering innovation through the oil and gas price cycles if they are to meet demand safely and at competitive cost through to 2050 and beyond. Nevertheless, rapid changes in price – such as the halving of the oil price between 2014 and 2015 – naturally bring into focus the need for oil companies and their suppliers to reduce costs to maintain viable returns. Technology offers help on two fronts.

The first is in raising short-term production, the denominator in the cost-per-barrel equation. The other involves attacking capital costs and operating expenses head on. Both place an emphasis on efficiency.

A focus on efficiency is not new to the oil and gas sector, but IHS Energy observes that until recently it has been limited to select industry 'pockets of excellence'. One such pocket has been the exploitation of shale gas and tight oil resources. Their phenomenal growth since the late 2000s can be attributed largely to continuous improvements in manufacturing-style drilling and well-completion technologies and techniques. In the lower-oil-price environment post-2014, producers need to mirror such improvements across their broader portfolios. The resulting areas of active technology development that aim to deliver on these expectations include:

- Automation and mechanization – automating high-cost, repetitive oil and gas activities. Drilling automation is an opportunity area that is attracting significant research and development attention.
- Data-driven analytics – leveraging the 'big data revolution' to develop solutions that draw key insights from high-volume data streams, such as detecting when a piece of equipment is going to fail or identifying 'sweet spots' in unconventional oil and gas plays.
- Robotics and unmanned systems – adapting technologies developed in the defence and manufacturing sectors to oil and gas operating environments. Applications include deploying robots to inspect difficult-to-access elements such as offshore risers, and piloting unmanned aerial systems into areas that are dangerous for human intervention.
- Optimization – applying sophisticated modelling and simulation tools to increase production regularity and run equipment and facilities closer to their designed capacities.

A common thread running through these areas is the increasingly critical and enabling role of digital technologies. Evidence analysed by IHS Energy in the past decade confirms that digital technologies applied in practice can improve oilfield performance on several fronts, including:

- Increasing oil and gas production by 2–8%.
- Reducing facility capital costs by 1–3%.
- Lowering operating costs by 5–25%.

The new emphasis on efficiency places high demands on a digital infrastructure that is able to collect, transmit, analyse and act on data acquired throughout asset operations. It is also setting oil and gas companies on the path to becoming true digital organizations, thereby accelerating a movement that was already under way. More broadly, a host of upstream technology innovations – seismic imaging, drilling, engineering, enhanced oil recovery, digital technologies – will help to unlock oil and gas resources; however, the industry will need to be nimble to prioritize different technology elements throughout the price cycle.

2.1 Conversion and end use

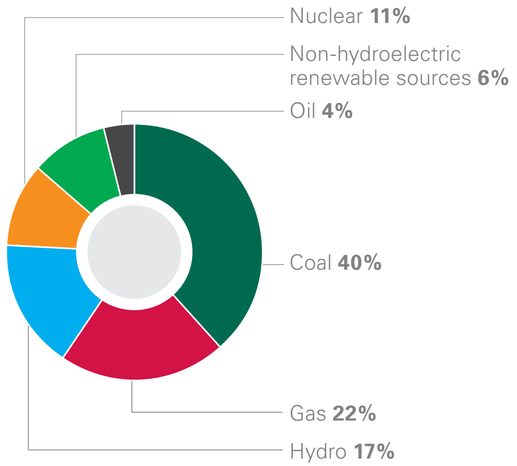
The continued growth in energy demand, particularly in non-OECD countries, provides the backdrop for the changes in primary energy conversion and use. In the future, new extraction, conversion and consumption technologies – at times encouraged by government policies – will compete with more established power generation and transport fuels production pathways. This competition is likely to result in some market volatility and disruption for incumbents.

In the following section, we focus on the electricity generation and transportation sectors, which together accounted for approximately 61%[1] of the world's primary energy consumption in 2014. We have placed less emphasis on the heat sector, which accounts for around 50%[1] of global final energy demand today, delivered either:

- Directly through the combustion of fossil fuels and biomass, or from natural sources such as solar and geothermal.
- Indirectly by electricity or through the recovery of waste heat from combustion.

In the US, for example, nearly 70%[2] of heating demand is met directly by fossil fuels and nearly 30%[2] indirectly by electricity. Technologies that reduce the demand for heating, such as insulation, could have major impacts on the carbon footprint of heating in more mature economies, as more generally could heat supplied from lower-carbon sources, such as electrification combined with heat pumps. It is difficult to compete cost effectively with the sheer instantaneous scale of energy delivery of heating fed by

Sources of global electricity supply in 2014



Nuclear, non-hydroelectric renewable sources and hydro data is from *BP Statistical Review of World Energy 2015*. Oil, gas and coal data are estimated.

Source: BP.

[1] *IEA World Energy Outlook 2014.*

[2] US Department of Energy and US Energy Information Administration.

Consistent with historical trends, we would expect the costs of onshore wind and utility-scale solar PV to continue to decline at around **14%** and **24%** respectively per doubling of cumulative installed capacity.

natural gas systems. The future shape of the heat sector is likely to be influenced most by the relative costs of different feedstock options and policies that could jointly drive greater electrification of heating and decarbonization of the electricity sector.

The electricity generation sector

Current status

The electricity sector has long seen competition between different primary energy feedstocks and conversion technologies, with coal, gas, hydroelectric and nuclear each individually providing more than 15% of annual global electricity supply at any one time in the past 25 years. In 2014 approximately 90% of global electricity was supplied from these sources with a small, but growing 6% from non-hydroelectric renewable sources (predominantly bioenergy and onshore wind). Since 2010 global wind generation capacity has grown at an average rate of 17% per year reaching a total of 370 gigawatts (GW) by the end of 2014. A total of 40GW of new solar PV capacity was installed in 2014, almost as much as the cumulative amount installed up to 2010, to reach a total installed capacity of around 180GW at the end of 2014.

In recent years wind and solar PV installations have been the dominant form of new-build capacity additions in some regions of the world. Their impact on global electricity generation output, however, has been less significant than this growth might imply because of the intermittent nature of sunlight and wind. Consequently, the amount of electricity that can be generated for a given period from 1GW of wind or solar PV capacity is much lower than from 1GW of fossil-fuelled or nuclear generation.

Depending on the location and quality of the resource, for any given year, average utilization levels are likely to range from 20% to 50% for onshore wind and 10% to 25% for solar PV. Despite these relatively low levels of potential generation and the recent economic downturn placing pressure on the public finances, which have been needed to subsidize and incentivize their deployment, wind and solar have grown significantly, albeit starting from a low base.

Electricity generation technology cost trends

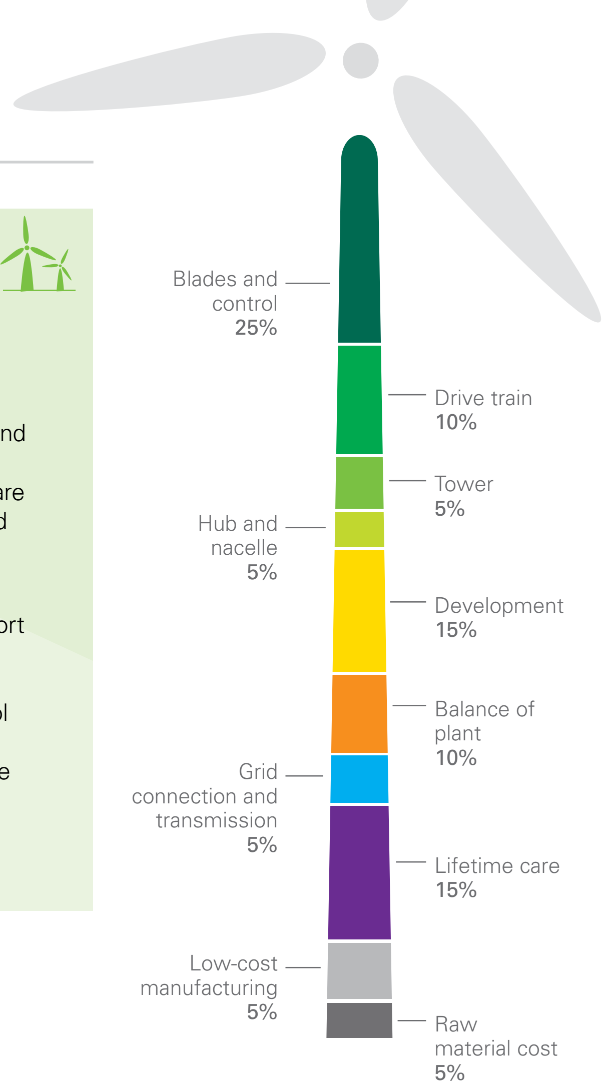
Incremental improvements in technology have continued to feature across most conventional electricity generating technologies. For instance, in the past decade or so, there have been incremental advances in combined-cycle gas turbine (CCGT) power-plant design that have taken conversion efficiency from approximately 50% to 53%, on a higher-heating-value basis. The recent growth of wind and solar PV capacity has been driven by technology advances and economies of scale. Consistent with historical trends, we would expect the costs of onshore wind and utility-scale solar PV to continue to decline at around 14% and 24% respectively per doubling of cumulative installed capacity. This shows how the costs of small modules, such as onshore wind turbines, batteries or solar cells, can decline much faster than those of large capital intensive modules, such as nuclear or CCS. However, such developments themselves would also benefit from economies of scale and mature, extensive supply chains, albeit to a lesser extent.

Onshore wind technologies

Technology advances in onshore wind, such as increasing tower heights, longer rotor blades, improved site optimization and increased turbine efficiency, have led to improvements in recent years in resource capture. For instance, increasing the height of towers to accommodate 50-metre-diameter rotor blades, in average wind speeds of 7.5 metres/second, has increased the amount of wind energy captured by approximately 20%. Turbines with 50-metre-diameter blades and larger rotors accounted for more than 80% of installed capacity in the US in 2014, compared with 50% in 2012 and less than 10% in 2009. Advances such as these are contributing to significant reductions in the levelized cost of electricity for new-build onshore wind.

Continued advances in onshore wind technology are expected to occur across a range of elements such as ground base and structure design technologies to support taller towers, and new materials and manufacturing processes to further increase blade sizes and reduce failures at higher loads. Improved blade designs will enable construction of larger-scale components, with developments in sensors and control systems enabling active aerodynamic control throughout the blade length. Better drive design and improved gearbox reliability, together with prognostic maintenance systems, predictive technologies and active control systems, will further increase turbine reliability and efficiency. In short, significant scope remains for wind technology to improve performance and reduce costs.

Areas of opportunity for cost reduction in onshore wind turbine technology



Source: BP.

Solar PV and onshore wind are two technologies that are destined to play an increasingly important role in the future.

Operators assembling a turbine rotor at ground-level, before it is lifted on to the tower at the Cedar Creek Wind Farm in Weld County, Colorado, US.

Cooling towers of a nuclear power plant, Clay Station, California, US.

Increasing contribution from intermittent renewable generation

For electricity, it is imperative that supply and demand are constantly matched within very narrow operational parameters. Unplanned or sudden deviations (intermittency) in electricity supply or demand have been an ever-present challenge for power-system planners and operators seeking to maintain system stability and 'keep the lights on'.

The frequency and magnitude of intermittency, however, has grown with the addition of some renewable sources of electricity generation, particularly wind and solar PV in recent years. Although no generating asset will ever be 100% reliable, gas, coal, nuclear, biomass, geothermal and some forms of hydroelectric plant are considered sufficiently reliable (at rates higher than 80% availability) to be deemed firm (dependable) and therefore able to provide baseload generating capacity.

Assuming current levels of system flexibility, some power systems may be able to accommodate 25–50% intermittent renewable electricity penetration. Beyond this level, or if current levels of system flexibility are not maintained, the increased penetration of intermittent sources of electricity generation will create challenges for the continued stable operation of electricity networks, and will result in greater curtailment and/or other mechanisms for managing 'over-generation'.

The incremental cost of integrating intermittent generation such as wind and solar into electricity systems, which increases as greater volumes are connected to the grid, is generally not included when considering their respective investment economics. It is a highly complex variable that depends on factors such as generation and demand profiles, the scale and variety of the installed generation base (including the reserve margin) and the levels of flexibility and reliability inherent in any given network.

To manage intermittency, there are essentially four technology-based options:

1. Increased connectivity and integration of transmission and distribution grids.
2. Flexible generation (typically fossil fuelled).
3. Electricity storage.
4. Demand response (smart grids).

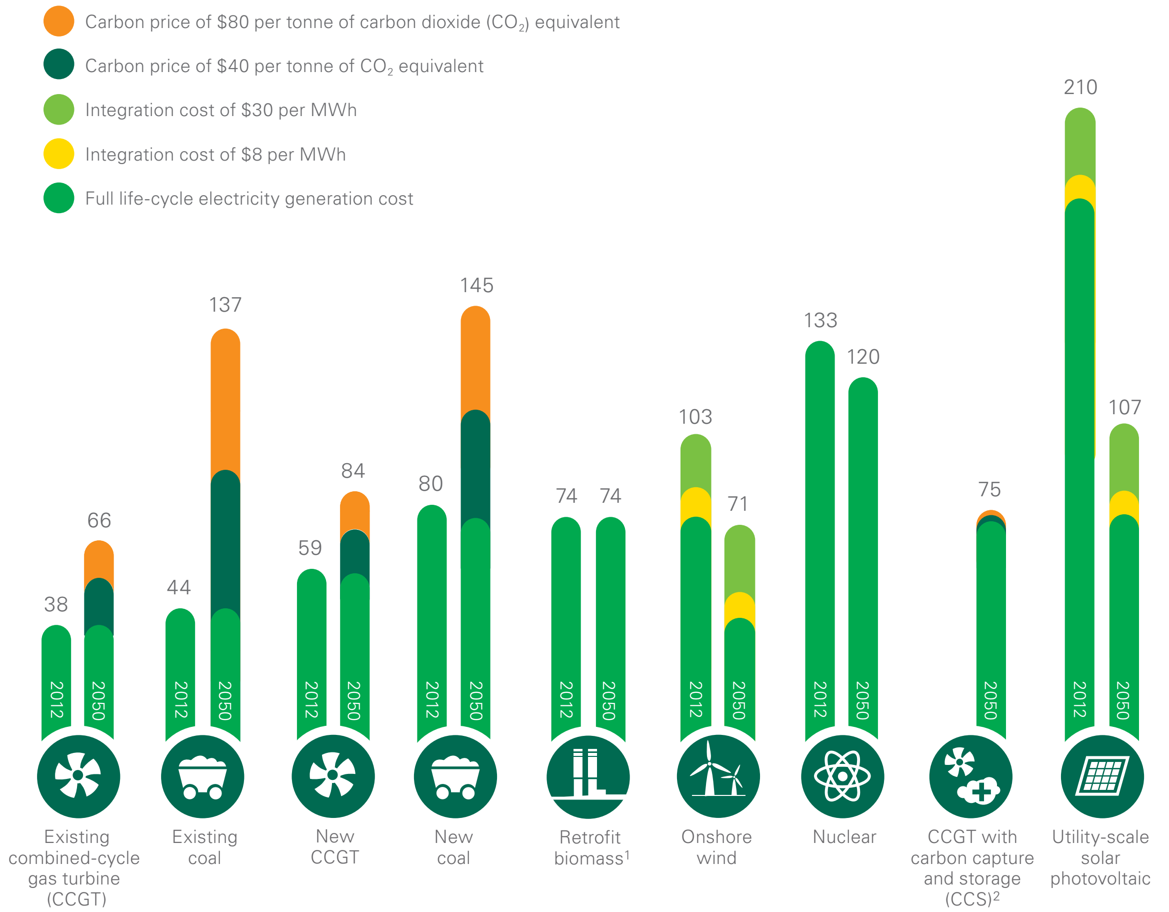
The last two are largely nascent and currently expensive. Flexible generation offers the most immediate solution to intermittency in many countries.

