BP Technology Outlook
2018

How technology could change the way energy is produced and consumed

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Energy and technology

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About the BP Technology Outlook

The BP Technology Outlook examines the potential of technology to change the way we produce and use energy to 2050.

It draws on a series of studies carried out over three years by BP and eight partners in universities and research institutes, using a combination of fundamental analysis and energy system modelling to produce insights into long-term trends.

It examines three regions, China, Europe and North America, which together account for more than 50% of the world's primary energy consumption but have very different energy systems.

It is designed to inform thinking in business, governments, academia and beyond.

BP would like to thank its partners in the production of this publication: IHS Markit for studies on the oil & gas resource base and buildings sector; Ricardo for a study on ground transportation; Marakon for a study on the industrial heat sector; the Cambridge University Foreseer team and the Resource Efficiency Collective for studies on air quality and energy efficiency; KanORS-EMR for energy systems modelling and Imperial College, London, for a study on integrating renewables into power grids.

The Technology Outlook explores how technology could affect the whole energy system – from production through to use in power, transport and heat.

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A highway intersection in Los Angeles – the BP Technology Outlook examines energy systems in China, Europe and North America.

To make best use of this Outlook, it is important to understand what it seeks to do – and what it does not do – and how it differs from other views on future trends.

The Outlook uses 'techno-economic' analysis to show how the costs and deployment of a range of energy-related technologies could develop out to 2050. This approach takes account of factors such as investment, operating and fuel costs, capacity factors, and advances in technology including 'learning rates', whereby costs fall as experience is accumulated.

The core analysis therefore does not factor in the impact of policies, such as those aimed at reducing greenhouse gas emissions or improving air quality. However, in the studies on power, transport and heat, a carbon price has been overlaid on the core calculations to see what difference it could make.

By taking this approach, the Outlook provides an insight into how the world of energy could evolve independently of policy or regulation. It may therefore help policy-makers consider what additional incentives and measures to introduce.

The Outlook is thus not a set of forecasts – as forecasts would try to anticipate societal and policy-driven change in order to predict outcomes. Instead the Outlook uses modelling and analysis to provide insights into what technology advances could deliver, other factors aside.

The Outlook is based on developments anticipated in technologies known today without attempting to predict breakthrough innovations that might arise out to 2050.

This publication is the second BP Technology Outlook; the first was published in 2015.
The research undertaken for this edition, carried out during 2015-17*, has been expanded to include deeper studies of important areas, including:

- Energy-system modelling of a lower-carbon future
- The costs of providing back-up for wind and solar power when used at scale
- Options for energy storage, particularly advanced batteries and their implications for electric vehicles and power grids
- Air quality in cities, examining sources of emissions and potential solutions.

* Initiated in 2015, the study uses long-term price assumptions for a range of fuels, including $75 per barrel for Brent crude oil and $4 per million British thermal units for Henry Hub natural gas.

Taking the long-term view

It is an exciting time to be involved in the energy industry. Access to heat, power and mobility is continuing to help millions emerge from poverty across the developing world, and to underpin growth in industrialized economies.

However, as demand for energy grows, the way it is supplied is changing. Renewable energy is growing rapidly. Oil and gas are also still growing and being produced and used ever more efficiently. Meanwhile global coal use looks set to plateau and the prospects for nuclear power vary by region.

Although the speed of change seems to accelerate every day, the energy industry still needs a long-term view, as it is making investments in projects, developments and systems today that will last for decades.

Bob Dudley
Group chief executive

Such investments need to be informed by an understanding of what the future may hold and BP has always made this topic a priority. As we look to the future, our technology teams work with our businesses, specialists and partners to understand technological trends and forces. We are grateful to the experts in academia and elsewhere who have contributed to the research underpinning this Outlook.

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So far in my own career, I have seen technology transform the energy world through advances such as seismic imaging, shale production techniques, manufacturing innovations and reductions in renewable energy and battery costs.

This second BP Technology Outlook looks to the next generation of advances in the period to 2050. It reaffirms many of the insights from the first Outlook in 2015; for example, that energy resources remain abundant. It highlights how energy systems vary from region to region. It reminds us that it is less costly to reduce carbon emissions in power than in transport or heat. And it examines how digital technology is transforming energy.

However, the 2018 Outlook also provides some important new insights into technologies where progress has been even faster than expected three years ago. For example, the potential for growth among electric and self-driving vehicles is explored in more detail, as are the increasing competitiveness of wind and solar power and the rapidly falling costs of batteries.

The modelling shows us what technology has the potential to achieve over the coming three decades. The changes in prospect are exciting and profound – such as digitization and artificial intelligence, the electrification of transport, and the scaling up of renewable energy.

However, while such advances strongly support the transition to a low-carbon economy, our analysis also suggests they will not deliver it by themselves. Some further impetus will be needed, particularly policies that put a cost on carbon and encourage all of the ways in which emissions can be reduced – from greater energy efficiency and investments in low-carbon forms of energy to the wider use of carbon offsetting programmes.

Modelling insights are always approximate and certain to differ from what actually transpires, but the message is clear. As the statistician George Box said, “All models are wrong, but some are useful.”

Another important insight is the continued importance of natural gas. The analysis suggests gas can remain an integral part of the energy mix in a lower carbon world. It can be used in transportation as well as in heat and power, and it can be deployed along with carbon capture use and storage (CCUS) to provide the back-up that renewables need when used at scale. The study also suggests that CCUS is a critical component of a lower-carbon future.

While a study such as this Outlook can provide insights into the future of energy technology, it also highlights many uncertainties and ‘wild cards’. Digital technology is bound to continue to have a profound impact, including artificial intelligence, robotics and automation.

Emerging technologies, such as those covered here, from laser drilling to new types of solar photovoltaic modules, could also disrupt the trends and economics of the energy system.

Over the past few years, the BP Technology Outlook and its companion publication the BP Energy Outlook have helped shape BP’s choices. For example, our new investments in long-term natural gas projects reflect our projections of its strong growth and potential use in many technologies for decades to come. Digital technologies that are helping us discover and produce oil reserves – oil that will be used with increasing efficiency as vehicle technology evolves. Meanwhile our increased venturing investments in a range of high-technology start-ups, from bio-jet fuel made using domestic waste to artificial intelligence, embrace many new technologies that have potential to support the transition to a low-carbon energy system.

I hope that the BP Technology Outlook 2018 will prove valuable for all those who work in the world of energy or take an interest in it.

BP Technology Outlook
2018

For more information on the BP Technology Outlook: *www.bp.com/technologyoutlook*

How can technology help provide more energy and a sustainable environment?

Asia at night – energy-hungry megacities shine the brightest.

Why energy technology matters

The technology used to produce and consume energy has always been important. Today, however, it is critical to the future of the global economy and the environment.

The Industrial Revolution transformed economies through energy technologies such as the steam engine, locomotives and electricity. It started an era of unprecedented growth in which the world's population has grown eightfold and life expectancy has doubled.

That era of industrialization has provided benefits undreamed of by previous generations, but it also has contributed to a growing world population facing challenges such as increased greenhouse gas emissions and overcrowded, polluted cities.

The dual challenge

Society now faces a dual challenge – to meet increasing demand for energy at the same time as reducing emissions of greenhouse gases. Other issues such as air quality and water pollution also need to be managed.

This dilemma can be addressed by using energy as efficiently as possible, thus limiting the total consumed – energy saving; and by shifting to lower, zero or negative carbon sources of energy – energy switching. As well as using renewables or nuclear energy, switching can include substituting gas for coal in electricity generation as gas has roughly half the carbon emissions of coal when burned for power.

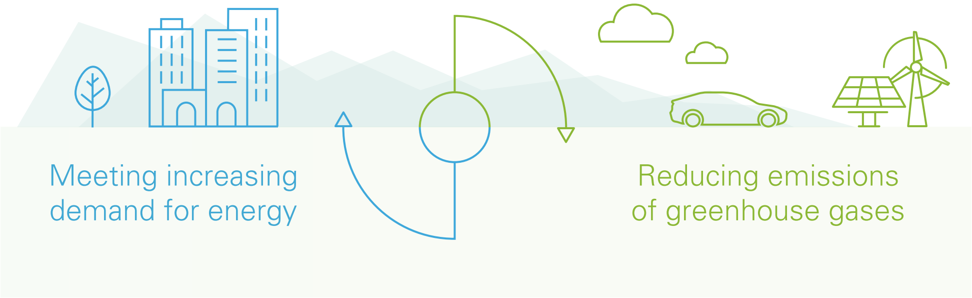
Technology has a key role to play, in both areas: increasing the efficiency with which energy is used and improving the affordability and availability of low-carbon energy.

Game-changing technologies

This Outlook is based on analysis of around 130 energy technologies including: oil and gas production, refineries and power stations; renewable power such as wind and solar; vehicles from conventional cars to electric cars and hybrids; heat technologies from gas boilers to electric heat pumps; and energy storage from batteries to hydrogen.

Many technologies have a part to play in resolving the dual challenge. However, this report highlights five particular areas in which our analysis suggests technology can play a game-changing role.