We estimate that grid integration costs could range from $8 for each megawatt hour (MWh), supplied by the intermittent generator in a mature, no-growth system with established reserve capacity and existing increasingly under-utilized flexible plants providing backup, to $30/MWh for a growing system with new flexible gas-fired plants built to provide backup. Gas-fired single-cycle gas turbines (SCGT) generally provide one of the most economically viable and immediate options since they are highly responsive and have low construction and fixed costs. These are important considerations when building plants that will have low operating hours – and can be deployed quickly and at scale. Integration costs are likely to be even higher if intermittent renewables provide the major share of electricity production.

Looking at the medium to long term, system operators will be able to source some of the balancing services, required to manage intermittency, by deploying smart grids enabling greater and more immediate demand response. In the short term, however, these are a more expensive proposition than sources such as flexible generation that are readily available today.

Levelized cost of electricity in North America to 2050

The costs shown in the chart are our expected case in 2012 US dollars.
$ per megawatt hour (MWh)



Power sourced from gas or coal will remain the lowest cost without a carbon tax or price.

Renewable power costs will continue declining.

[1] Reconfigure coal power plant to biomass power plant.

[2] Because, in 2012, there were no commercial-scale CCS plants we have not included a cost profile for 2012. Zero cost is assumed for CO_2 transportation and storage, because storing CO_2 could have both a net cost (in case of standard CO_2 storage) or a net value (when CO_2 is used for enhanced oil recovery).

Not shown are niche technology options such as geothermal, and even higher-cost renewable options such as concentrated solar thermal, offshore wind, engineered geothermal systems, wave, tidal or ocean thermal power.

Values for coal of $80/tonne, gas of $5/mmBtu and pelletized biomass of $80/tonne have been used for consistency. Weighted Average Cost of Capital (WACC) = 10%.
All assessments exclude incentives and special provisions.

Source: BP.

We see **conventional gas and coal remaining the lowest-cost options for generating electricity in North America** and most other regions through to 2050, although it would only take a modest carbon price (~$40/tonne of CO_2) for new-build gas and increasingly lower-cost renewables to displace existing coal.

Electricity generation technology cost projections

Public policy measures can vary the cost of electricity generated from power plants by requiring the adoption of emission control technologies or imposing a cost on emissions such as CO_2 via a carbon tax or emissions trading system. These favour the substitution of higher-carbon options with lower-carbon ones – such as renewables for fossil fuel or natural gas for coal in the fossil-fuel sector. Other public policy measures, including subsidizing lower-carbon technologies such as wind, solar PV and nuclear, can make them cost competitive. The cost assessments in this publication do not include any incentives or special provisions for any technology, but do include grid integration costs (ranging between $8/MWh and $30/MWh) to facilitate a fairer comparison. Solar PV and wind are particularly sensitive to the quality of their primary energy resource and capital expenditure costs, leading to higher uncertainty with their projections.

We see conventional gas (excluding imported liquefied natural gas) and coal remaining the lowest-cost options for generating electricity in North America and most other regions through to 2050, although it would only take a modest carbon price (~$40/tonne of CO_2) for new-build gas and increasingly lower-cost renewables to displace existing coal. In North America, new-build onshore wind farms have the potential to provide energy at less than $50/MWh but would require flexible back-up generation, such as gas-fired power, in times of low wind and/or high demand.

With a higher carbon price, natural gas is increasingly advantaged over coal. Without a carbon price and excluding CO_2 transportation and storage costs, adding CCS to coal and CCGT plants would increase the cost of generation by $25/MWh and $16/MWh respectively by 2050. However, a higher carbon price makes CCS increasingly competitive and consistently lower cost than nuclear, especially when used with natural gas, as illustrated for North America. Although CCS is a nascent option, it could provide flexible, dependable and near zero-carbon generation at costs lower than many renewable generation options.

Jenny Chase
Solar Analyst,
Bloomberg New Energy Finance (BNEF)

External perspective

Major savings through new energy technologies

Solar PV and onshore wind will become increasingly attractive as the cost of production reduces through improved technology.

The major changes in power in the next 40 years are likely to be in energy storage and integration technologies, whereas the changes in the past 10 years have been about decreases in wind and solar photovoltaic (PV) costs.

Solar PV, in particular, has become cheaper, with PV modules priced around $0.60/W in 2015 compared with $4.49/W in 2005 (in 2014 dollars). This has been mainly driven by the establishment of special factories for solar-grade silicon, thinner wafers, better-shaped busbars for higher efficiency and numerous other incremental tweaks. These will continue to reduce costs to $0.21/W by 2040, even if there are no dramatic breakthroughs (such as perovskites adding a second active layer to the cell). Balance of plant, engineering, control and monitoring system costs will also come down.

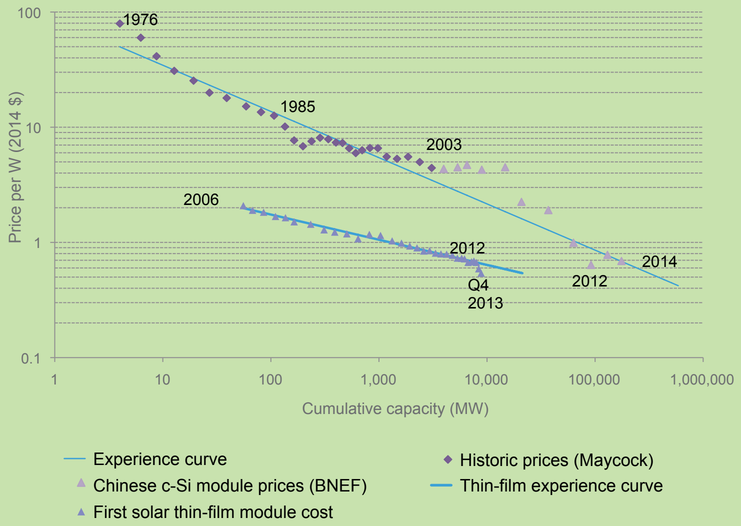
In wind, the story is similar, with both capital expenditure reductions and performance improvements, including lighter materials, improved aerodynamic control, better operation and maintenance strategies, and site-specific turbine design. When combined, these factors will contribute to a fall in the cost of wind from about $100/MWh in 2000 to about $60/MWh in 2015.

Solar PV and onshore wind generation costs now begin to be attractive at a system level for power infrastructure planners, even though provision must be made to manage intermittency, for example, by running fossil-fuel plants at low utilization and by having the means to curtail renewable generators when necessary to avoid damage to the grid.

Consequently, solar PV and onshore wind generation costs are not directly comparable with the generation cost from fossil fuels and, in most places, intermittent generation will carry a discount.

BNEF expects the average cost of residential stationary energy storage systems to fall from $1,600/kWh in 2015 to below $1,000/kWh in 2020 and $260/kWh in 2040. Although there are products currently below this price point, these are not yet on the market and are currently subject to supply constraints.

The silicon PV experience curve



Source: Maycock, Bloomberg New Energy Finance.

Liquid fuels, including biofuels, will continue to dominate the transportation market.

The transport sector

Fuels production

Global demand for energy for transport is likely to be met largely by liquid fuels. Crude oil will be abundant enough to sustain refining as the major source of transport fuels and will offer low feedstock and conversion costs. A few alternative pathways may compete, such as sugar cane ethanol, but most other pathways will need major advances.

Consumption of energy in the transport sector is expected to continue growing at approximately 1% per year in the coming decades, although it will slow after 2025. The growth comes primarily from non-OECD countries due to a rapid increase in vehicle ownership there. This is expected to be partly offset by a decline in OECD demand, caused by vehicle efficiency improvements outpacing slower growth in the size of the vehicle fleet.

Refining, coal- and gas-to-liquids (CTL and GTL) and biofuels production are the key fuel conversion pathways. Raw materials (or feedstocks), plant, infrastructure and operating costs play out differently in each of these pathways.

Raw materials' costs typically represent 70–80% of refining production costs, so efficiencies in operations and capital expenditure, while valuable, will have less impact on overall fuel production costs. Although refining technology is relatively mature, we expect that incremental improvements in refinery efficiencies will continue to be made through the development of conventional technology and new-build refineries or major upgrades, resulting in higher efficiency. Refineries will have to adapt to changes in crude composition and impurity levels (nitrogen and sulphur compounds or metals, for example) that have an impact on processing. In addition, research into new vehicle engine technologies may encourage changes in fuel quality, such as higher-octane gasoline.

The implementation of GTL technologies, which make liquid fuels and chemicals from natural gas, may be spurred by the abundance of shale gas in North America. Current GTL Fischer–Tropsch technology using natural gas at $3–4/mmBtu will compete today with conventional refining using crude at $80/per barrel (bbl).

Compared with crude oil and liquid products, natural gas is much more difficult to transport over long distances, creating niche opportunities for liquids production using low-cost gas from stranded fields.

Today, production cost is one of the factors limiting biofuels penetration into the transport fuel market, although some pathways have the technical potential to be competitive. Brazilian sugar cane ethanol can already compete economically with fossil fuels, but other types of bioethanol currently rely on government support. Corn milling and fermentation technologies are mature (there are more than 150 plants in the US alone) so they have limited scope to improve manufacturing yields and operating costs. Roughly half to two-thirds of the production cost is due to the price of corn, although this may be partly offset by co-products such as animal feed.The cost of transporting raw biomass is significant. With biomass logistics often constraining the scale of biomass conversion facilities, achieving economies of scale becomes critical.

Liquid fuel production cost in North America to 2050

The costs shown in the chart are our expected case in 2012 US dollars.
$ per gigajoule

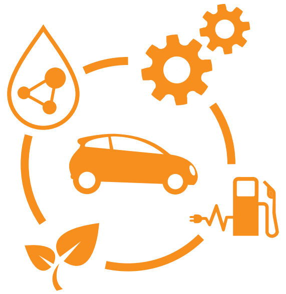
Values for oil of $80/bbl Brent, gas of $5/mmBtu, pelletized biomass of $80/tonne and sugar cane of $33/tonne have been used for consistency. Energy grass for LC ethanol declines from $73/tonne to $44/tonne over the period. 10% cost of capital for fixed-asset investments. No taxes or subsidies included.

Source: BP.

Brazilian sugar cane is forecast to remain the lowest-cost fuel to 2050, even with a carbon price applied.

Lignocellulosic (LC) ethanol is the most expensive fuel today, but with technology advances could be cheaper than corn ethanol in the 2050 timescale.

Biomass-to-liquids have few opportunities to reduce costs and look to remain uncompetitive.



Technologies for creating a more efficient, less energy intensive vehicle fleet include hybrid vehicles, and advanced fuels and lubricants.

The cost of producing LC ethanol, which is derived from the de-polymerization and fermentation of energy grasses, wood or agricultural residues, is around double that of diesel and gasoline when crude oil is at $80/bbl. To achieve cost parity on an energy basis with fossil fuels in the US and other temperate regions, cellulosic biofuels are likely to need policy support for at least a decade or more.

There is, however, significant potential to improve. In particular, better pre-treatment and enzymes can improve LC operating costs and ethanol yields. Today, the cost of raw materials represents about one-quarter to one-third of the total cost of production, depending on local conditions and including the value of co-products. Improving the yield reduces the feedstock element of the ethanol production cost and also reduces the size of equipment needed and hence capital expenditure. In part, the long-term economics depend on technology development, but will also be influenced by improvements arising through experience from developed commercial-scale LC operations.

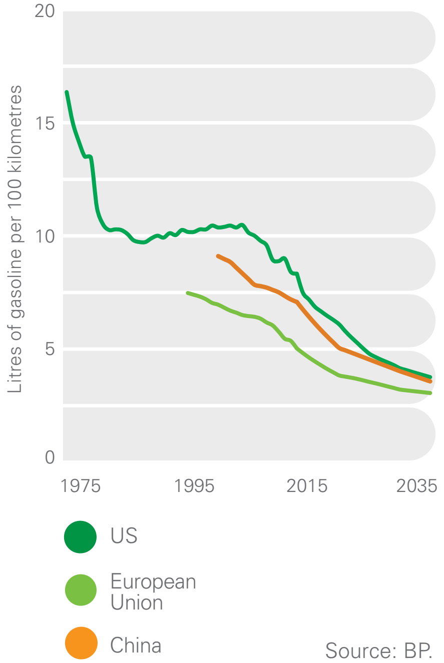
Alternative bio-molecules, such as bio-butanol, provide an option to increase the renewable energy content in fuel blends. Most gasoline vehicles manufactured to date have a 10% limit on the amount of ethanol that can be present in the gasoline they use. A 16% bio-butanol gasoline blend would be compatible with these vehicles and double the renewable energy content, helping to transition the ethanol *'blendwall'*.

Transport vehicles

Demand for personal mobility is growing rapidly in the developing world, but slowing in OECD countries as the market saturates. Vehicles with internal combustion engines (ICEs) offer a range of reliable choices to the consumer. Refined fuels from oil serve most of the road transportation energy demand worldwide, with some exceptions such as ethanol in Brazil and the US, and natural gas where available locally at low cost, such as in Argentina, Bangladesh, Egypt and Pakistan.

Vehicles powered by liquid fuels, including biofuels, are likely to dominate global sales through to 2035 and beyond. We expect the average efficiency of new light-duty vehicles offered to the market to improve by 2–3% per year as a result of increased hybridization and improved powertrains combined with advanced fuels and lubricants. Liquefied natural gas (LNG) could displace diesel from some of the heavy-duty market, with compressed natural gas (CNG) increasing its share of the light-duty vehicle market in regions with low-cost natural gas and policy support.

Fuel economy of new car fleet



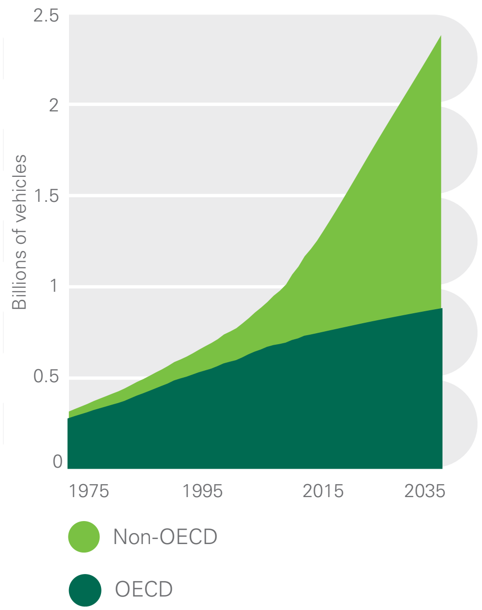
Source: BP.

Vehicles powered by liquid fuels, including biofuels, are likely to dominate global sales through to 2035.

Technicians preparing a car for fuel economy testing at BP's Technology Centre in Bochum, Germany.

Vehicle refuelling at BP service station, Chicago, Illinois, US.

Global vehicle fleet



Source: *BP Energy Outlook 2035.*

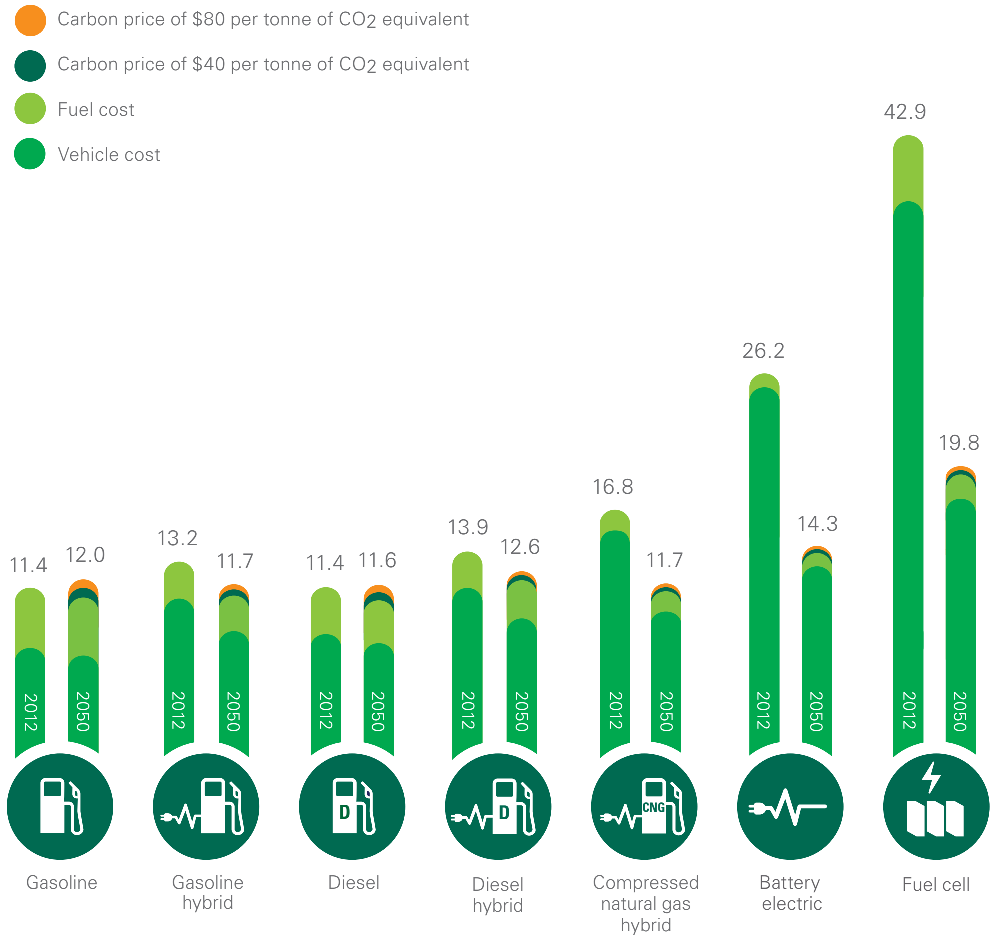
Vehicle technologies such as direct fuel injection, engine downsizing and turbocharging, as well as the use of advanced fuels and lubricants, are boosting the effectiveness and efficiency of the internal combustion engine. Such innovations mean that gasoline engines could approach the efficiency of diesel engines.

Advances in battery technology mean that electric vehicles are likely to be a viable future option, especially in urban environments where stop–start driving is typical. Hybrid vehicles are becoming available at more modest costs and, although electric vehicle batteries remain relatively expensive, technology advances and economies of scale are likely to reduce their costs over the next two to three decades. Life-cycle emissions from electric vehicles vary as the electricity used may come from renewables and nuclear power, or from fossil energy such as coal or gas-fired power stations. In regions where coal is the primary source of power generation, the overall emissions associated with electric vehicles can exceed those of diesel or non-plug-in hybrid vehicles.

As their only tailpipe emission is water, fuel-cell vehicles running on hydrogen provide local environmental benefits. However, steam methane reforming, which generates CO_2 emissions, is currently the main route to making hydrogen. Toyota and Hyundai have already launched fuel-cell vehicles in certain markets, and some other Original Equipment Manufacturers (OEMs) plan launches soon. Several OEMs have also built up their capability in fuel cell technology. However, given the technical, hydrogen production, storage and refuelling infrastructure challenges, as well as the relative vehicle costs (see opposite), it is unlikely that significant adoption of these vehicles will take place in the immediate future.

Technical potential of transport vehicles to 2050

Medium-sized passenger vehicle cost (in 2012 US cents per km).



Vehicle cost per kilometre (km) is based on North America average distance travelled of ~194,000km over the vehicle life. Fuel cost includes a 10% weighted average cost of capital for fuel production plant with nominal oil and gas prices of $80/bbl and $5/mmbtu. Vehicle and fuel costs do not include taxes or sales margins.

Source: BP.

The internal combustion-based vehicles have very similar cost profiles due in large part to a trade-off between fuel and vehicle cost, and there is little to choose between them on a lifetime-cost basis.

Currently, electric vehicles cannot compete on cost but, if the overall vehicle cost can reduce by about 50% over time, they will start to become economically competitive.

Fuel-cell vehicles are currently about four times the cost of a conventional vehicle. Very significant technical progress, as well as an economic hydrogen infrastructure, is required for them to become cost competitive.

The gains in future vehicle efficiency will be driven by a shift in vehicle fleet mix toward more fuel-efficient powertrains, including manufacture of cars with powertrains other than those shown in the figure, which may have powertrain additions (for example, turbocharging) and/or combinations (for example, plug-in hybrids).

Andreas Schamel
Director Global Powertrain,
Research and Advanced Engineering, Ford Motor Company

External perspective

The continuing evolution of automotive technology

Over many years technology has transformed the design and manufacture of our everyday vehicles. There is more computing power in the average car today than there was in the Apollo 11 space craft when it landed on the moon in 1969.

Advances in design, engineering, computing, materials, engine efficiency, fuels and lubricants have greatly improved vehicle reliability, safety and performance while progressively reducing environmental impact.

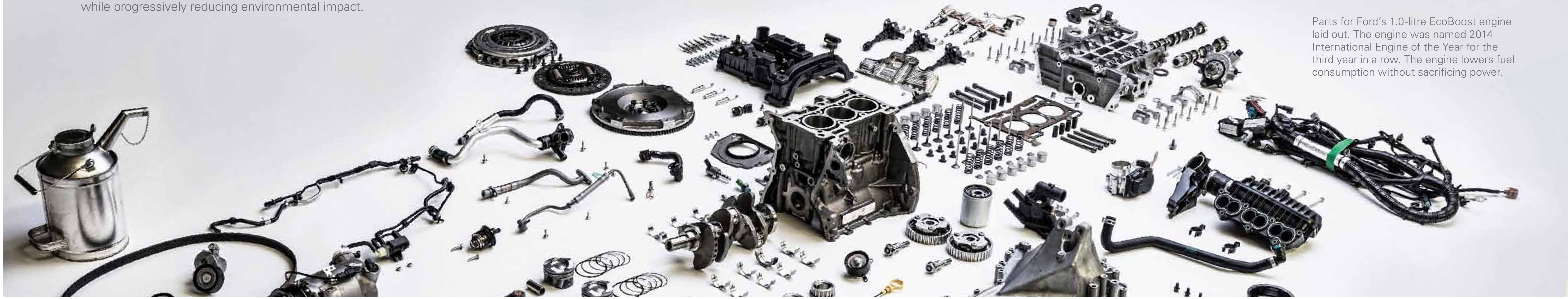
There is no sign of the pace of technological change slowing in the automotive market. So, what technologies might come to the fore in the face of growing customer demand, the need for cost competitiveness and increasing environmental requirements?

For the past 100 years, the internal combustion engine has dominated car manufacturing. It is easy to see why, with the availability of large quantities of relatively cheap oil, combined with the simplicity of the chemical reaction involved. Continuing advances in engines, fuels and lubricants – such as boosting and injection technologies, as well as in-air flow management – are in development and could deliver significant improvements in engine thermal efficiency.

Hybrid vehicles – of which there are already more than three million on US roads – are set to become more popular. The 'stop–start' applications in use now are basic levels of hybridization and we can see opportunities to develop that more. Hybrids still rely on efficient combustion engines. Pure electric and hydrogen fuel-cell vehicles offer alternative solutions, although they, too, have their challenges. Unlike a combustion engine, a battery must carry the fuel, the reactant and the waste product within it, resulting in limitations in a car's performance and travelling range. The other challenges are about fuel source – notably whether the electricity is produced from sustainable sources or from fossil fuels – and battery charging speed.

Hydrogen fuel-cell stacks are likely to be cost competitive with the internal combustion engine in the next five to 10 years, although their take-up will be affected by the overall vehicle cost, availability of supporting infrastructure and the original energy source used for hydrogen production.

Engines aside, next steps in computational technology could fundamentally change the way in which we drive. For example, the car that handles traffic jams on motorways and returns control to the driver once the jam clears, has already become a reality. Developments such as this predict a radically different driving environment to that we experience today, just as technology has revolutionized our experience of the automobile in the past 50 years.



Parts for Ford's 1.0-litre EcoBoost engine laid out. The engine was named 2014 International Engine of the Year for the third year in a row. The engine lowers fuel consumption without sacrificing power.

Key influences on energy technology

So far we have discussed current technologies and how they may develop in the future. The directions taken by energy technologies depend on many factors beyond technology and innovation alone. In particular, future outcomes may be influenced by increasing constraints related to natural resources and new possibilities from emerging technologies, many of them relevant to a range of industrial sectors.

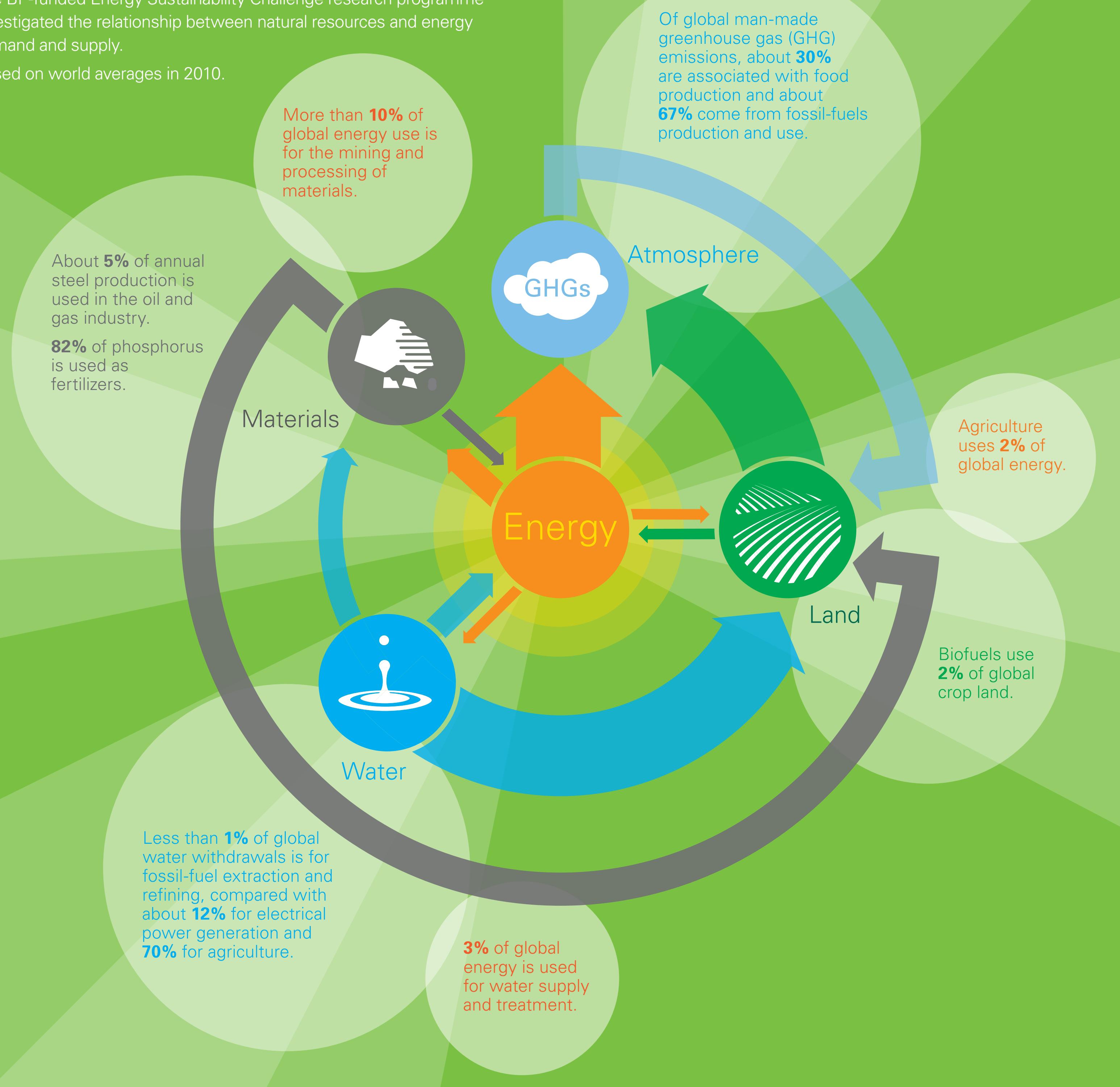
Diverse factors will shape the future technology landscape, influencing the direction of travel and the final destination.

Hsin-Chu City, Taiwan.

Energy and natural resources

The BP-funded Energy Sustainability Challenge research programme investigated the relationship between natural resources and energy demand and supply.