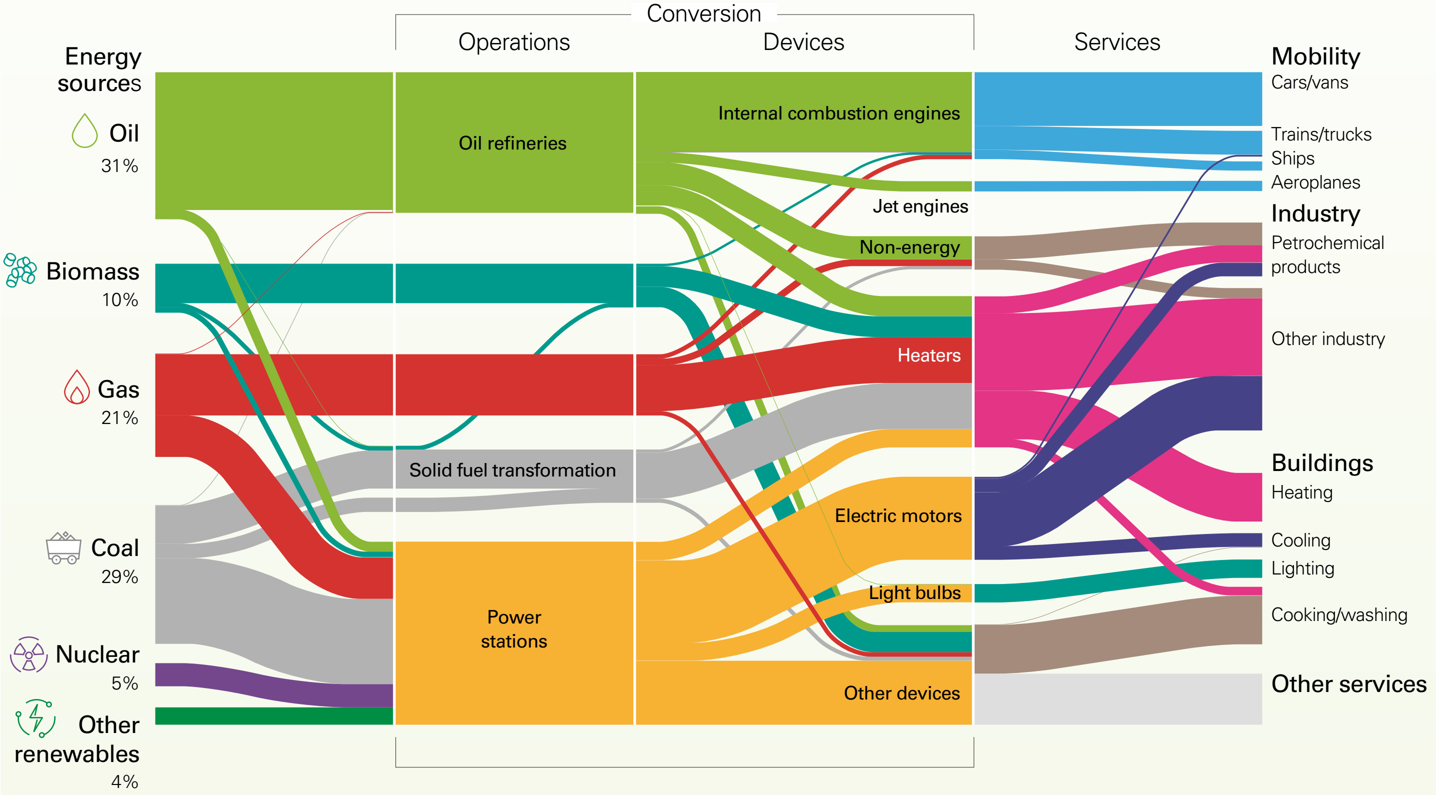
The dual challenge



As populations and economies grow, so does demand for energy – but at the same time, greenhouse gas emissions need to fall to meet environmental goals.

A complex system

This chart, known as a Sankey diagram, shows how energy is converted and consumed. On the left are the natural resources that provide energy – known as primary energy. The diagram shows how these resources are converted, for example in industrial operations such as oil refineries or power stations, and then consumed using devices from engines to light bulbs in order to provide us with the energy services shown on the right, such as mobility and lighting. Gas resources, for example, are used to generate power but also piped directly into homes for use in heating or cooking. The width of each strand indicates the quantity of energy involved. Although not reflected in this diagram, energy losses and inefficiencies occur at each stage, and can be material.



Based on IEA data from the World Energy Statistics and Balances © OECD/IEA 2013, www.iea.org/statistics.
Licence: www.iea.org/t&c; as modified by the Resource Efficiency Collective – University of Cambridge and BP.

A solar 'farm' – helping meet demand with low-carbon power.

Energy efficiency: The energy system that has emerged since the late 19th century is a complex one with multiple supply chains, in which primary energy such as oil, gas, coal, uranium (for nuclear power) and renewable resources are converted through processes such as refining and power generation and consumed to provide services such as heat, light and mobility. During the process, most of the energy consumed is lost before consumers experience the benefits. On pages 10 and 11 our partners in the University of Cambridge Resource Efficiency Collective describe specific technically feasible measures by which up to 40% of global primary energy could be saved, cost considerations aside, by wider use of higher performing technologies, many of which are available today.

Digitization: Digitization has the capacity to achieve new types and levels of energy efficiency, from smart grids and demand management in power systems to self-driving vehicles and ride-sharing that optimize use of vehicles and lower fuel consumption. In this Outlook, we cover digital technology in a special feature in section 1.4 as well as in the sections on energy production, power and transport.

Renewable power: Renewable power, particularly wind and solar, is already growing fast, driven by a combination of technology advances and supportive policies. The analysis suggests that the process is set to accelerate significantly to 2050, with wind, when available, projected to become the cheapest source of new-build power in the regions covered by this Outlook and solar becoming highly competitive. We cover renewable power in the sections on power (section 2.2) and a lower carbon future (section 3.0).

Energy storage: Storage options include battery technology which is undergoing major change after decades of dominance by lead-acid batteries. Lithium-ion batteries are developing rapidly and are projected to bring down the cost of electric vehicles – of which they represent a major part. Other emerging developments include metal-air, solid-state and flow batteries. Grid-scale batteries offer more options for storing electricity in power systems. In this Outlook we cover energy storage in the sections on power (section 2.2) and transport (section 2.3).

Decarbonized gas: Natural gas can be decarbonized through the application of carbon capture use and storage (CCUS), as well as by blending it with hydrogen or biogas – gas produced from biological materials. CCUS involves capturing the carbon dioxide created by the combustion of gas or other fuels at power stations and elsewhere, and either using it in a value-adding way that also includes keeping the CO_2 from the atmosphere, such as enhanced oil recovery or other industrial processes, or storing it underground. Decarbonized gas is not currently projected to make progress at a pace comparable to digital innovation, renewable power and energy storage. However, we include it among our game-changers because our projections suggest it has an important role in the most cost-effective energy mix for a lower-carbon future, and putting a price on carbon could drive wider-scale deployment. Decarbonized gas and CCUS are covered in the sections on power (section 2.2) and a sustainable energy system (section 3.0).

This study combines analysis and modelling to examine the potential impact of these and other technologies to help society resolve the dual challenge and meet future energy demand sustainably.

Dr Jonathan Cullen

Leader of the Resource Efficiency Collective, Cambridge University Engineering Department

> Areas with greatest potential for energy saving include cars, heating, cooking, washing and power plants.

For more information on the Resource Efficiency Collective visit: *www.refficiency.org*

Efficiency in the global energy system

The global energy system consists of a diverse range of technologies for transforming and using energy. Yet it is the delivery of energy services – such as mobility or heating – rather than energy itself, which drives consumer energy demand. The more efficiently these technologies operate, the less energy is required to deliver energy services.

Despite efforts to develop improved energy conversion technologies, the energy system as a whole remains woefully inefficient. Previous research into the efficiency limits for energy technologies has shown that global primary energy demand could theoretically be reduced by 85% today, if all energy technologies were operated at a 'technical maximum efficiency' limit calculated using thermodynamic theory and simple engineering models.

While the 85% savings established by the earlier studies represents a theoretical technical upper limit, they are unlikely to be fully achieved in the foreseeable future. This is because efficiency studies typically find average efficiency values for each technology, which can overestimate energy savings as they assume that all devices within a group can reach a 'best practice' efficiency. For many technologies this is unrealistic. For cars, for example, this would be akin to asking everyone to drive the same small efficient model of car.

In our latest study conducted with BP, we use distributions of current efficiency and consider both the maximum practical efficiency and the potential reduction in the spread of efficiencies within a given technology class. We examine global energy use across 35 technologies, provide a technology ranking and show that total primary energy savings of 217 exajoules (EJ) – about 40% of current supply, and half the technical efficiency limit – could be achieved. Areas with greatest potential for energy saving include cars, heating, cooking, washing and power plants (see graphic). If the maximum practical savings were made, demand for coal, oil, natural gas and biomass would be reduced by 31%, 47%, 40% and 40% respectively, resulting in annual emissions savings of 13.5 gigatonnes of carbon dioxide ($GtCO_2$). Energy savings of this order, if proved to be economically viable, would affect every aspect of the energy supply system, and deserve careful attention when making decisions concerning future energy provision.

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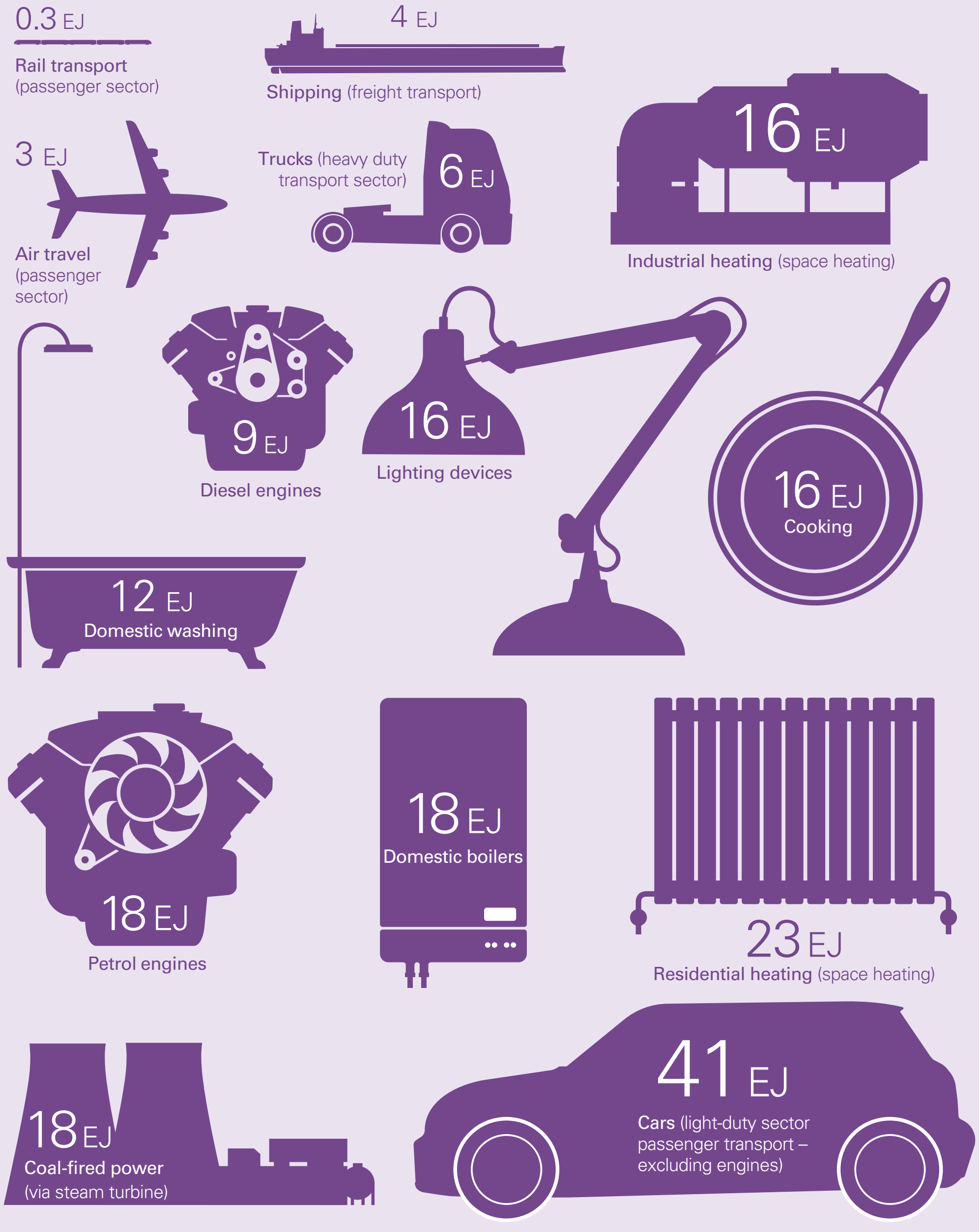
Potential for energy savings through efficiency improvements in fourteen different technologies

Using energy better

Thirty five technologies were analysed in this study – from cars and power plants to domestic cooking and washing – setting out the current range of efficiencies along with an assessment of the best available technology today and in 2050.

The top ten of these technologies, in terms of potential energy savings from improvements, account for more than three-quarters of the total estimated savings.



Larger images represent greater potential energy savings.

Potential annual energy savings are shown in exajoules (EJ), the joule being the standard unit of energy. One Exajoule is approximately equal to the average annual energy consumption of 26 million homes in North America or 160 million barrels of oil equivalent.

(EJ – 10^{18} Joules).

The total savings were calculated by tracking the energy savings back to primary energy – the volumes of oil, gas, coal, biomass, renewables and nuclear energy that would not need to be used.

The digitization of energy

How can digital technology change the energy system?

While the future of the energy system will be shaped by a wide variety of technological changes across energy production, power, transport and heating, one factor is common in driving transformation across energy production, processing and use – and that is digital innovation.

The impact of digital technology

We estimate that application of digital tools, including sensors, supercomputing, data analytics, automation and artificial intelligence (AI), all supported by the networked computers of the 'cloud', could reduce primary energy demand and costs in sectors of the energy system by 20-30% by 2050.

Right: Augmented reality – wearable technology, like these 'smart glasses' worn by a BP worker, is part of the digitization of the manufacturing industry.

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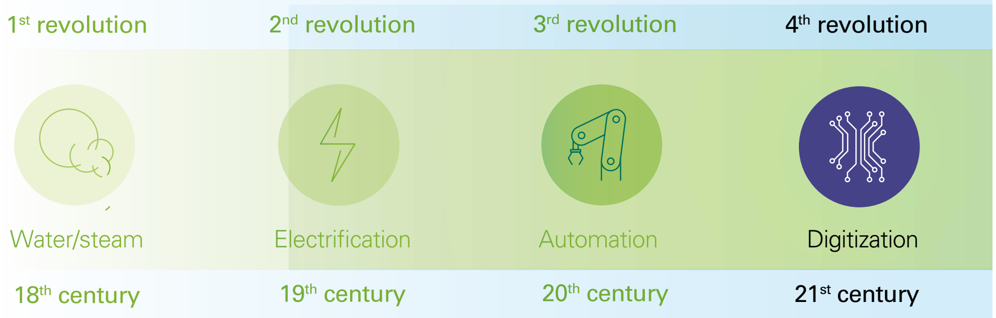
Digitization – the fourth industrial revolution

The fourth industrial revolution is projected to have a high impact across many industries.



1st revolution	2nd revolution	3rd revolution	4th revolution
Water/steam	Electrification	Automation	Digitization
18th century	19th century	20th century	21st century

ⓘ The first industrial revolution saw the introduction of steam engines and mechanization of manufacturing. The second saw the advent of electricity, while the third brought about the full automation of industrial processes, often using software or robotics. The fourth industrial revolution represents a fusion of the preceding three, with digital systems being used to monitor and control physical and biological systems.

Energy is experiencing what some have termed a ‘fourth industrial revolution’, following those of steam, electrification and automation. Digital and tangible assets and systems are being connected to create an integrated cyber-physical realm – or ‘the internet of things’ – that can be monitored and controlled using increasingly powerful and intelligent software.

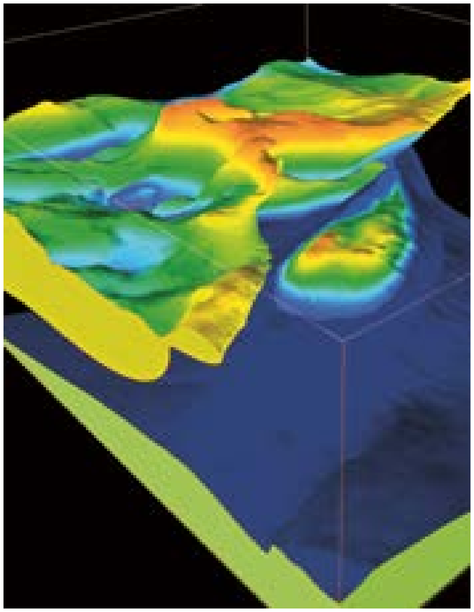
Building blocks of the digital energy industry include sensors that stream data and provide digital representations of mechanical systems, for example by monitoring of oil rigs, refineries, vehicles and power systems.

‘Big data’ software rapidly processes and analyses vast volumes of data generated by the sensor network, enabling simulations to be carried out to model and optimize outcomes before and during operation.

The full potential of machine intelligence cannot be predicted and some even foresee a so-called technology ‘singularity’ during which computers become – at least in some ways – more intelligent than humans.

The evolution of digital technology is sometimes described in terms of four ‘horizons’ – each of which has implications for the energy industry.

The first horizon has already been crossed in the energy world, for example with the use of machine learning algorithms to build models that describe and predict system behaviour. These models can analyse and compare sets of data from sensors to perform tasks such as locating possible oil or gas reserves or detecting when a piece of equipment may need maintenance.



Digital processing has long been used in the oil industry to create images of reservoirs from data acquired using seismic technology.

A robot rides a motorcycle to test Castrol lubricants – robots are used to improve test repeatability and safety.

A second horizon consists of technologies already deployed in some sectors, but with further scope for application in the energy industry. These systems include vehicles connected to networks, advanced imaging and blockchains, which facilitate transactions, tracing and auditing.

The third horizon includes innovations that are taking shape in some industries and have potential in energy and elsewhere. Autonomous smart machines and cognitive computing fall into this category, both being developments of artificial intelligence that go beyond problem-specific machine learning to absorbing human knowledge through interaction, working with imprecise and conflicting information and mimicking more complex human thought processes.

Fourth horizon technologies are those whose potential is only starting to be understood. These innovations include quantum computing, a developing processing technology using probability-based analysis to speed up computing time, and 'LiFi', a technology for transmitting data at very high speed through lighting.

BP's Centre for High Performance Computing in Houston, USA, home to one of the world's largest supercomputers for commercial research.

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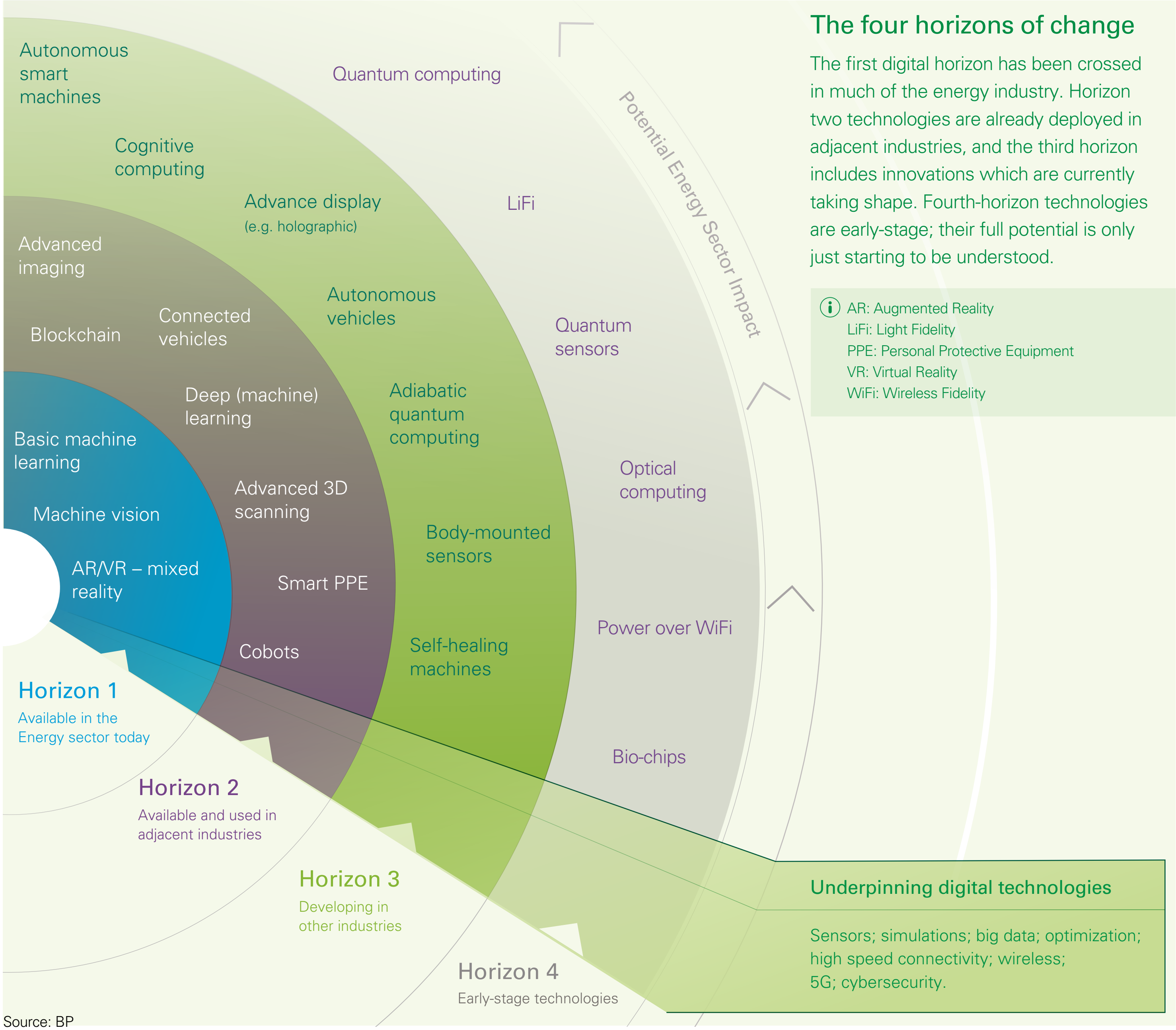
Digital transformation

The four horizons of change

The first digital horizon has been crossed in much of the energy industry. Horizon two technologies are already deployed in adjacent industries, and the third horizon includes innovations which are currently taking shape. Fourth-horizon technologies are early-stage; their full potential is only just starting to be understood.