Based on world averages in 2010.



3.0 Natural resource constraints

Energy production and consumption result in GHG emissions and associated climate change – a truly global challenge. These processes also require the use of natural resources – water, land and minerals – with varying impacts around the world.

The energy technology choices we make can have a significant impact on the mix and scale of natural resources needed when producing and using energy.

For example, power plants need water for cooling, and oil production facilities need water for 'waterflooding' and other uses. However, the volume of water withdrawn or consumed varies enormously according to the processes being used. Similarly wide variations exist when considering the land, water and fertilizers used by bioenergy crops or the minerals underpinning solar PV energy, wind farms, electric motors and batteries.

Energy production results in GHG emissions. In 2010 emissions from fossil-fuel production and use accounted for about 67% of global man-made GHG emissions, much of the rest being from other activities such as agriculture and land use.

Increasing stresses on natural resources, driven by socio-economic and population growth, present major challenges to providing affordable energy sustainably. Scarcity of resources already creates significant issues in some regions of the world, while GHG emissions and associated climate change are a global problem.

Historical analysis of the relationship between growth and GHG emissions shows that a major shift will be required to decouple GHG emissions from continued economic and social development, particularly where development has been built on fossil energy.

Technology plays a vital role in managing natural resource constraints and making the transition to a lower-carbon future affordable and sustainable.

Impact of technology on cost of reducing CO_2 emissions today vs 2050

Emissions reduction in power is generally cheaper than in transport.

Continuous improvement in internal combustion engine cars will reduce emissions at low cost, but large-scale decarbonization can be achieved at a lower cost in the power sector.

In transport, technologies such as downsized gasoline engines and diesel powertrains are the most cost-effective options for reducing comparatively smaller amounts of CO_2.

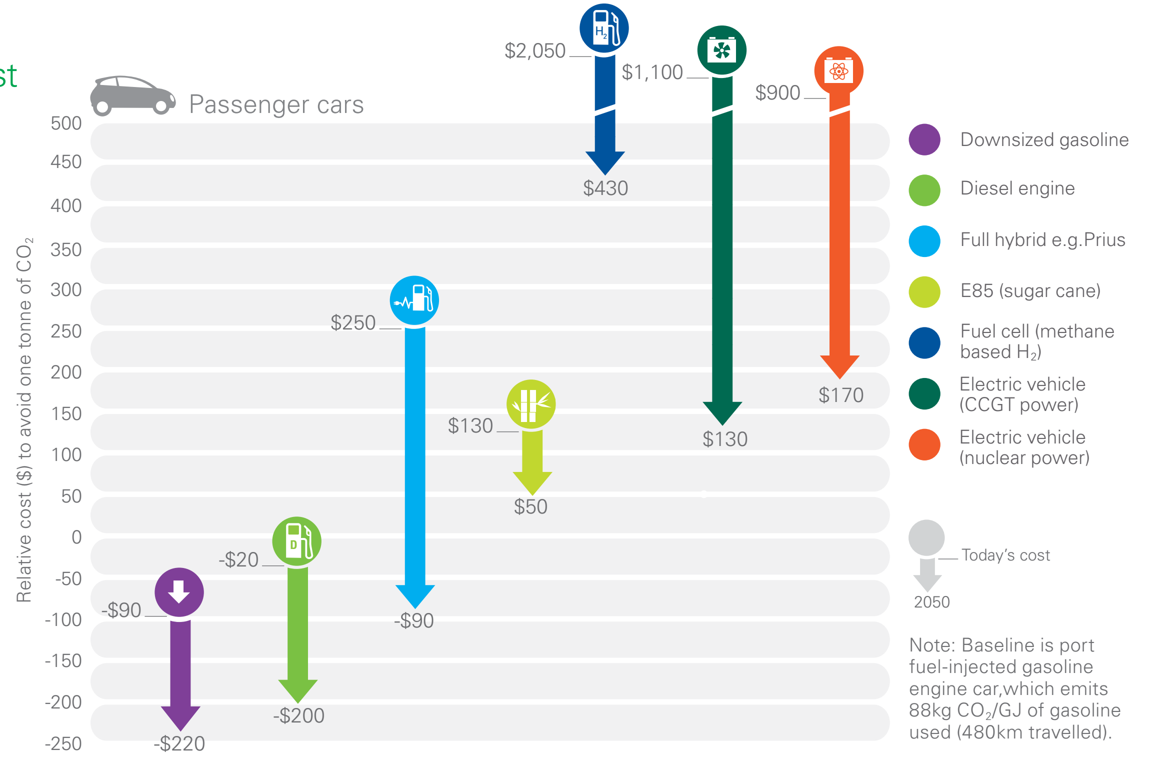
The cost to reduce CO_2 via electric and hydrogen fuel-cell vehicles is high, and will continue to be so, even with a rapid decrease in battery and fuel cell costs.

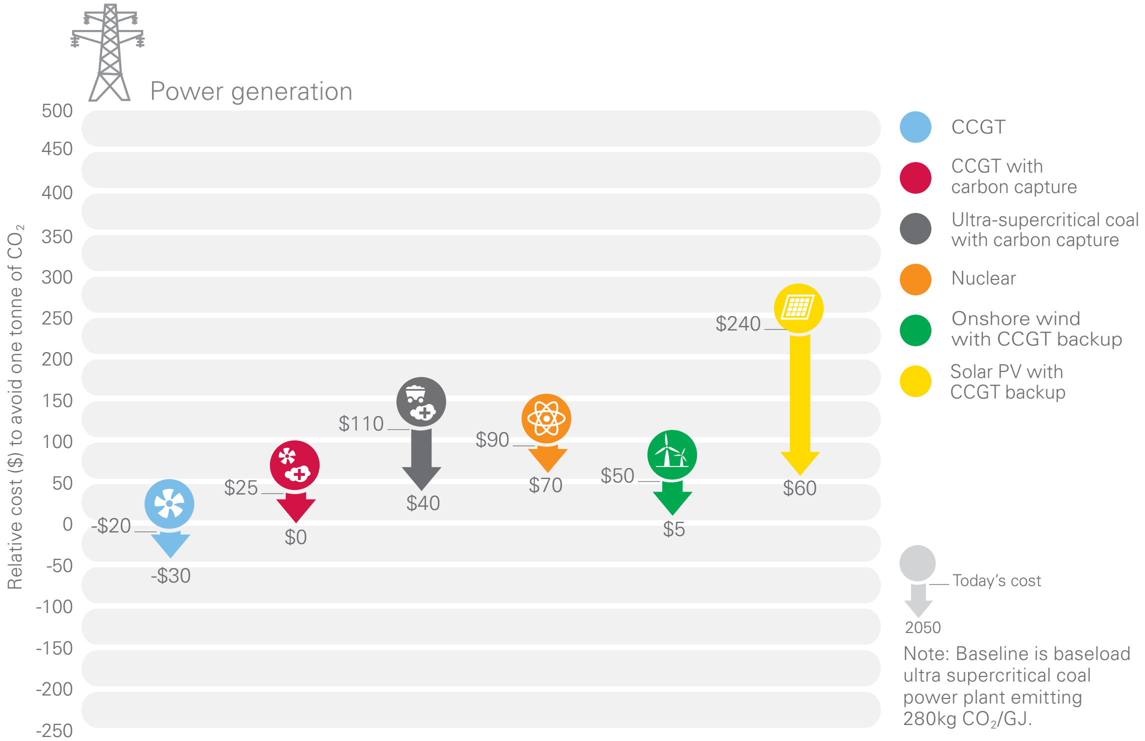
In power, new-build natural gas combined-cycle power plants already offer negative avoidance costs relative to ultra-supercritical coal power plants in North America. Reducing emissions by adding carbon capture and storage (CCS) to combined-cycle gas turbines (CCGT) appears low cost relative to the coal power plant, but the cost of CO_2 avoided increases to $140/tonne today comparing CCGT with and without CCS.

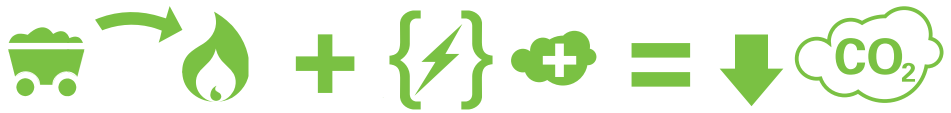
Intermittent wind and solar photovoltaic (PV) power require backup sources, which increase their cost and likely greenhouse gas footprints.

Assumptions: North America cost basis. 10% cost of capital for fixed-asset investments. No taxes or subsidies included. Values for oil of $80/bbl Brent, gas of $5/mmBtu and sugar cane of $33/tonne have been used for consistency. Emissions are on a 'well-to-wheel' basis.

Source: BP.







A global shift from coal to natural gas for power, improvements in energy efficiency and ultimately CCS technology could be key parts of the transition to a lower-carbon energy future.

Climate change

In *BP Energy Outlook 2035*, we project that GHG emissions from energy use will rise by 25% over the next two decades, mainly driven by increased energy consumption in emerging economies. Although the growth of emissions is expected to be less than that of energy demand as energy use becomes less carbon intensive, the projected rate of increase is still higher than the level that scientists and governments say would be needed to keep the global mean surface temperature rise within 2°C of pre-industrial levels during the twenty-first century.

An effective energy transition will require an increase in energy efficiency, while switching from higher- to lower-carbon-intensity sources. This involves GHG-mitigation technologies across the whole economic system (including food and construction sectors) and lower-carbon energy production deployed at scale. Energy companies have a vital role in providing and using energy competitively as well as finding the most flexible and lowest-cost routes to large-scale, lower-carbon energy production and energy efficiency.

Decarbonization can be achieved at lowest cost in the power sector. A global shift to natural-gas-fired power in place of coal, for example, represents a significant opportunity to create a bridge to a lower-carbon future.

CO_2 emissions per MWh from CCGTs are less than half those from modern coal-fired plants. To secure this benefit through the whole value chain, fugitive methane emissions from natural gas systems need to be monitored and managed. Gas is readily available in most parts of the world. For these reasons we project it will be the fastest-growing fossil fuel in the next two decades.

Nuclear power also provides a material option for the power sector to decarbonize with some national power systems, such as France, already close to being zero-carbon via a large nuclear contribution. In France, 73% of power comes from nuclear and the average electricity emissions factor of 70 grams of CO_2 per kWh is 85% lower than the global average. New-build nuclear power, however, is expected to face cost and acceptability challenges, such as those around safety, liabilities for decommissioning and the long-term storage of waste.

Renewables have the potential to make a large impact in the medium to longer term. Taking into account a modest carbon price and costs for grid integration, they are likely to become competitive against coal, but require backup, for example, from gas-fired power in North America.

The costs of GHG-mitigation technologies such as CCS are likely to fall. However, even following a prolonged period of dedicated support for CCS demonstration, we believe a sustained carbon price of at least $100/tonne is needed for it to be competitive for the majority of power stations and industrial plants where large amounts of CO_2 would otherwise be emitted to the atmosphere. Exceptions are the rare instances where industrial plants have particularly highly concentrated CO_2 streams and where projects can be linked to local EOR initiatives.

12%

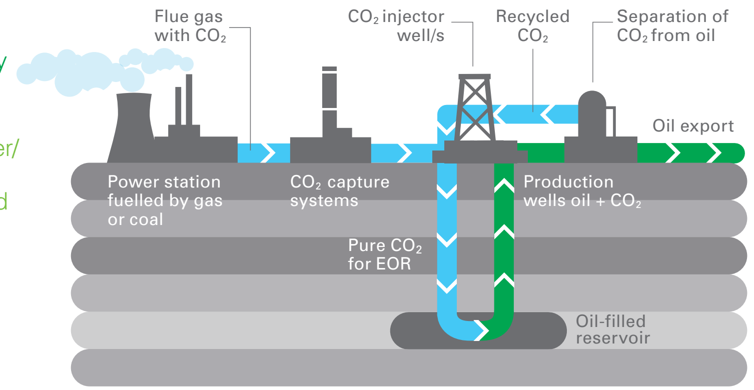
Only about **12%** of primary energy captured at source ends up as useful heat, light and motion.

Recharging an electric vehicle.

In Salah Gas operators at the Krechba, Algeria, gas field, where approximately 4 million tonnes of CO_2 has been captured and injected between 2004 and 2011.

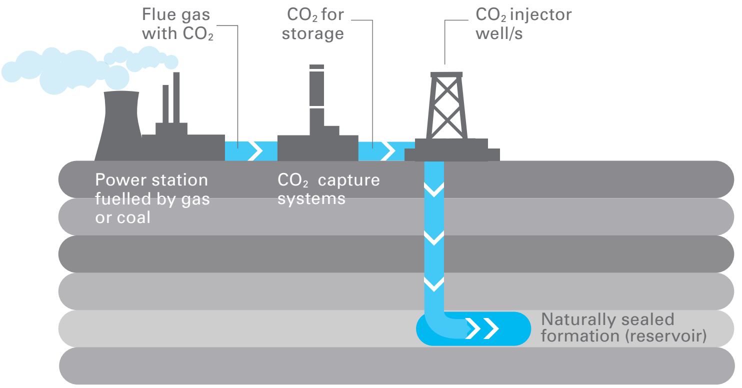
Carbon capture and storage (CCS) and enhanced oil recovery (EOR)

Carbon dioxide (CO_2) emissions from power/ industry mitigated by capture, transport and injection for EOR.



CCS only

CO_2 emissions from power/industry mitigated by capture, transport and injection in geological storage.



Energy efficiency provides many of the most affordable and practical means to reduce GHG emissions in the near term. Today only about 12% of global primary energy captured at source ends up as useful heat, light and motion. Wide-scale implementation of energy-efficiency technologies that could render the entire energy system more efficient would:

- Increase affordability (by using less energy).
- Support energy security (by reducing import dependence).
- Help sustainability (by reducing emissions).

In many cases this could be achieved cost effectively. As such, energy efficiency can be seen as being 'good for all seasons'. In commercial and residential buildings, for example, where energy consumption is forecast to grow rapidly, many opportunities exist for improved design and more efficient energy use, which could reduce energy demand.

Better product design could also substantially reduce carbon emissions. For example, despite the global vehicle fleet potentially doubling in size over the next 20 years, fuel demand is only predicted to rise by 29%, driven mainly by more efficient fuel and transportation technologies adopted by the market. Tailpipe emissions of CO_2 have fallen in many countries in the past decade and government targets exist to continue this downward trajectory. Measures that promote more efficient use of products, such as raising awareness about energy efficiency or more innovative approaches such as vehicle sharing and dynamic road management systems, also have a role to play in minimizing consumption and reducing emissions.