AR: Augmented Reality
LiFi: Light Fidelity
PPE: Personal Protective Equipment
VR: Virtual Reality
WiFi: Wireless Fidelity



Underpinning digital technologies

Sensors; simulations; big data; optimization; high speed connectivity; wireless; 5G; cybersecurity.

Source: BP

Mark James

CTO Beyond Limits

> Intelligence is the most powerful and precious resource in existence, but there are countless untapped opportunities for intelligence to make the world a better place. The key is actionable intelligence – which could be harnessed by our digital world where everything can potentially be connected to generate data.

For more information on artificial intelligence visit: *www.beyond.ai*

The future of artificial intelligence in energy

Intelligence. In its varied forms, from the mysterious brain of the octopus and the swarm intelligence of ants to Go-playing deep learning machines and driverless vehicles, intelligence is the most powerful and precious resource in existence. Beyond recent advances in Artificial Intelligence (AI) that enable it to win games and drive cars, there are countless opportunities for intelligence to help make the world a better place. One such area is energy, including the modernization of the oil and gas industry. This is a global landscape rich in opportunities for protection of the environment, more efficient discovery of energy sources, workplace safety, plus diagnostics for more informed decision-making.

We live in a digital world where everything can potentially be connected. The key is actionable intelligence – data that's been analyzed to aid human decision-making. One important strategy is embedding intelligence so, decisions can be made at the sensor rather than "phoning home" to headquarters. Imagine an intelligent sensor on a drill bit that can manage its residual lifespan, avoiding the costly practice of pulling it up for inspection just because its Mean Time Between Failure rating (MTBF) says to.

Downstream, cognitive AI is now being applied to track tankers to determine when they leave port, where they're going, and how much petroleum or LNG they are transporting. Predicting what is being shipped, plus refinery destination and arrival times, will help traders make smarter decisions.

Removing friction from port scheduling operations requires a rare form of machine intelligence called cognitive intelligence (or human-like reasoning). This involves the fusion of the key cognitive capabilities of multi-agent scheduling with reactive recovery, asset management, rule compliance, diagnostics, and prognostics to ensure seamless autonomous operation.

My final prediction is about a development which I feel will become of increasing importance: embedding intelligence in silicon. While the world may think of AI running on mammoth computers, as in sci-fi movies, that approach is becoming a thing of the past. In the near future you will see the emergence of true intelligence being deployed in tiny blocks of silicon – even more disruptive than the transition from tubes to microelectronics.

Our wider vision of AI for the future of energy includes cognitive systems that intelligently and fluently interact with human experts and provide articulate explanations and answers. Across the board, you will see, and work with, systems endowed with rare and valuable intelligence.

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Production and uses of energy

Resources and production

How can technology improve the production and processing of energy?

In order to meet demand, the energy industry uses technology to find, produce and convert primary energy resources, including oil, natural gas, coal, uranium for nuclear power, biomass, solar and wind.

From the earliest oil wells to the latest wind turbines, technology developments have driven advances in the way that energy is discovered and produced – and many more developments are anticipated in the decades ahead.

Above: Onshore drilling in the United States – advanced drilling technologies have unlocked tight and shale resources.
Right: Fermentation tanks at a plant producing biofuels from sugarcane in Brazil.

In recent years, the oil and gas sector has experienced the 'shale revolution', enabled by technologies such as horizontal drilling and hydraulic fracturing, while renewable technologies have also been growing rapidly.

This analysis looks at how technology could continue to increase the volumes of primary energy resources that can be accessed, at the same time as decreasing their production costs, with a particular focus on oil and gas. Renewable energy is also covered in the power section.

See section 2.2

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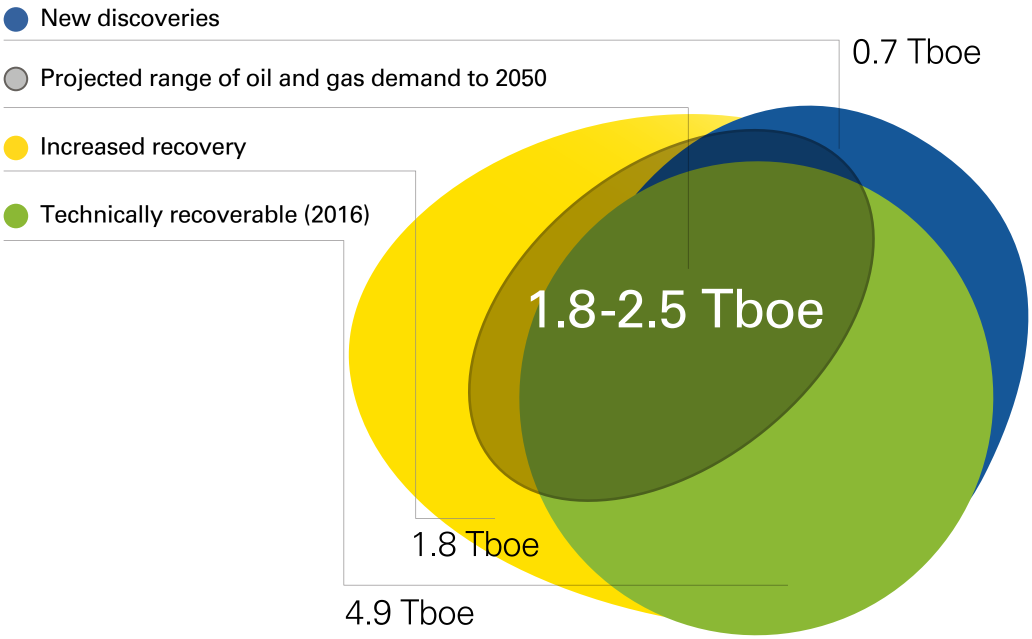
Abundant energy resources

Around 55 trillion barrels of oil and gas (measured in trillions of barrels of oil equivalent or Tboe) have been discovered around the world. Of these, we estimate that around one-tenth, or 4.9 Tboe, could be recovered using today’s technology. By applying evolving technology through to 2050, these recoverable volumes could be increased by more than one-third to around 7.3 Tboe. This volume is more than enough to meet the world’s projected demand to 2050 – estimated at 1.8 to 2.5 Tboe. However, exploration and technology development remain important in this sector to provide resource options that are more economical or have lower environmental footprints than some of the discovered resources. Oil and gas production from a reservoir declines naturally over its lifetime and our analysis supports the International Energy Agency’s estimate that investment of around $600 billion per year industry-wide could still be needed to produce sufficient oil and gas to satisfy demand – a figure which allows for impacts to oil and gas production from announced policies and pledges toward achieving the Paris Agreement.

Along with renewable energy, nuclear power and coal, which is still widely used although projected to plateau, there is no shortage of options to meet the world’s needs, despite the potential for the world’s economy to more than double by 2050, with the population projected to rise from around 7.5 to around 9.8 billion.

Potential new options to meet energy demand

The world has already discovered more than enough oil and gas to meet demand to 2050 – but technology could open up alternative options with lower costs and/or less environmental impact.



Source: IHS Markit & BP

ⓘ Estimates indicate that 4.9 trillion barrels of oil equivalent (Tboe) of oil and gas resources are recoverable using today’s technology. By applying technology as it evolves through to 2050, recoverable resources could increase to 7.3 Tboe, providing new possibilities to meet the projected range of demand of 1.8 to 2.5 Tboe.

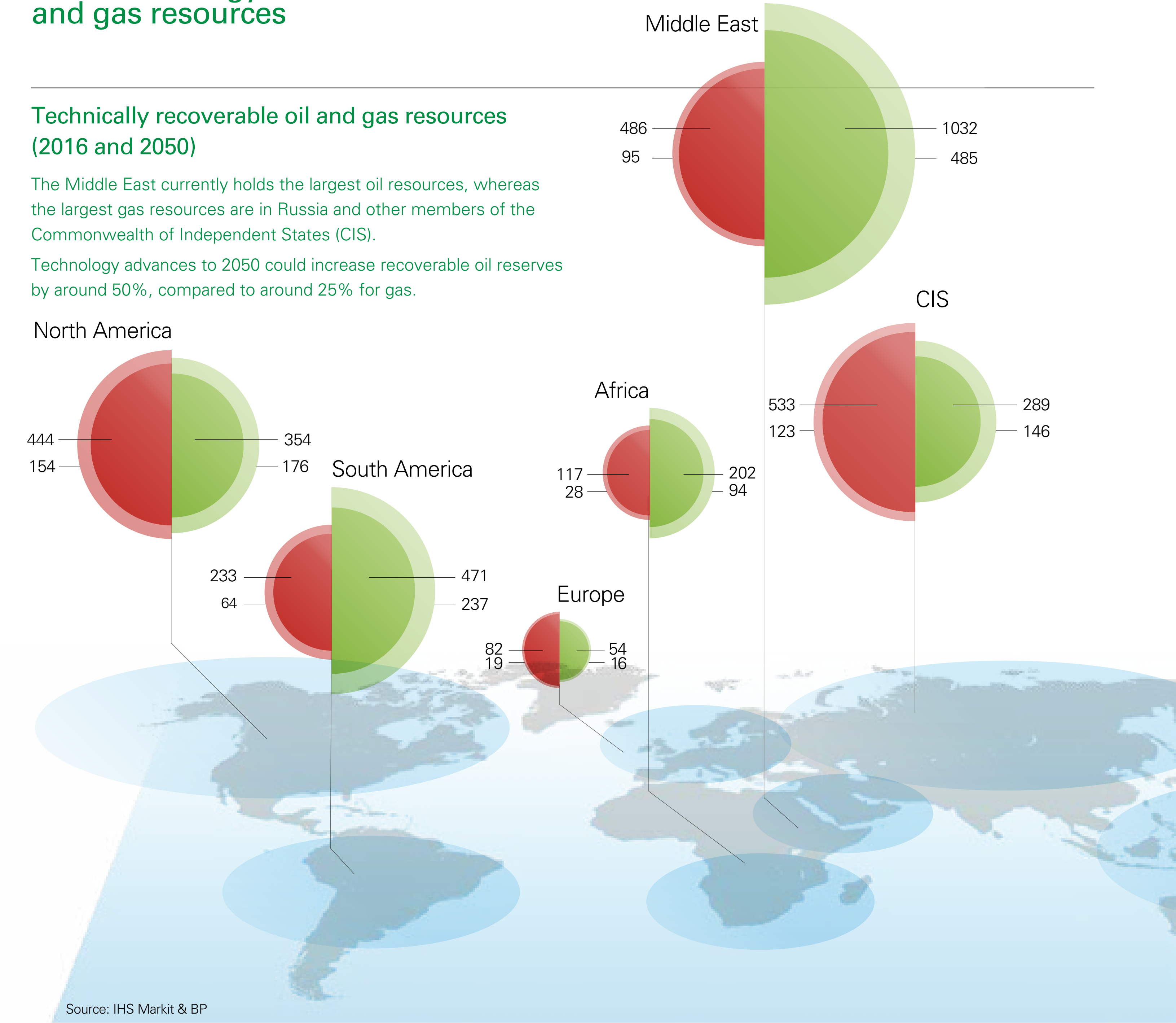
Potential demand could be met through various combinations of improved recovery, new discoveries and technically recoverable resources. Image indicative only.