Efficient powertrain technologies and internal combustion engines that use lower-carbon biofuels offer a particularly cost-effective pathway to a lower-carbon future. Electric and plug-in hybrid vehicles may provide an increasingly common route to emissions reduction, providing the power sector is decarbonized in parallel. Our current projections suggest that combined hybrid and battery electric vehicle sales will grow from approximately 2% of global vehicle sales in 2014 to approximately 10% in 2025. However, even full-battery electric vehicles are not emissions free and significant technological advances are required to make them more affordable and extend their range.

Industrialization and urbanization are making air quality an increasingly important issue for public health. Since 1950 the global urban population has increased fivefold, and is expected to increase by another 60% by 2050, when about 6.3 billion people are projected to live in urban settlements. In China, rapid urbanization of the population has been accompanied by the growing use of cars for personal transport, and coal for home heating and power generation.

Compared with natural gas, combustion of these fuels releases higher amounts of compounds and particulates that have adverse impacts on human health. A shift from coal to gas for power and to higher-efficiency engines and more advanced fuels in the transportation sector could substantially cut emissions of harmful particulate matters, and sulphur and nitrogen oxides.

Professor Rob Socolow
Co-Director of The Carbon Mitigation Initiative, Princeton University (New Jersey, US)

External perspective

What's the price of atmospheric CO_2?

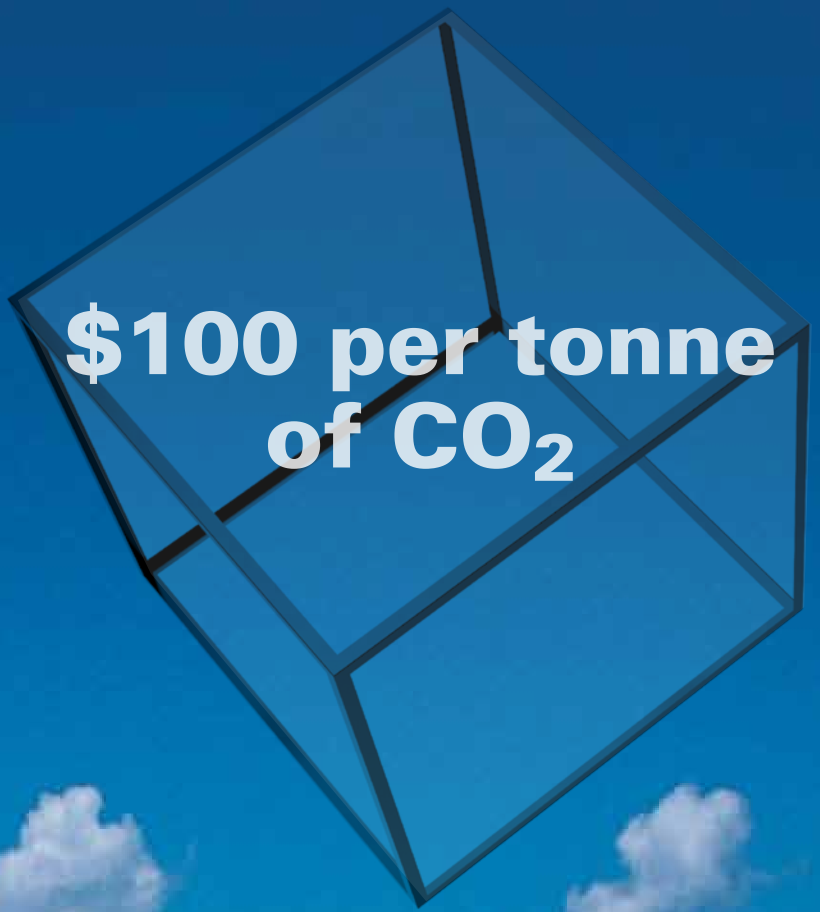
All aspects of the flow of carbon through the global economy will be affected by policies that embed a concern for climate change. At the extraction stage, the carbon in coal, oil and gas will be monitored and many relatively low-cost opportunities to reduce associated atmospheric CO_2 emissions will emerge, such as avoiding methane leakage and gas flaring.

Major investments will shrink the carbon footprints of networks that move energy by pipeline, rail, ship and electric power line. A new network may be added that moves CO_2 from sites of capture, such as refineries, cement and power plants, to sites of use, such as for enhanced oil recovery or safe permanent storage in saline aquifers.

Gas will gain on coal, and carbon capture and storage with coal and gas power may become viable. On average today in industrialized countries, 70% of the electricity leaving a power plant is consumed in a residential or commercial building, so decarbonization will be further achieved by investments that create efficiencies in heating, cooling, lighting and appliances.

New technology will enable all of these responses. To stimulate the technological imagination, it is useful to think through how various industries would respond to a significant economy-wide price on atmospheric CO_2 emissions, say $100/tonne of CO_2.

The impacts of such a price are particularly dramatic upstream: it is equivalent to an increase in production costs of $40/bbl for oil, $5/mmBtu for natural gas and $200/tonne for high-quality coal. Downstream, the consequences are more muted because the addition of unchanged distribution costs leads to smaller percentage increases in retail prices. At $100/tonne of CO_2, a US gallon of gasoline costs an additional 80 cents, while a kilowatt-hour of electricity costs an extra 8 cents if produced from coal and an extra 4 cents if produced from natural gas.



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$40 per barrel of oil

or

$5 per million Btu of natural gas

or

$200 per tonne of high-quality coal

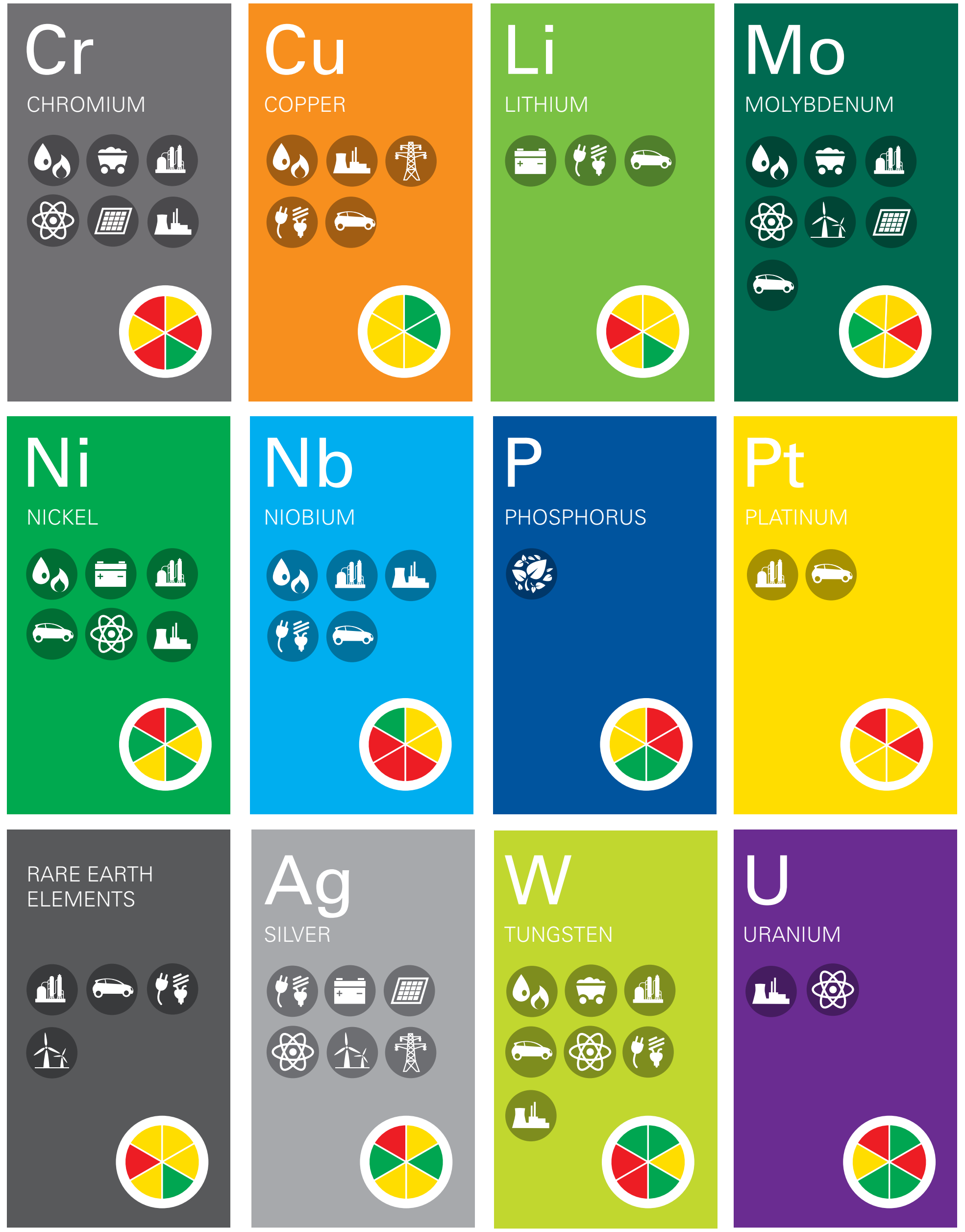
Materials used in the energy sector and their criticality

This chart shows the main uses of key materials in energy pathways and the factors that are critical to their production and supply. These factors include reserves, trade, environmental impact, processing, substitutability and recyclability.

Energy supply chains are critically dependent on several key materials in making them efficient, economic and clean.

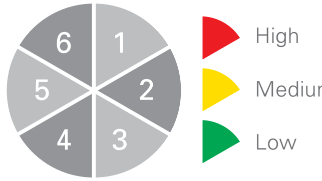
Changes in the energy system, driven by the need for decarbonization, will bring dramatic changes in the demand for certain materials.

Time is an important factor in addressing the criticality of materials. For example, a strike or fire in a large mine could suddenly affect supply (and price) worldwide – and it typically takes years for a new mine to progress from initial exploration to production.



Source: *Materials critical to the energy industry – An introduction (2nd edition).*

Criticality indicators



1. **Recyclability**
   Difficulty in recycling due to the availability of suitable technology, logistics and concentration of materials in end-of-life products.
2. **Substitutability**
   Loss of performance using alternative (non-critical) materials.
3. **Processing**
   Complexity of production technology.
4. **Reserves**
   An indication of shortage based on reserve-to-production ratios.
5. **Trade**
   Influence of monopolies and/or non-open markets.
6. **Ecological impact**
   Impact, including on humans, due to toxicity, radioactivity or handling risks.

Main uses

- Automotive
- Batteries
- Biofuels
- Coal
- Appliances and lighting
- Generation
- Nuclear
- Oil and gas
- Photovoltaics
- Refining
- Transmission
- Wind

History has shown that reserves of materials are dynamic and that economics, geological understanding and new technologies continuously drive reserve growth to meet demand.

Materials

Materials are widely used across the energy system. There would be no electricity system as we know it without copper, nor any piston, drilling rig, pylon or nuclear reactor without chromium for their corrosion-resistant steel. Material extraction and production are also energy and carbon intensive. Energy technology choices may, in turn, fundamentally affect the requirements for materials and ores.

In recent centuries energy demand and its technologies have dramatically increased the demand for materials. The pursuit of new energy pathways will only be made possible by having a sufficient supply of critical materials at prices that make economic sense.

Material complexity also brings risks. The potential substitutes for most materials are generally inadequate, supply constrained, non-existent or not yet discovered. For example, silver could be a substitute for copper, but price excludes its widespread use. Replacing molybdenum, cobalt, nickel or rhenium for specialist steels with alternatives usually results in a decrease in performance. There is no known substitute for dysprosium used in temperature-resistant permanent magnets. This suggests that material design in the future may well proceed in a transformative fashion, rather than incrementally.

Research shows that many elements have a wealth of reserves. More importantly, history has shown that – similar to oil and gas – reserves of materials are dynamic and that economics, geological understanding and new technologies continuously drive reserve growth to meet demand. In addition, increased recycling rates and better recycling technologies – together with substitution and more efficient manufacturing – can provide a substantial contribution to supply. Fortunately, metal-based materials can generally be used and repeatedly reused.

Ultimately, material reserve is a poor indicator of criticality. It is the effectiveness of markets, and the complexity of supply chains that determine availability of materials for well-functioning energy systems.

Worldwide, thermal power generation withdraws **20 times** more fresh water than fossil-fuel extraction.

Water

Water use in different energy sectors can vary greatly depending on local water availability, regulations and technological choices. Where water scarcity is an issue, technology can help reduce demand for fresh water.

The proportion of fresh water withdrawn for fossil-fuel extraction is less than 0.5% of total freshwater withdrawals worldwide. This can be reduced further through technologies that allow reuse, recycling or replacement of fresh water by lower quality water.

In thermal power generation – which withdraws more than 20 times the fresh water used in fossil-fuel extraction – the choice of cooling technology affects water use more than the fuel choice. Improved plant efficiency and the replacement of fresh water with alternatives are examples of methods that can reduce water use in the power sector. However, they can cost more and may need incentives to drive their adoption. In analyzing options it is important to distinguish carefully between water withdrawal and water consumption and to consider the trade-offs between the two. Most water withdrawn in power generation is not consumed but is returned to its source. Water consumption in cooling towers – the source of the columns of water vapour associated with power stations – can be reduced by alternatively using once-through cooling. However, with its requirement for larger amounts of water to be withdrawn from and returned to its source, the use of once-through cooling may be precluded by constraints on water availability or regulation.

There are also important trade-offs between water, energy and emissions. For example, in China the expansion of inland nuclear power plants will reduce emissions, but may increase freshwater demand. Unintended consequences can also occur with the expansion of air-cooled condensers (dry cooling) for thermal power generation. While reducing water requirements, this technology also reduces the average efficiency of power generation, leading to higher fuel consumption and emissions, as well as increased capital costs.

Water in energy

Ranges of freshwater consumption intensities in key energy sectors. Amounts displayed in cubic metres per terajoule (m³/TJ) on logarithmic scale.

Withdrawal occurs when water is removed from surface or groundwater, at least temporarily. Consumption is the portion of withdrawal that is not returned to the source from which it was removed.

The amount of fresh water used varies greatly within each energy sector. Best available technologies – including reuse, recycling and replacement of fresh water – could drastically reduce water use.

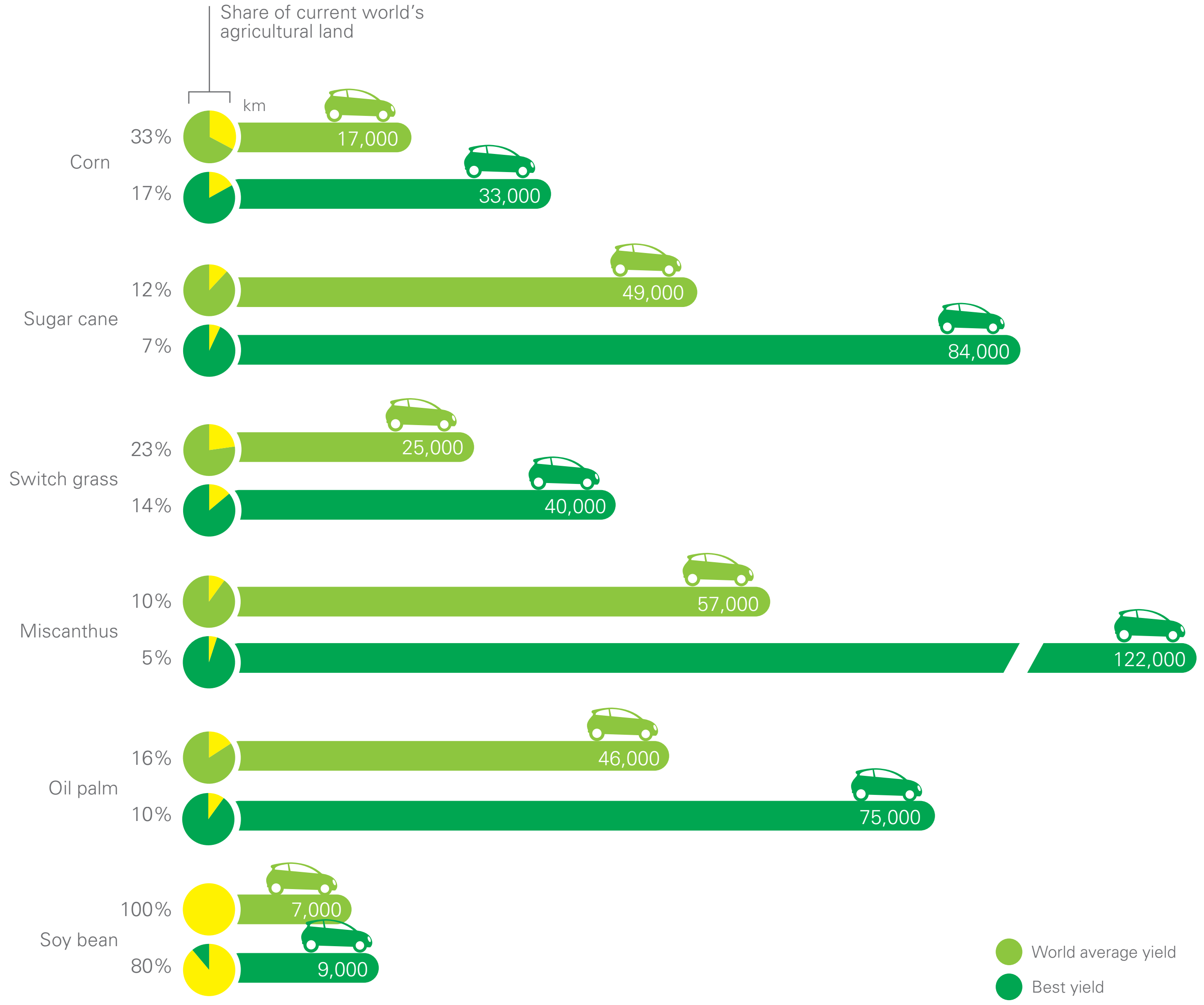
On average, natural gas is by far the most water-efficient fossil fuel. For biofuels, the extent to which a crop is irrigated is a key factor in freshwater consumption; however, economics usually limit irrigation.

In thermal power generation, the choice of cooling technology affects freshwater use more than the fuel choice. Also, important differences and trade-offs exist between water consumption and water withdrawal.

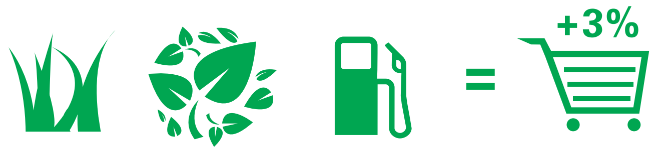
Source: *Water in the energy industry – An introduction.*

How far can we travel on biofuels?

An assessment of the annual distance that can be travelled today by a typical US family car using biomass from one hectare of land. Also shown is the share of the world's current agricultural land that would be required to meet the global road transport energy demand today using exclusively biofuels (based on current world weighted average annual yields and greatest recorded yields).



Sources: *Biomass in the energy industry – An introduction. FAO Statistics. IEA Energy Technology Perspectives 2015.*



A large bioenergy industry could increase average food prices by only **3%** by 2050.

Bioenergy and land use

Biomass supplies 10% of today's global primary energy, mostly for traditional small-scale heating and cooking. It is often seen as part of a lower-carbon future, mainly because of the potential for biofuels in transport and biomass in power. Agricultural land is a finite resource however, and different bioenergy crops require water and fertilizers in varying amounts. Understanding how land can be best used to meet energy needs, while minimizing the impact on other natural resources, requires consideration of the many different ways to optimize crop production for food, feed and fuel.

Our research shows that production of 150–200 exajoules (EJ) of primary energy per year – which is comparable in size to today's oil sector – from biomass could be sustainably achieved by 2050. This would represent a significant energy source and a substantial increase from the current biomass utilization of about 50EJ per year (EJ/yr). To realize this potential, the productivity of crops would have to increase, through advances in agricultural techniques. Alongside this, improvements in the processes used to convert biomass to fuels will be necessary. Careful selection of land, crop management, technologies and uses are all required. The choice of crop must balance high yield with low inputs, low impact on the environment and net positive climate impact, together with understanding of how to grow the crop over large acreage.

Because of its high yield, sugar cane ethanol is already a competitive transport fuel in some regions and, in the longer term, LC ethanol from crops such as miscanthus or switchgrass could be a cost- and carbon-competitive fuel in many parts of the world.

The use of biomass for energy has proved a contentious issue, with differing perspectives in different parts of the world about land use, accompanied by concerns about food availability. Research at the Massachusetts Institute of Technology (MIT), supported by BP, has shown that the impact of a large bioenergy industry worldwide on food prices would be relatively modest: a 150EJ/yr bioenergy sector in 2050 would result in an average food price increase of approximately 3% compared with business as usual. This is because technology, crop choices and efficiency improvements in fuel conversion and food production will mitigate competition with food for land.

Research at the MIT also shows that a large bioenergy system does not necessarily imply a decrease in natural forests, providing these are protected with dedicated land-use policies, including a price on land carbon.

Professor Zheng Li
Director, Tsinghua BP Clean Energy Research and Education Center, Tsinghua University (Beijing, China)

External perspective

Energy technology choices to reduce demand on natural resources

Guangxi Province, China.

Although energy production and consumption are closely linked to natural resources consumption, technology innovation could play an important role in reducing demand in three ways.

The first way is to improve technology incrementally, either with higher energy efficiency or with less natural-resource consumption per unit of energy or service. An example is replacing coal-fired subcritical steam power plants with ultra-supercritical ones. This increases the net power generation efficiency from about 38% to about 44–45% and consequently decreases cooling water consumption.

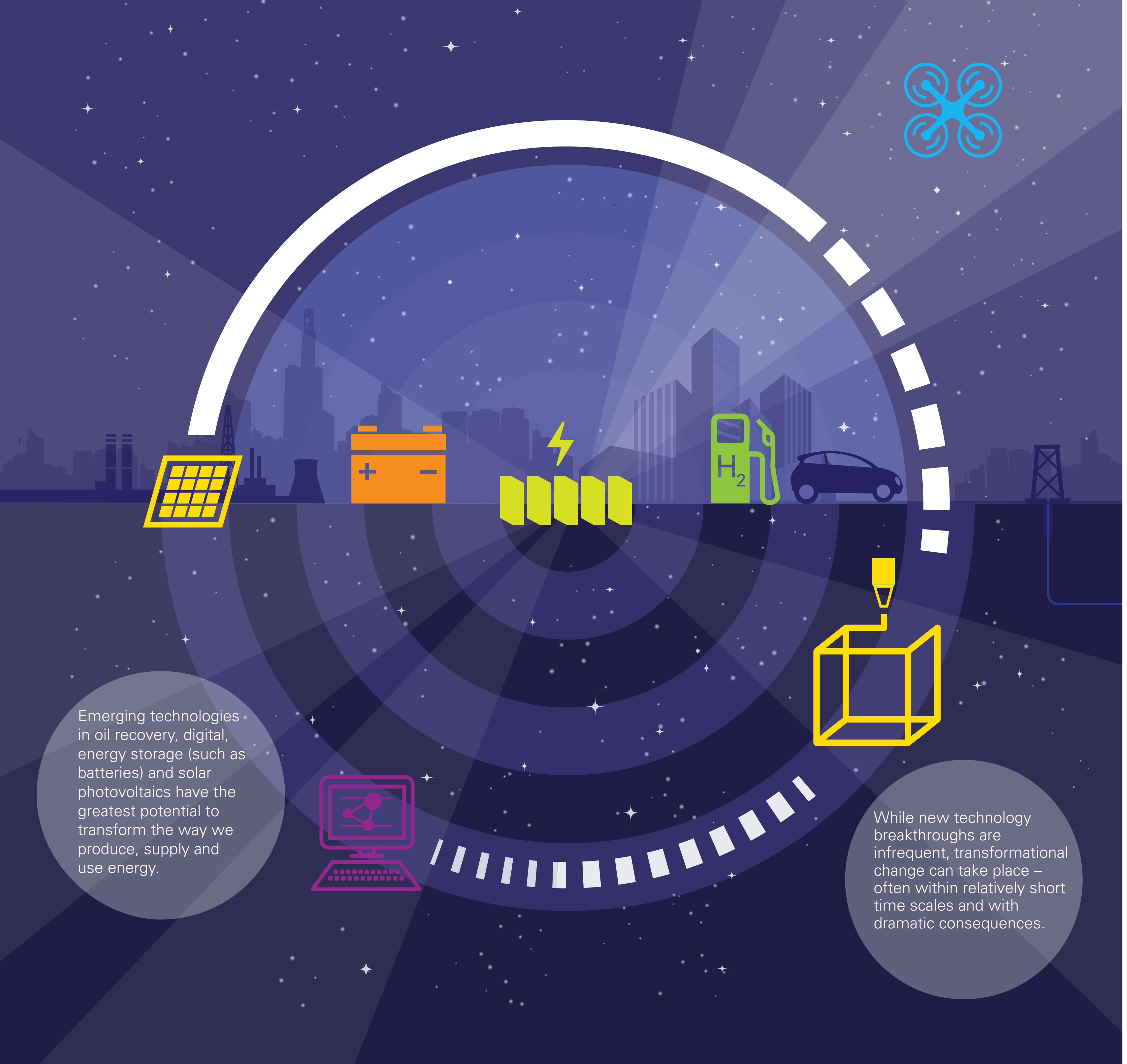
The second way is to develop alternative technologies that consume fewer natural resources. One example is replacing coal-fired power generation with wind. The advantages are significant: using wind instead of coal reduces air pollution, carbon emissions and – since it requires no cooling during operation – eliminates water consumption.

The third way is the optimization of the entire supply chain. Taking the coal-power supply chain as an example, trade-offs exist between water consumption in upstream coal washing and downstream power generation. Increasing the amount of water being used for coal washing may actually result in less water used during power generation. This is because washed coal, with less ash, sulphur and heavy metals:

- Increases combustion efficiency thereby decreasing specific water consumption per kWh produced.
- Reduces electricity demand for railways, which have to carry less weight of coal.
- Reduces the parasitic electric load from flue gas desulphurization (a process that also requires water).

Because of these benefits, coal washing, a technology that previously did not get enough attention, is bound to be applied more and more.

In practice, the three ways above should be pursued simultaneously to minimize natural resources consumption and other environmental effects.



3.1 Emerging technologies

Emerging technologies present business risks and opportunities for the energy industry.

While new technology breakthroughs are infrequent, transformational or disruptive change can take place – sometimes within relatively short time scales and with dramatic consequences. In these cases, breakthroughs often come when tools, techniques or approaches in one sector are applied in another. Advances also happen when a known technology reaches an economic tipping point as a result of multiple incremental innovations.

The pace of innovation and development is increasing. This is being facilitated by diverse institutions working together on large-scale and long-term initiatives in collaborative partnerships. Developments may involve private companies, universities, research institutes, specialist consultancies and funding bodies all working together.

Some technologies with the potential to enhance existing business models are either ready now or on the cusp of benefiting the energy industry.

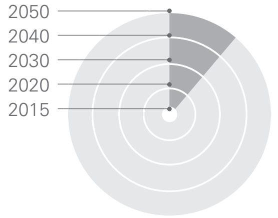
In the oil and gas sector, for example, remote sensing via satellites and unmanned aerial vehicles are already undertaking surface mapping, contaminant characterization, inspection and spill detection. Technologies applicable to oil–water separation, crude oil desalters or water/organic-chemical processors are also advancing, and are likely to have a positive impact on existing refining and processing activities.

Developments in new materials technologies, such as lightweight construction materials, coatings and membranes, have great potential to improve many parts of the energy value chain. For instance, corrosion-inhibiting coatings can improve uptime and reliability in oil and gas production as well as further downstream in refining, petrochemicals manufacture, lubricants blending, product transportation and storage. Advances in understanding corrosion mechanisms and prevention can also have widespread applications across other industrial sectors, such as aerospace, marine and automotive.

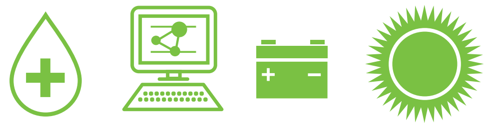
Quantum technologies have the potential to process huge data sets at faster rates than today's silicon-based, digital computers can. They use electrons or even polarized light that can be interlinked to perform many operations at once, greatly increasing computation speeds. While currently at an early stage of development, quantum and nano technologies have been identified as having significant potential.

Emerging technologies

Time range from commercialization to significant impact.



Source: BP.



Emerging technologies in oil recovery, digital, energy storage (such as batteries) and solar PV have the greatest potential to transform the way we produce, supply and use energy.

Digitization

Exponential increases in the power and speed of computers and the accompanying decrease in costs are having a huge impact on the energy business and have the potential to do much more.

Data analytics, visualization tools and computational techniques are addressing long-standing challenges when operating in hostile natural environments in the upstream oil and gas business, including understanding the subsurface, tackling hydrate formation and maintaining facility reliability. For example, intelligent data analysis is guiding exploration teams on where to drill and improving their understanding of reservoir depletion. This is also enabling the development of better strategies for enhanced oil recovery.

In fuels and lubricants, molecular-level models can determine if certain types of molecule can reduce friction in engines.

In chemicals, molecular modelling is driving improvements in catalysis.

In biofuels, the scale and speed of data analysis, such as the pioneering work on gene sequencing, is helping to drive understanding of the microorganisms that increase yield and deliver better products.