How technology unlocks oil and gas resources

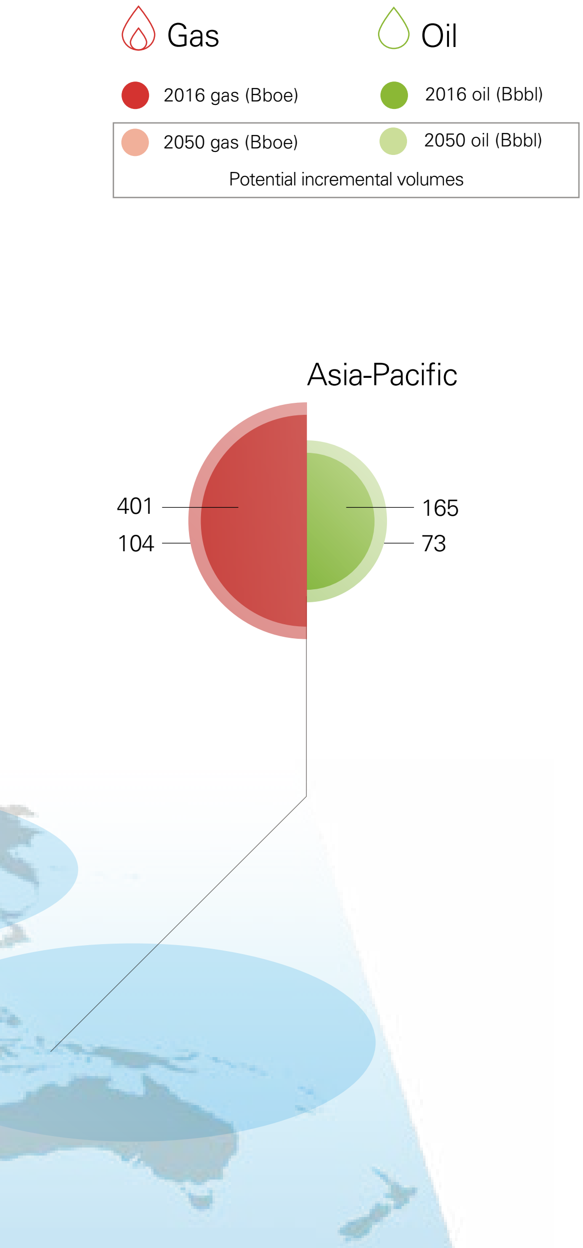
Technically recoverable oil and gas resources (2016 and 2050)

The Middle East currently holds the largest oil resources, whereas the largest gas resources are in Russia and other members of the Commonwealth of Independent States (CIS).

Technology advances to 2050 could increase recoverable oil reserves by around 50%, compared to around 25% for gas.



Source: IHS Markit & BP



Excludes undiscovered resources

The Khazzan gas field in Oman – our modelling shows gas demand remaining strong in a lower carbon world of 2050.

Oil and gas resources

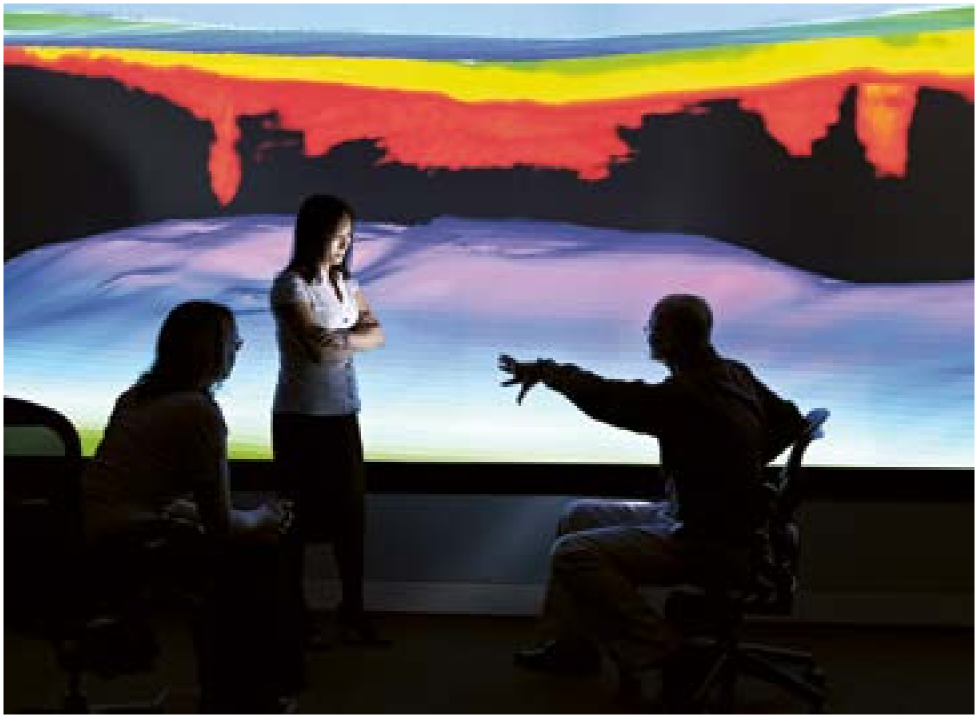
Around two-thirds of recoverable oil and gas resources are known as conventional because they can flow to the surface naturally, for example with water injection. The remainder of resources are known as 'unconventional', requiring changes to the physical properties of the fluids or the reservoir rock to enable them to be produced.

Unconventional resources include shale oil (oil found in fine-grained rock formations), tight oil and gas (oil and gas found in reservoir rocks with low permeability and porosity), oil sands (sand or sandstone that contains viscous oil) and oil shale (shales that need heating to produce oil).

BP's economic analysis in the BP Energy Outlook – 2018 edition suggests that oil and gas could still provide more than 40% of the world's energy in 2040 in a system on course to meet the Paris Agreement's goal of holding the rise in the global average temperature to well below 2°C above pre-industrial levels, as set out by the International Energy Agency's 'Sustainable Development Scenario'. In a scenario where policies and technologies evolve as in the recent past, BP's analysis shows demand for gas continuing to grow to 2040, while demand for oil grows and then plateaus, reflecting major efficiency gains in transport while gas demand remains broad-based across power, transport and heat. Gas can also be decarbonized using CCUS.

~30%

The potential reduction in average lifecycle* costs for oil and gas resulting from technology advances.



Geoscientists examine an image of the subsurface created from seismic data in a BP facility.

Costs of supply

The lifecycle costs of different oil types and gas resources vary considerably, depending on factors including the complexity of extraction, the depth and scale of the reservoir, and its geography.

Costs are also affected by factors such as regulatory incentives, taxes and logistics beyond the scope of this analysis.

There is strong and increasing competition between resources in the middle of the cost range.

As shown opposite, our analysis indicates that technology advances can play a major role in improving access to oil and gas and in reducing the costs of production.

*The combined cost of development and operation over the life of the field.