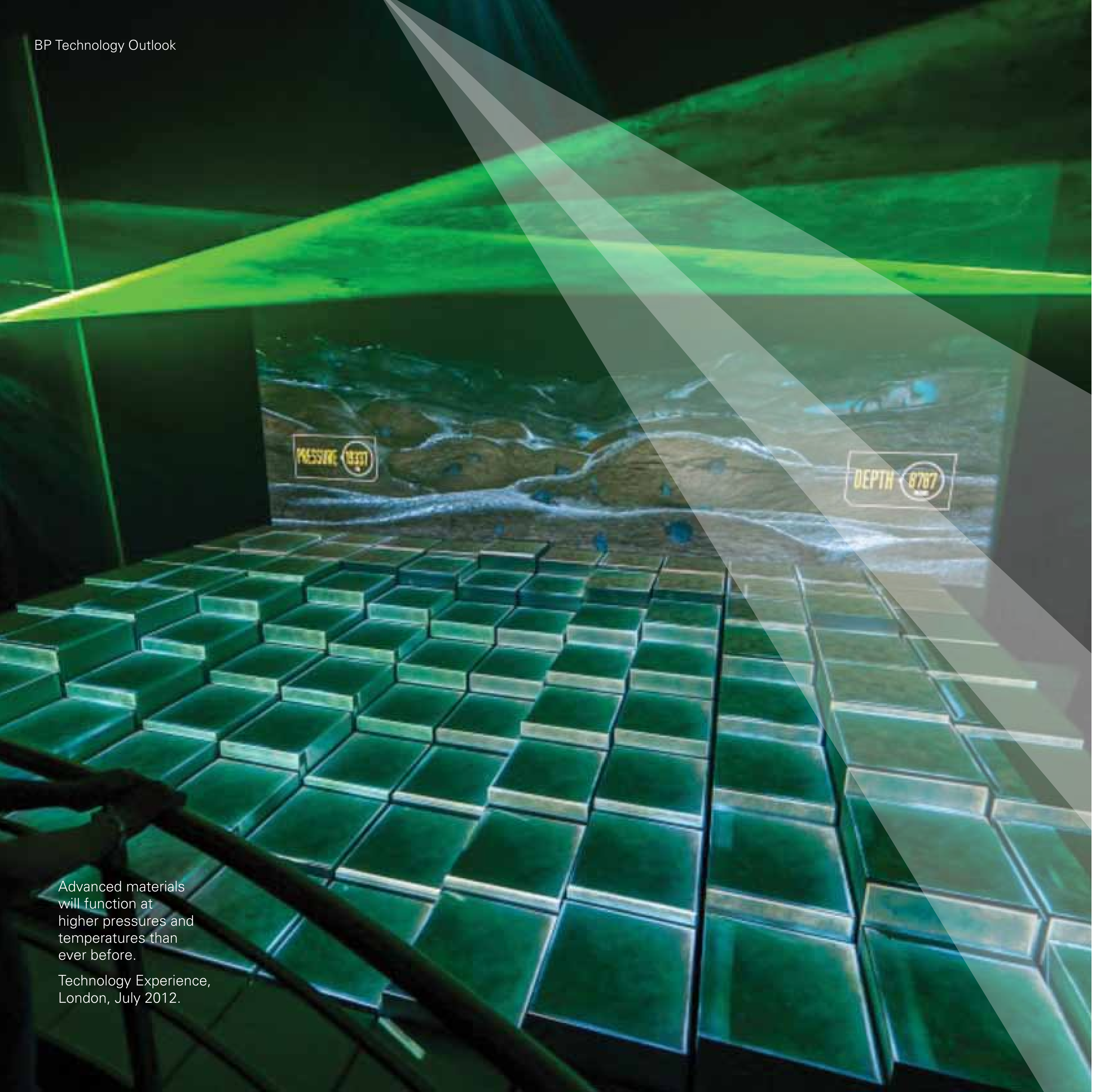
In the power sector, data analytics will lead to improved infrastructure management and operational efficiency. Examples include the emergence of smart grid systems to maximize the uptime of generating assets and improve reliability for the customer.

Energy storage: battery technology advances

Batteries for vehicles and electricity-grid applications, such as energy storage technologies, have significant potential to influence future fossil-fuel demand in the transport sector and enable greater penetration of intermittent renewable energy.

Battery technologies for transportation are improving to meet performance demands. Particular progress is being made on battery reliability, costs, safety and capacity for enhanced range. These developments are having an impact on the forecast production of electric vehicles.

Next-generation batteries, such as rechargeable lithium sulphur batteries, are expected to increase energy capacity threefold by 2025 from 150Wh/kg to 450Wh/kg and to reduce vehicle weight and cost. Next-generation batteries could be established in the electric vehicle market by 2025–30. The continued development of these technologies is supported by regulatory pressures for greater fuel economy and lower tailpipe emissions per kilometre driven, which makes their contribution to better urban air quality a particular advantage. Consumer demand is also likely to increase.

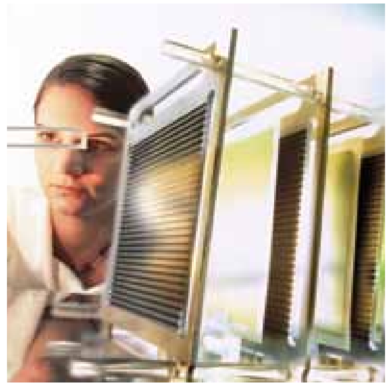


Advanced materials will function at higher pressures and temperatures than ever before.

Technology Experience, London, July 2012.

High-temperature solid oxide fuel cells.

Technician with a 16kW fibre laser coupled to a six-axis Kuka robot in the Manufacturing Technology Research Laboratory at the University of Manchester, part of the new BP International Centre for Advanced Materials.



Other emerging technologies could radically transform existing markets. In the energy sector, these include alternative forms of transportation, energy infrastructure and storage – each of which could significantly disrupt existing paradigms.

In transportation, advances in batteries for vehicles and fuel-cell vehicles are potential disruptors. In the power sector, the continued development of cost-effective energy storage (for intermittent energy management) and next-generation solar could have a significant impact on future power supplies and could lead to a reduction in dependence on fossil fuels.

Technology crossover from other fields such as information technology will continue to have an impact on how the energy industry operates. Advances in bio-engineering can bring benefit to biofuels and EOR. In addition, biotechnology itself has significant potential to continue to deliver improvements in agriculture, which in turn would provide more biomass at lower cost. Advanced nuclear power, as a source of lower-carbon energy, could also be a future disruptor in the power sector.

Modular power generation: fuel cells

The development of fuel cells and associated hydrogen infrastructure will significantly affect future fuel demand. Fuel-cell vehicles typically have a potential range of 400–500km, which would alleviate the ‘range anxiety’ inherent with today’s battery-powered electric vehicles. However, fuel-cell vehicles have to overcome significant hurdles of cost and low levels of hydrogen availability for consumers before mass adoption can occur. The introduction of fuel cells in the utility sector has the potential to enable establishment of a more distributed power generation network.

In some markets, tax credits and subsidies are supporting the growth of consumer hydrogen infrastructure, which will be essential for fuel-cell vehicle market penetration. For example, plans are being made for networks of hydrogen fuelling stations in Japan and the US and, in both markets, automobile manufacturers have plans for launching fuel-cell vehicles.

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External perspective

Future energy landscapes

Solar PV farm, France

The future energy landscape will be shaped by a significant growth in energy demand and a shift towards energy supply from unconventional and renewable resources. Solar photovoltaics (PV), stationary energy storage and methane hydrate recovery represent three emerging and disruptive areas of innovation within this new supply paradigm.

Solar energy is our most abundant natural resource, with tremendous potential to transform the energy landscape. PV technologies have grown particularly rapidly in recent years, as maturation of wafer and thin-film PV manufacturing has dramatically reduced PV module costs and government incentives have further stimulated market demand. The global urbanization megatrend and growing scarcity of available land in high population areas necessitates that PV increasingly integrates with the built environment, with easy installation and low maintenance requirements. To drive greater penetration of solar power into electricity supply, industry players must focus on reducing the costs of installation, overheads, financing and power electronics. They will also need to achieve smooth electricity grid integration through energy storage or other means of mitigating solar intermittency. Longer-term challenges involve increasing cell and module efficiencies, reducing materials use and reducing manufacturing complexity and costs.

Stationary energy storage for electricity-grid services is disruptive in its capacity to support the integration of renewable energy sources with the electricity grid, to mitigate the need for new transmission and distribution infrastructure and to provide demand management and ancillary grid services. Widespread adoption of advanced grid storage technologies must meet safety and performance requirements while being cost competitive. Performance requirements include the ability to ramp to full power in minutes, sustain full power for hours, cycle between charging and discharging with high efficiency and operate for thousands of cycles. The development and/or demonstration of novel technologies, such as flow batteries, molten-salt batteries and compressed air storage, are still required. In the near term, energy storage technologies available now, such as lithium batteries, will increasingly be deployed for off-grid and local distribution systems, setting the stage for the uptake of large-scale grid storage.

Methane (or gas) hydrates represent an enormous recoverable resource at least of the order of shale gas. Gas hydrate resources are global and Asian economies that are heavily dependent on imported energy are making gas hydrate recovery a strategic imperative. By 2050 gas hydrate recovery may account for 5% or more of all global gas production, if public and private sector initiatives develop safe and cost-effective extraction technologies based on depressurization, thermal stimulation and chemical or gas injection.

Each emerging technology domain described requires industry to develop and demonstrate state-of-the-art technologies and then optimize supply chains and manufacturing capabilities for commercialization. Industry leadership will catalyse markets ready to adopt the new generations of technology that will inevitably follow from further advances in biological, material and geological sciences.

4.0 Conclusions and implications

The long-term trends discussed in this publication depict an energy sector of increasing diversity and complexity. New resources are becoming available, led by shale oil and gas. Energy prices have returned to their traditional pattern of volatility. Policies and regulations on environmental issues vary from country to country and may develop in different ways.

Within this complex and uncertain picture, two trends that will have a bearing on the entire framework are clear. Firstly, we will need to deliver more energy to more people at lower cost. Secondly, the growth in energy demand needs to be met while reducing GHG emissions and making a transition to a lower-carbon energy system.

The key metrics that will show how these trends evolve are the amount of energy used and the level of GHG emissions. Both are influenced by a series of factors. Energy supply and demand are governed by factors such as economic and demographic growth and the capacity of technology to produce resources cost effectively. Emission levels are influenced by policy and regulation, for example, by the pricing of carbon through taxation or emissions trading, by subsidies and quotas for renewable energy, and by regulations such as building standards and tailpipe emission limits for cars.

At first glance, the idea of using more energy with less environmental impact seems contradictory. Over time, however, it can be achieved: firstly, by using energy more efficiently and thus limiting the total volume consumed and, secondly, by switching the energy that is used towards lower-carbon forms of fuel and power. This includes replacing coal with gas in power stations, using CCS at power plants and other facilities, and using more renewable and nuclear energy.

So what technologies will be the most important as this journey unfolds? In the short term, we can expect a continued emphasis on technologies, such as seismic imaging and EOR, to find and produce fossil fuels as cost effectively as possible while also continuing to enhance and reduce costs of lower-carbon energy. In the medium to longer term we expect to see technology enable lower-carbon energy to mature and become deployed at increasing scale while the remaining hydrocarbons are used even more efficiently.

In the early stages of the journey ahead, there will be a continuing need to discover more fossil-fuel resources as existing fields are depleted. Technology is also transforming oil field recovery rates. No longer is it routinely expected that around two thirds of the oil in a given field will remain underground. Recovery rates well in excess of 50% are now in prospect thanks to EOR technologies.

Technology will give greater choice in how we meet future energy demand – securely, affordably and sustainably.

These new technologies that enhance oil and gas recovery from already discovered fields will be at least as important as those that help explorers find new ones.

At the same time, in periods when oil and gas prices are low and operators are seeking efficiencies, technologies that reduce costs of finding, producing and processing energy resources will be prized – putting greater emphasis on the need for effective research and development in areas such as digital technologies and advanced materials.

Such developments in the conventional energy system are expected to be augmented by the progressive development of lower-carbon technologies, with government support. As and when governments act to constrain or mitigate emissions more strongly, we can expect a greater drive to invest in research, development and deployment of lower-carbon technologies, including those that are nascent, such as CCS. Technologies that increase energy efficiency will become increasingly important as they help reduce energy costs and limit CO_2 emissions – a 'win–win' outcome.

In the power sector, the substitution of lower-carbon natural gas for coal can make a significant contribution to reducing carbon emissions, supplemented by renewable technologies such as wind and solar PV accounting for a higher share of generation. In transport, we expect vehicles to remain fuelled mainly by oil-based liquid fuels and, to a lesser extent, biofuels. We expect engines and vehicles to become lighter, more efficient and smarter, complemented by advanced, increasingly efficient lubricants and fuels.

In the medium to long term, we can expect progressive decarbonization in the transport sector with a greater move toward hybrid and electric passenger cars. Liquid fuels will be much more difficult to displace from commercial transport such as shipping, trucks and aircraft, however, due to their high energy density.

The IEA has developed a scenario for a world in which the global mean surface temperature rise on pre-industrial times is limited to 2°C – widely seen as the threshold to avoid significant climate change. In that scenario, the world uses a lot less energy than in business-as-usual projections, but with around half in 2050 still coming from fossil fuels, led by gas, the cleanest fossil fuel. We can expect technology to help us use fossil fuels much more efficiently and sparingly, while it also underpins commercially viable lower-carbon energy – renewables, nuclear and CCS.

Within an environment that supports innovation and encourages the private sector to invest, energy companies have a vital role to play in responding to the challenges ahead by developing and deploying the innovative technological and commercial solutions that meet society's needs and aspirations.

The future is uncertain, but we know that technology will help provide the energy the world needs, and the means to use it more efficiently, with lower GHG emissions. Most of all, technology will give greater choice in how we meet future energy demand – safely, securely, affordably and sustainably.

Technology will help provide the energy the world needs.

Our approach

In *BP Technology Outlook* we provide a perspective on future trends in technology and their potential impact on the energy system, using insights from our research. This analysis, carried out with our external research partners since 2012 and building on similar assessments in 2005 and 2009, describes what lessons can be learnt from technology evolution and how these might shape our future energy choices.

This publication includes selected highlights from our research into the potential future impact of technology across the energy system, from the availability of energy resources through to their conversion and eventual end use. We focus on developments in primary energy resources, oil and gas extraction, power generation, transport fuels and vehicles.

We provide an industry-wide assessment of what is technically possible and while it is impossible to predict with any certainty what is likely to occur, it sets out a vision of the way technology may shape the energy landscape over the next 35 years. We draw on BP's view of the global energy system as reflected in *BP Energy Outlook 2035* and *BP Statistical Review of World Energy 2015*. Both these publications have become standard references for those with an interest in the energy industry.