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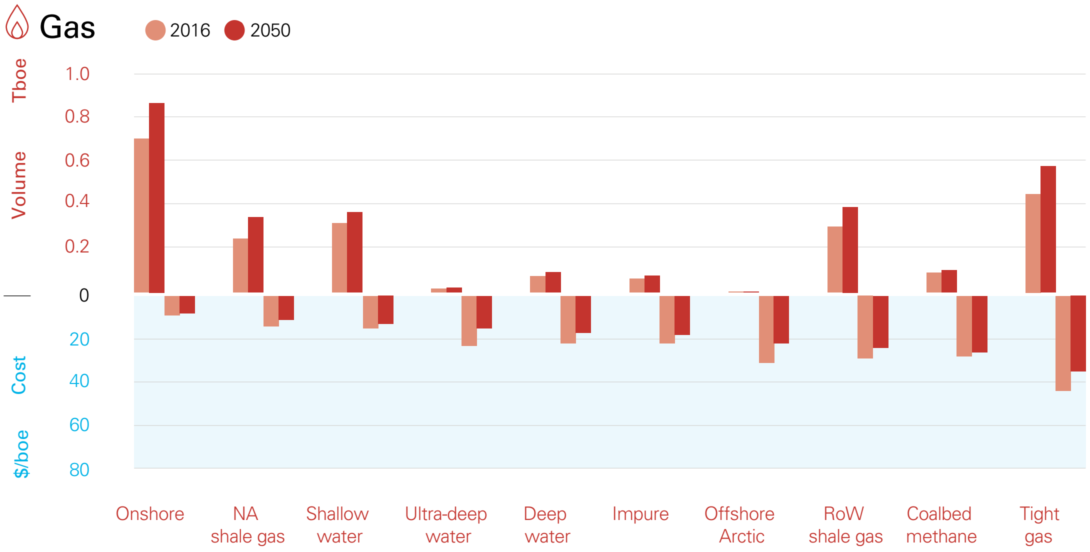
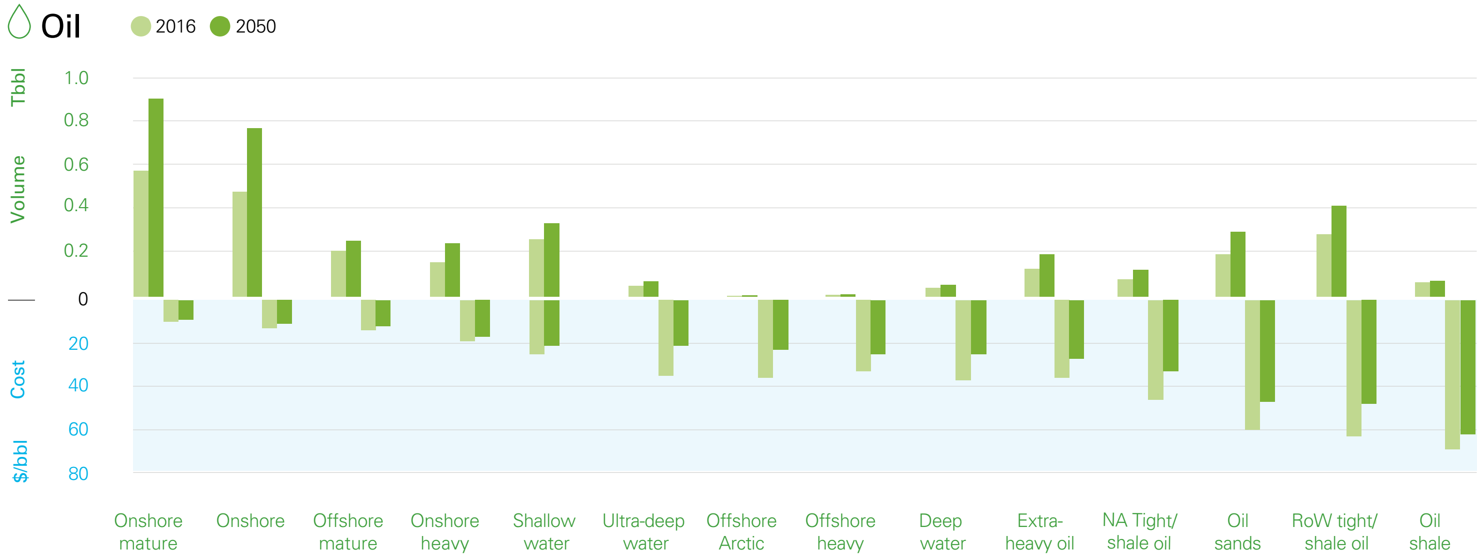
More energy at lower cost

Potential volume increases and cost reductions through technology 2016-2050.





ⓘ Resource volumes are shown unaffected by factors beyond technology and economics, such as policy.

Data excludes undiscovered resources.

Costs are full lifetime, undiscounted, i.e. not reduced for factors such as costs of capital including inflation.

NA: North America

RoW: Rest of World

Source: IHS Markit & BP

James Haywood

Director, Global Growth Strategy
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> There is massive scope for technology to transform the energy industry – reducing capital expenditure, lowering operating costs, and increasing production and reservoir recovery factors.

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Energy production to 2050

Despite great advances in technology in recent years, only around 35% of the oil in a typical field is recovered and only around 3% of data captured at oil and gas operations is used. There is therefore massive scope for technology to transform the energy industry, reducing capital expenditure, lowering operating costs, and increasing production and reservoir recovery factors.

This transformation is well underway, embracing both digital and physical developments.

For example, the ability to collect vast data, digitally twin physical and virtual assets, and predict asset parameters in real-time, allows optimization of oil field reliability and performance. Such systems integrate data from hundreds of thousands of sensors, providing real-time visibility and insightful predictive analytics.

Wells are becoming more sophisticated – self-regulating, sensing and reacting to the reservoir, automatically optimizing production, minimizing intervention requirements, and lowering overall costs per barrel.

Inspection and maintenance can also benefit from automation and digitization. Today, many inspection tasks are carried out manually. This approach is not only time consuming and costly, but can also be hazardous, often requiring inspection shut-downs. Robotics, high-performance computing, and artificial intelligence are extending the range of tasks machines can do better than humans. A drone system recently reduced inspection time from over a month to a few days, eliminating the need for a rope crew and cranes.

Looking to developments in infrastructure, non-metallic flexible pipes made from composite materials are offering game-changing advances in the ‘risers’ that transport oil and gas from offshore fields to the surface, with reductions in weight (lowering by 30%), system complexity, and cost (lowering by 20%), as well as risk.

Elsewhere, as renewables generate more capacity, there will be increasing need for storage systems to cover their intermittency. Liquid Air Energy Storage (LAES) and Compressed Air Energy Storage (CAES) systems provide large scale, long duration energy storage that can deliver 5–200 MW.

These disruptors represent just a few of the emerging technologies now starting to have an impact. Others include additive manufacturing or 3D printing, molecular and nanoscience, novel forms of carbon capture, and advances in energy recovery. Taken together, these technologies are set to modernize working practices, increase efficiency, lower costs, and change the face of the energy industry.

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Improving access to oil and gas

Areas in which technologies are most effective in increasing access to oil and gas reserves include seismic exploration, enhanced recovery and wells. Seismic analysis is already benefitting from the use of supercomputers to analyse results quickly and provide highly detailed pictures of oil and gas reservoirs. We anticipate further advances in seismic imaging and the processing and interpretation of the vast volumes of data acquired. One example is the use of 'full waveform inversion', in which complex algorithms enable accurate predictions of reservoir behaviour. The analysis indicates the largest impact will be onshore where acquiring seismic data can be difficult, with improved imaging enabling explorers to optimise well locations.

Improved and enhanced oil recovery (IOR/EOR) technologies continue to develop, with new techniques such as modified salinity water and use of nanoparticles supplementing more established methods. Our estimates suggest that IOR/EOR could deliver around 500 billion additional barrels of oil, or a 10% aggregate increase in total remaining recoverable resources, by 2050.

Well technology development offers potential volume increases from stimulation, completions and intervention, with the greatest benefit for those, mostly unconventional, resources developed using large numbers of wells.

Lowering production costs of oil and gas

We estimate that, by 2050, technology has the potential to reduce average lifecycle costs by around 30% per barrel of oil equivalent across all oil and gas resource classes.

The types of resource with the greatest scope for cost reduction are the most capital intensive, such as deep and ultra-deep water, and those requiring large numbers of wells – such as unconventional resources including tight and shale oil. Deep water resources can benefit from improved rig and platform design as well as subsea and flow line development.

At onshore sites, such as shale fields with large numbers of well pads, a standardised, repetitive manufacturing-style approach could reduce costs. Optimising production operations and field development could also lead to cost savings.

Digital production

Digitization is projected to underpin 25% of the increased volumes and one-third of the cost reductions associated with technology improvements, with the greatest impacts potentially coming from artificial intelligence.

Digitizing the search for gas – vibrator trucks carry out seismic operations for BP in the desert of Oman.

Nuclear power has been growing in some regions, particularly in China, while declining in others, such as Europe.

The industry is also looking ahead to major advances in automation of well design and construction, maintenance and processing activity in facilities, and optimization of production. There may be other breakthroughs in technologies that are today at a very early stage, such as various forms of non-mechanical drilling using lasers, burners or electrical discharges. Digital innovation could also have a key role in preventing losses of energy during production, for example through the use of sensors and blockchain technology to track methane and reduce leaks.

Other forms of primary energy

As well as oil and gas, primary energy resources include coal, uranium for nuclear power and renewable resources such as hydroelectricity, wind and solar power.

Coal remains the largest global source of fuel for electricity generation today, as well as being used widely for heating in buildings and industry. It is plentiful, mined in more than 50 countries, with more than one trillion tonnes available in the world’s reserves - enough for more than a century of production at current usage rates. However, coal has the highest carbon content of any form of primary energy. Its share of energy is starting to fall, partly as a result of policies and preferences for lower-carbon fuels and partly due to natural

A barge carries coal along the Huangpu River in Shanghai – as of 2016 China used four times more coal than the next largest coal consuming country.

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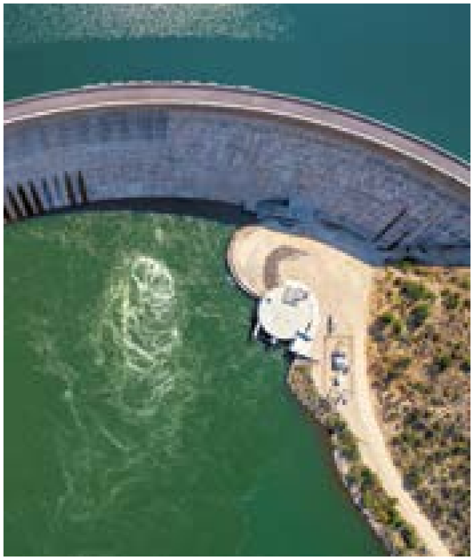

A hydroelectric power facility in Idaho, US – hydroelectricity supplied 60% of the state's net power generation in 2016.

Europe's largest floating solar farm – at the Queen Elizabeth II reservoir near London – built by Lightsource BP.

gas and renewables becoming increasingly available and competitive. While demand appears set to plateau, coal usage is likely to remain significant for some years. Potential advances in its exploitation include greater use of underground coal gasification (UCG) whereby oxidants are injected into coal seams, converting the reserves to gases that are produced through wells.

Nuclear power stations are fuelled by the heavy metal uranium, generating power by splitting the nucleus of the U-235 isotope in chain reactions that release a very large amount of energy from a relatively small quantity of uranium. Discovered uranium resources are plentiful, enough to last about 90 years. Underground and open-pit mining have steadily given way to in situ leach (ISL) mining, whereby ore holding the uranium minerals is dissolved, allowing the uranium to be pumped out of the ground. ISL mining now accounts for nearly half of total world production. Nuclear generation creates hazardous waste which is typically stored at or close to the plant while levels of radioactivity decline before disposal, for example being encased in glass and left deep underground.

Many **renewable energy** resources comprise of natural forces such as wind, sunshine and water flows which can be converted directly to power (see section 2.2). Biomass is different in that it uses energy from a variety of materials from wood and grasses to crops and waste. Bio-materials have been a source of energy for millennia and are now increasingly used in industrialized economies as a feedstock for fuels, power, lubricants and chemicals. Biomass can be used for power generation where there is low-cost and sufficient supply of feedstock. The industrial biotechnology sector is growing, offering biological and biodegradable alternatives for a range of materials that are typically oil-based today, as well as some completely new materials.

➔ **See section 2.2**

Wood pellets – a form of biomass energy used from domestic boilers to large power plants.

Digital technology has the potential to drive major advances in the efficiency of manufacturing facilities, particularly in monitoring and automating operations.

Refining

Once crude oil has been produced, much of it is converted to fuels in refineries. Mainstream refining processes are mature technologies which are more likely to see incremental efficiency or process improvements and cost reductions than transformational changes, with the possible exception of processing of bio-products. Generally, operational excellence, in areas such as cost performance, availability, and product optimization, is anticipated to be more significant in reducing costs than new conversion technologies.

Such operational improvements are set to be accelerated by digital technology which has the potential to drive major advances in the efficiency of facilities, particularly in monitoring and automating activities, managing maintenance, co-ordinating work schedules and increasing the 'wrench time' spent by employees on productive activity.

By the mid-2020s, energy facilities are routinely expected to use remote-controlled maintenance, real-time process optimization and autonomous inspections. Technologies that enable such developments include data standardisation, big data, wearables – such as smart watches or activity trackers – artificial intelligence, robotics and edge computing, where computers located at the sources of data complete some processing functions whilst also interacting with others over the networked computers of the 'cloud'.

With such technologies, refinery maintenance can increasingly become preventative rather than reactive, minimizing downtime and maximizing productivity. The prize is significant, given that a 1% increase in mechanical availability has been estimated to result in greater safety and a 10% reduction in maintenance costs.

Technologies converting non-crude oil feedstocks to liquid fuels for vehicles and aviation – such as gas, coal, biomass and municipal solid waste – are at various stages of maturity. Some gas-to-liquid and coal-to-liquid facilities are currently operated at a commercial scale. Biofuels for road vehicles are manufactured at scale in some regions, including ethanol (a gasoline substitute) made from corn in the United States, ethanol from sugarcane in Brazil, and biodiesel, for which Europe is the largest market. The biojet market for aircraft is small but growing as the aviation industry seeks to meet its target to cap greenhouse gas emissions at 2020 levels.

See section 2.3

BP's Whiting Refinery – refineries are expected to benefit more from digitization and other advances that improve efficiency than from transformational changes in technology.

Adnan Z. Amin

Director-General of the International Renewable Energy Agency (IRENA)

> Renewables are transforming the global energy system at unprecedented speed. It is increasingly clear that low-carbon technologies are no longer the energy system of the future, but the energy system of today.

For more information on IRENA visit:
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Technology is powering renewable energy's rise

Renewable energy cost reductions are transforming the global energy system at unprecedented speed. Since 2010, the cost of generating electricity from solar photovoltaic (PV) and onshore wind has fallen by 73% and 23% respectively and both now compete with fossil fuels – onshore wind doing so at the lower end of the average cost spectrum.

This falling cost trajectory promises to fundamentally reshape the global energy landscape. Our belief is that by 2020 all forms of renewable energy – including concentrating solar power (CSP) and offshore wind – will compete with fossil fuels for new power generation needs, a fact that now underpins a compelling business case for renewable energy.

Behind the headline numbers is a story of constantly improving technology. New solar PV cell architectures offer improved efficiency, larger wind turbines sweep greater areas, harvesting more electricity at the same site, and powerful new 250-metre-tall floating turbines such as the ones developed for Scotland's Hywind project offer a glimpse into the future for offshore technology.

CSP is not being left behind, with auction results in 2017 signalling that it will soon compete head-to-head with fossil fuels on price in some locations. A 700-megawatt solar project in Dubai, for example, will use molten salt thermal energy storage to deliver electricity overnight – at around 70 US $ per MWh – competing with fossil fuel power generation without subsidy, highlighting that dispatchable solar power for the global energy system is possible and economic.

Power generation technology is only part of the energy transformation story. Stationary storage technology is continuously improving, and costs are falling steeply. While pumped hydro systems currently dominate total installed power storage capacity, our analysis shows that the cost of stationary batteries such as lithium-ion and flow batteries could fall by up to 66% by 2030, in turn stimulating 17-fold growth in storage capacity.

This momentum is representative of a new energy paradigm – a smart, responsive, low-carbon way to generate and consume energy, defined by a mix of utility-scale and decentralized, digitalized technologies. Indeed, it is increasingly clear that this is no longer the energy system of the future, but the energy system of today.

How might technology affect the future of electricity generation?

Power currently accounts for 42% of primary energy demand globally and has greater potential than transport or heat for reducing greenhouse gas emissions, economically and at scale.

The power generation market currently has a wide range of options, including use of coal, gas, hydropower, nuclear, oil, onshore and offshore wind, biomass, solar photovoltaics (PV) and other renewables.

Competition between different sources of power is complex, and depends on many factors, including technology development, regional variations in supply chain maturity, system flexibility to accommodate intermittency, storage improvements, cost of capital, quality of wind and solar resources, the relative costs of fossil feedstocks, and carbon pricing or other environmental policies.

Current trends

In 2015, around 39% of the world's power demand was met by coal-fired generation, 23% from natural gas, 16% from hydropower, 11% from nuclear power, 4% from oil, 3% from wind power, 1% from solar power, and the balance from other sources.

A major transition is underway in the power sector as demand for energy continues to increase, with renewables growing rapidly and gas expanding as coal consumption plateaus. Wind and solar are the fastest growing forms of power: wind capacity more than doubled in the five years to 2015, the baseline for this analysis, while installed solar grew six-fold. Coal remains the largest source of power world-wide and accounted for the largest additions to global capacity between 2010 and 2015. However coal consumption has started to plateau for both economic and environmental reasons,

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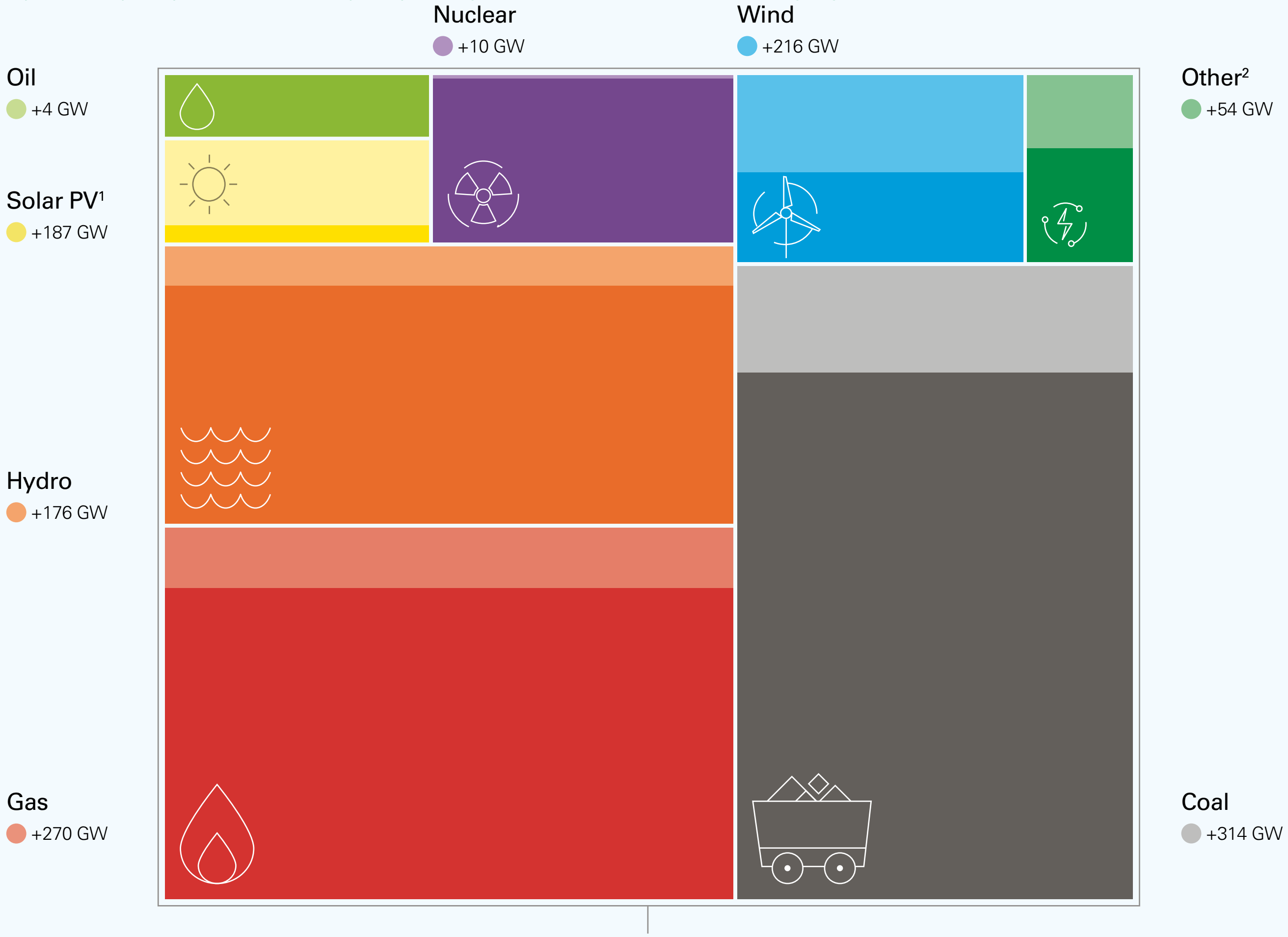
The changing world of power

Global power capacity in 2015 with capacity changes between 2010 and 2015 highlighted.



2015 Total grid capacity: 6,400 GW

Key: ● Dark shade: 2010 ● Light shade: 2010-2015

[1] Photovoltaic.

[2] Biomass, geothermal, ocean and concentrated solar power.

Note: sizing proportionate to generation capacity.

Based on IEA data from the World Energy Statistics and Balances © OECD/IEA 2012&2017, www.iea.org/statistics. Licence: www.iea.org/t&c; as modified by BP.

ⓘ Between 2010 and 2015, most new generating capacity worldwide came from coal, followed by gas, wind, solar and hydropower. Newly built renewable capacity broadly matched that of the new additions in coal and gas combined.

Engineers check the steam turbine in a gas-fired power station. Combined cycle gas turbine power stations use both a gas turbine and a steam turbine to generate electricity.

including improving air quality and lowering greenhouse gas emissions. Gas-fired power has grown as it offers an economical option with flexibility, including back-up for renewables. Hydropower is also growing steadily while the decline of nuclear power in Europe has been balanced by a major expansion in China, which is also investing heavily in renewables to meet growing demand while reducing reliance on coal.