Today's global energy system is already complex, and projecting the direction in which it might evolve to 2050 is bound to involve and introduce uncertainties. The absolute figures in this publication, therefore, are less important than relative comparisons and the long-term trends they might imply.

These trends include probable and possible changes in resource availability, conversion and end use, and the implications these could have for decision makers in government, business and society.

Our research covered eight geographic regions that resulted in 30,000 possible routes or 'value chains', extending from the harvesting of primary energy resources to their conversion into products and to their consumption. At each stage of the value chain, we considered various options for how each energy source or product might be transported. For instance, natural gas can be transported by pipeline, shipped as LNG or converted to electricity and transported as 'gas-by-wire'.

Technology underpins each element of every chain and the way in which technology develops will shape how we think about energy and use it in the future. Consequently, each value chain has a unique set of technologies, costs, efficiencies and sustainability implications that influence the choices we make.

We developed a view of how each element might evolve to 2050, drawing on expert opinion, historical trends and third-party benchmarks. To ensure a clear focus on technology, we excluded the impact of above-ground factors such as government policy, incentives and subsidies. Our research comprised two major components: analysis of the world's primary energy resource base and comprehensive value-chain modelling.

We complemented these elements by analyzing emerging and disruptive technologies and assessing the role of technologies to address climate change and constraints on natural resources such as fresh water, land and minerals.

In assessing the primary energy resource base, we covered a spectrum of fossil fuels, fissile material (nuclear) and renewable resources. We considered the performance and costs of the technologies used to gain access to resources and projected how they might evolve to 2050. We gave particular consideration to the potential for improvement in two metrics: our ability to recover more energy more efficiently and the scope to reduce access costs.

For oil and gas, we assessed 22 different resource classes spanning conventional and unconventional types located in onshore and offshore environments. With some resource classes such as methane hydrates and offshore unconventionals excluded, the assessment can be considered to be conservative. For renewable energy, the accessible resources for solar, wind, geothermal, biomass, hydro and marine were also evaluated by region, alongside coal and nuclear.

For value-chain modelling, we adopted a techno-economic approach to determine cost-effective pathways for creating products from primary energy fossil and renewable resources and for delivering end use services such as mobility in transportation and heating in buildings. To complete the full value-chain assessment, we also modelled mid-stream elements such as electricity generation, refining and petrochemicals. Views on how technology might progress took account of anticipated learning-curve effects, extending from the level of a technology's current maturity and projecting to 2050. This required us to develop a view on likely demand and deployment rates. For example, we deemed that onshore wind and PV technologies would continue on the pathway of rapid growth based on trends in recent years.

For each technology we developed a view on capital, fixed and variable costs, along with projections relating to efficiency and carbon emissions. We included sensitivity analysis, which assessed the impact of carbon emission policy (in the form of a carbon price). Policy measures of this type serve to increase the full life-cycle cost of any value chain that is dependent on fossil fuels at any point.

The climate perspectives have been informed – in addition to internal research and reputable sources such as the IPCC and the IEA – by the Carbon Mitigation Initiative, a 15-year partnership between BP and Princeton University with the goal of finding solutions to the carbon and climate challenge. Our assessment of the relationships between natural resources and the supply and use of energy, including how technologies can mitigate the potential effect of resource scarcity, builds on the Energy Sustainability Challenge. This is a BP-funded global multidisciplinary research programme established in 2010, involving 15 leading universities around the world.

Glossary

- 3D printing
- Automotive
- Automation via robotics
- Appliances
- Batteries
- Biofuels
- Biomass-to-liquids (BTL)
- Combined-cycle gas turbine (CCGT)
- Carbon capture and storage (CCS)
- Coal
- Corn ethanol
- Diesel
- Directional drilling
- Digital
- Enhanced oil recovery (EOR)
- Electric car
- Energy storage
- Floating facilites
- Fuel cells
- Facilities
- Gas
- Greenhouse gas (GHG)
- Gas-to-liquids (GTL)
- Geothermal
- Hybrid
- Hydraulic fracturing
- Hydro
- Hydrogen storage
- Imaging
- Land
- Lignocellulosic (LC) ethanol
- Liquid fuel
- Lubricants
- Materials
- Marine
- Nuclear
- Offshore wind
- Onshore wind
- Oil
- Power generation
- Photovoltaics (PV)
- Refining
- Renewables
- Seismic imaging
- Solar
- Sugar cane
- Shale gas
- Tight oil
- Transmission
- Unconventional gas
- Wells
- Water

Blendwall: Most gasoline vehicle drivetrains on the road in the US today and many gasoline storage and dispensing systems are designed to handle gasoline blends which contain no more than 10% ethanol. As a result, 10% ethanol represents a maximum practical level for gasoline blends, and has been described as the ethanol blendwall.

Biomass-to-liquids (BTL): process of chemically converting woody biomass into liquid fuels via a syngas intermediate. In principle, this could involve Fischer–Tropsch or MTG technology, but as yet BTL is not commercial.

Carbon capture and storage (CCS): process whereby CO_2 is collected from industrial exhaust streams and injected into underground storage sites.

Carbon price/tax: financial cost applied by governments to emissions of carbon dioxide or other greenhouse gases (e.g. methane) in units of carbon-dioxide equivalence. The price can be set directly, as a carbon 'tax' on emissions. It can also be established indirectly, by requiring emitters to obtain emission permits, which are issued by the government in limited numbers to place an overall 'cap' on emissions, and which can then be bought and traded in a carbon market. The carbon price should ideally reflect the cost of the environmental damage caused by GHGs, and it provide a clear economic incentive for potential emitters to emit less, either by stopping or reducing an emitting activity or finding a way to perform the activity more efficiently.

Coal washing: process in the preparation of coal feedstock that improves its quality by removing impurities.

Combined-cycle gas turbine (CCGT): form of highly efficient energy generation technology that combines a gas-fired turbine with a steam turbine.

Data analytics: method of examining raw data with the purpose of creating information to enable conclusions to be drawn and decisions to be made better and faster. Also used to verify or disprove existing models or theories.

Depolymerization (of biomass): pretreatment process (sometimes using enzymes) that breaks polymeric biomolecules such as cellulose, hemicellulose or starch into their monomers,which are typically simple sugars.

Desalting: washing process to remove the salt impurities usually present in crude oil.

Digital technologies: term used to describe the use of digital resources to effectively find, analyse, create, communicate and use information in a digital context.

Direct fuel injection: engine where fuel is delivered directly into the cylinder rather than the intake port or pre-chamber of traditional gasoline and diesel engines, respectively. The technology is normally applied to improve efficiency, both directly via combustion improvements and as a key technology in enabling engine downsizing.

Drilling, well construction and completions: process of creating an oil or gas well by drilling into the Earth's surface and through rock formations, often to depths of more than 4,000 metres, casing the wellbore, ensuring structural integrity, installing barriers to prevent leaks and creating a flow path to enable oil or gas to flow into the well bore and to the surface.

Engine downsizing: use of a smaller engine in a vehicle that provides equivalent performance of a larger engine normally for the purpose of improving vehicle fuel efficiency. This is commonly achieved by applying turbocharging and direct fuel-injection technology.

Fermentation: biological process where micro organisms such as yeast or bacteria convert simple sugars into useful chemicals such as ethanol.

Fischer–Tropsch (FT): process for converting syngas into liquid hydrocarbons, mainly suitable for diesel engines or gas turbines. The syngas may be derived from natural gas, coal, residual oils or biomass.

Gas-to-liquids (GTL): process of chemically converting natural gas into liquid fuels via a syngas intermediate. There are several different types, including Fischer–Tropsch and MTG technology both of which have been operated commercially.

Greenhouse gas (GHG): gas that contributes to the Earth's greenhouse effect (a phenomenon in which the atmosphere traps radiation emitted by the sun) by absorbing infrared radiation. Carbon dioxide and methane are examples of GHGs.

Horizontal and directional drilling: method of drilling non-vertical wells. For oil and gas, it delivers a number of benefits, including exposing greater sections of a reservoir, enabling access where vertical wells are difficult or not possible, allowing multiple wellheads to be grouped together at a single location and creating less surface area disturbance. In conjunction with hydraulic fracturing, it is used extensively in accessing unconventional shale and tight oil and gas formations.

Hybrid vehicle: utilizes more than one form of propulsion system (prime mover) to power the vehicle motion. The most common application of this approach is in hybrid electric vehicles, which combine an internal combustion (IC) engine and a fuel tank with one or more electric motors and a battery pack. The hybrid system can improve vehicle efficiency by allowing the IC engine to operate more optimally and by recovering energy to the battery during braking. Plug-in hybrid vehicles are able to store and use energy that has been generated by an external source.

Hydraulic fracturing: fracturing of rock using high-pressure fluid consisting of water, sand and chemicals. Small grains of hydraulic fracturing proppants, usually either sand or aluminium oxide, hold the fractures open allowing oil and gas to flow.

Improved and enhanced oil recovery (IOR/EOR): range of techniques used to increase the natural volume of resources recoverable from an oil or gas field. They often involve injecting water with chemical additives and/or hydrocarbon gases or CO_2 into a partially depleted reservoir.

Levelized cost of electricity (LCOE): method to calculate the fully built-up cost of electricity from a generating asset in its lifetime. Key inputs to calculating LCOE include capital costs, fuel costs, electrical efficiency, fixed and variable operations and maintenance costs, depreciation and an assumed utilization rate for each plant type.

Lignocellulosic (LC) ethanol: biofuel produced from wood, grasses or the inedible parts of plants. The name derives from the primary components of this type of biomass: lignin, cellulose and hemicellulose.

Methanol-to-gasoline (MTG): process for converting syngas into methanol, then methanol into liquid hydrocarbons, mainly suitable for gasoline engines.

Offshore facilities: basket of technologies such as compliant towers, tension-leg platforms, spars, subsea systems, floating production systems, and floating production, storage and offloading systems used in offshore oil and gas production and enabling access to increasingly deeper waters.

Originally in place (oil and gas): total volume of oil or gas estimated to be in a reservoir, regardless of whether deemed recoverable or not, before the production starts.

Power plant cooling: systems to exchange the heat from the steam condensers commonly used in thermal power generation plants. The main types include: wet-tower cooling, a closed-loop system in which water is cooled by atomization into a stream of air, and heat is lost through evaporation; once-through cooling, an open-loop system in which heat in the steam condenser is removed using a stream from large surface-water sources such as lakes, major rivers or the ocean; dry cooling, which works in a similar way as engines are cooled in cars, by passing large volumes of air over a heat exchanger and using no water.

Predictive technology: tools capable of discovering and analyzing patterns in data so that past behaviour can be used to forecast likely future behaviour.

Pretreatment (of biomass): processes required to convert raw biomass such as cereals, energy crops or agricultural residues into simple sugars.

Proved reserves (oil and gas): generally taken to be those quantities of oil and gas that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions.

Remote sensing: acquisition of information about an object or phenomenon without making physical contact with the object and thus in contrast to in situ observation. Examples include satellite and unmanned aerial vehicle remote imaging.

Resources (oil and gas): a generic term covering primary hydrocarbon energy sources, whether original in place, or technically or economically recoverable.

Seismic imaging: range of techniques for investigating and imaging the Earth's sub-surface geological characteristics. They are used extensively in exploring for new sources of oil and gas and developing 3D- and 4D-modelling representations of structures to enable better reservoir development and management.

Single-cycle gas turbines (SCGTs): most frequently used in the power generation, aviation (jet engine), and oil and gas industry (electricity generation and mechanical drives). This differs from a combined-cycle operation in that it has only one thermodynamic cycle (i.e. no provision for waste heat recovery and steam cycle).

Steam methane reforming: process in which methane from natural gas is heated, with steam, to produce a mixture of carbon monoxide and hydrogen used in organic synthesis and as a fuel.

Syngas (synthesis gas): a mixture consisting primarily of hydrogen and carbon monoxide, with smaller amounts of other simple gases. It is typically made by gasifying a carbonaceous feed such as natural gas, coal or woody biomass.

Technically recoverable oil and gas resources: proportion of estimated original-in-place volumes deemed recoverable using current and future technology and regardless of whether it is economic to do so at current market prices.

Ultra-supercritical coal: power plant that operates at temperatures and pressures above the critical point of water, at which point there is no difference between water vapour and liquid water. These power plants deliver higher efficiency and lower emissions than subcritical coal plants.

Underground coal gasification (UCG): industrial process that converts coal into product gas. UCG is an in situ gasification process carried out in non-mined coal seams using injection of oxidants, and bringing the product gas to surface through production wells drilled from the surface.

Unmanned aerial vehicles: aircraft piloted by remote control or on-board computers.

Water flooding: water flooding or injection refers to the method in the oil industry where water is injected into the reservoir, usually to increase pressure and thereby stimulate production. Water flooding or injection wells can be found both on and offshore, to increase oil recovery from an existing reservoir.

Water withdrawal: water removed from surface or groundwater, at least temporarily, to produce or process energy, or for some other purpose. Water withdrawals are typically classified as either surface (from rivers, lakes or impoundments) or groundwater withdrawals.

Water consumption: portion of withdrawn water not returned to the surface or groundwater in the same drainage basin from which is was abstracted. Consumed water is evaporated, transpired, incorporated into products or crops, or otherwise removed.

Well intervention: operation carried out on an oil or gas well to extend its producing life by providing well diagnostics, improving performance or providing access to stranded or additional hydrocarbon reserves. Typical intervention services include wireline, tractors, coiled tubing and hydraulic workovers.

Energy unit conversions

1 tonne oil equivalent (toe) = 7.33 barrels of oil equivalent (boe)

1 megawatt hour (MWh) = 3.6 gigajoule (GJ)

1 million British thermal units (Btu) = 1.05GJ

1 tonne oil equivalent on a calorific basis = heat units
- 10 million kilocalories
- 42 GJ
- 40 million Btu

solid fuels
- 1.5 tonnes of hard coal
- 3 tonnes of lignite

electricity
- 12 MWh

More information

BP Energy Outlook 2035
Projections for world energy markets, considering the potential evolution of the global economy, population, policy and technology. Published annually.
bp.com/energyoutlook

BP Statistical Review of World Energy
An objective review of key global energy trends. Published annually.
bp.com/statisticalreview

Energy Sustainability Challenge
BP-funded multidisciplinary research programme involving 15 leading universities worldwide examining the relationships between natural resources and the supply and use of energy. Key findings have been published in a suite of handbooks on biomass, water and materials available at
bp.com/energysustainabilitychallenge

Information about technology at BP can be found at
bp.com/technology

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Paper
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Where might energy technology take us?

As the world's population grows and living standards improve, the demand for energy continues to rise. Technology is a vital lever in enabling the world to meet energy demand securely, affordably and sustainably.

This publication provides a perspective on future trends in technology and their potential impact on the energy system. It draws on BP's research into long-term technology potential and the factors governing its development and deployment.

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