Power generation technologies

Despite the potential plateau in demand for **coal-fired** power generation it remains a significant power source and technology-driven improvements are being pursued. If all coal-fired power stations used modern supercritical steam technologies with very high operating temperature and pressure systems, it is estimated that average efficiency across the world's fleet of coal-fired plants would rise from around 33% to 45% or more. However, greenhouse gas emissions would still be considerably higher than from gas-fired plants, due to the much higher carbon content of coal.

Gas-fired power stations have become cheaper and more flexible in recent decades, led by combined cycle gas turbines (CCGT) – a form of highly efficient energy generation technology that combines a gas-fired turbine with a steam turbine. The gas turbine creates electricity and the resulting waste heat is used to create steam, which in turn drives another turbine. Gas and coal plants can be built with carbon capture use and storage (CCUS) technology to capture and store carbon dioxide emissions. While CCUS is uncommon at scale today, most current installations supply the captured carbon dioxide for use in enhancing oil recovery.

Nuclear power capacity has remained broadly flat in recent years. Some countries have reduced investment while others, particularly China, have implemented major new nuclear programmes.

New types of nuclear facility include small modular reactors (SMRs) which are at the demonstration stage and could, in theory, be built in a factory and deployed relatively quickly. Many countries are researching nuclear fusion, which involves joining subatomic particles rather than splitting them as in fission, but fundamental challenges still exist and wide-scale deployment of this approach before 2050 appears unlikely.

The costs of renewable electricity continue to fall, leading to greater deployment. However, when used at large scale, they require back-up from other sources, as wind and sunshine are both intermittent.

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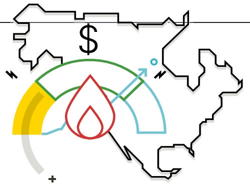

In the United States, gas-fired power has surpassed coal as the main source of fuel used to generate electricity.

Turbines at BP's Cedar Creek wind farm in Colorado – wind was one of the three fastest-growing forms of new power generation globally between 2010 and 2015.

Our projections show the costs of **wind power** decreasing as a result of technical advances such as taller turbine towers, longer, lighter rotor blades and more efficient control systems. These advances result in lower investment costs per megawatt (MW) of generating capacity and more wind energy being captured. Emerging wind technologies that may have a role include kites and bladeless turbines that create power by shaking rather than spinning. Our calculations assume that average costs of wind power – onshore and offshore – fall 19% for every doubling of culmulative global output.

Costs of **solar photovoltaic (PV)** projects are also set to continue to fall as a result of factors including lower production costs and increasingly efficient cells. Emerging solar panel technologies include thermo-photovoltaics that store energy as well as generating power, cells made of novel materials such as Perovskite and Kesterite and tandem cells that capture more of the light spectrum by stacking two or more sub-cells on top of each other. Our calculations assume that average costs of solar modules fall 23% for every doubling of culmulative global output.

Hydropower is a mature technology and improvements are anticipated to be incremental rather than transformational. Hydro-electric facilities harness the power of rivers using turbines. They can also be used to store energy. This storage function is increasingly important to provide back-up for the intermittency of renewables.

Other renewable sources, such as **geothermal** power, can be expected to play roles in specific areas, while some, such as large-scale **wave and tidal** power, are early-stage technologies that still require significant investment and technical development to grow.

Oil-fired power is still used in a few countries, for example in the Middle East where oil is plentiful, but generally has become uncompetitive with alternatives.

Power costs in 2015

The costs of different forms of power generation vary widely between regions, resulting in very different mixes of technologies used to generate electricity.

In North America, gas-fired power and coal are both plentiful and have been competing fiercely for their share of power generation. In 2015, the baseline for this analysis, electricity generated at existing coal-fired plants was a little cheaper on average than from gas-fired facilities. However, since 2015, with shale gas production rising, gas-fired power has become cheaper on average and replaced coal as the most used power feedstock in the United States. A shift in electricity generating stock, with closures of coal plants and increasingly efficient new gas-fired facilities, is also set to contribute to the strength of gas in the US power sector. The 2015 data also shows gas was cheaper than wind, on average, but wind costs have been falling rapidly and can be lower than those of gas in areas with strong wind availability such as the Mid-West. Costs of solar are also falling, dramatically in some cases, although, on average, they were higher than those of wind in the 2015 baseline. Average costs of nuclear power are several times higher than those of other sources.

In Europe, the pattern is similar, although, with less favourable resources, average costs for newly-built gas plants, solar developments and wind farms have been generally at least 30% higher than in North America, while nuclear has similarly high costs. In China, the picture is very different, with plentiful coal providing the most economical source of electricity, followed by nuclear power, with a cost around one-third of that in Europe and North America owing to an intensive building programme. Renewables have also been growing fast in China and the country now has the world's highest levels of wind and solar capacity.

Relative costs set to change by 2050

Between 2015 and 2050, the techno-economic analysis indicates the mix of technologies used for power generation in each region could change. In particular, wind and solar power are set to grow as their technology costs fall.[1]

The modelling indicates that by 2050, onshore wind farms will provide the cheapest source for new power supplies in China, Europe and North America, closely followed by solar PV.

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[1] Hydropower has been excluded from the analysis because the remaining accessible water resources are relatively limited, particularly in North America and Europe.

North American power generation costs in 2015 and 2050

Gas and coal were the cheapest sources of power in 2015 but onshore wind costs are set to fall below those of newly-built gas plants well before 2050. Solar is also competitive at lower penetration levels. Decarbonised gas represents the cheapest source of flexible power generation and potential back-up for renewables.

ⓘ Assumptions: 64 $/t for coal; 4 $/mmbtu for gas; 7% weighted average cost of capital (10% for carbon capture & storage and nuclear); CO_2 price applied to combustion emissions only.

The image shows average costs representative of the new build facilities. A large cost range exists – both today and in 2050. Advantaged sites and lower weighted average cost of capital (WACC) are particularly significant factors in the cost calculations and can result in costs falling below the average values shown here.

Source: BP

[2] Includes range of projections for capital investment and operation.

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In North America, gas is the cheapest form of back-up generation for renewables and with a carbon price of 100 $/tCO$_2$ it would be cost-effective to decarbonise gas-fired power using CCUS.

In Europe, the pattern is similar, although costs are somewhat higher, reflecting the less favourable resources.

In China, the programmatic manufacturing approach has resulted in costs for nuclear power that are only around half of those in Europe and North America. The natural back-up options for renewables in China are hydropower and coal, the latter with CCUS at higher carbon prices.

Managing the intermittency of wind and solar power

As both wind and sunshine are variable and intermittent, when used for power generation they require dependable back-up. This support can come from other forms of power generation or from energy stored in batteries or hydropower dams. Intermittency can also be managed using demand side response systems that lower electricity consumption among customers.

While the capital and operating costs of wind and solar are projected to fall, the costs of managing intermittency – known as ‘integration costs’ – rise as more renewable energy is deployed.

The intermittency costs incorporated in our modelling derive from a new study carried out with Imperial College London. This research modelled the integration costs of systems where wind and solar together made up 10%, 40% and 75% of all power.

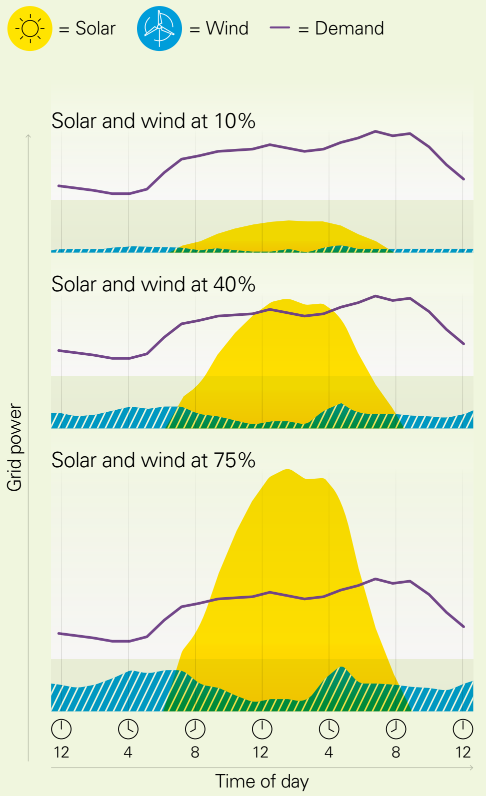
The study examined systems with two types of renewable component. In the first, ‘solar-dominated’, version, the renewable component comprised 80% solar and 20% wind – as might be found in the Middle East or Southern Europe. The second was ‘wind-dominated’ – 80% wind and 20% solar – as might be found in the US Mid-West or Northern Europe.

The modelling showed that rising integration costs are particularly pronounced with solar as it is less well correlated with demand at high levels of penetration, as sunshine declines in the early evening just as demand peaks. However, in very hot, sunny countries, solar can be highly cost-effective in driving cooling systems. In contrast, wind blows more variably through the day and night and has lower integration costs.

Intermittency of renewables

Solar and wind power need back-up as they vary through the day and night. These charts show an energy system operating in a sunny climate, like that of Spain, with the renewable component being 80% solar power and 20% wind. They demonstrate the contribution of the renewables when they make up 10%, 40% and 75% of annual power supply.

As well as variability during a typical day, as shown here, renewable power also varies by season and geography.

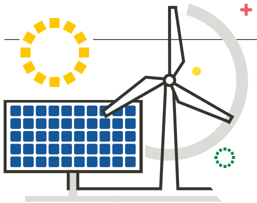


ⓘ The purple line shows daily demand for power, peaking around 6-8 pm.

When solar and wind make up 40% of annual power supply, significant back-up is needed.

At 75%, the renewable capacity provides more than enough power in the daytime, but still not enough at night-time. Some demand may be movable. Other measures to balance supply with demand include storing excess supply and discharging when dark, or providing supply from back-up technologies such as gas.

Source: BP



Renewable energy is intermittent and requires back-up, with costs projected to be lower for wind than solar.

For example, for a power system in North America, with a 40% contribution from renewables, dominated by wind, the study estimated that the integration costs would be less than 5 $/MWh for each additional MWh of power generated. However, if solar were the predominant source, the integration costs would rise to around 20 $/MWh. If the contribution from renewables increased to 75% of all power, the integration costs would increase to 25 $/MWh for a wind-dominated system or 55 $/MWh for a solar-dominated one. Applying these costs alongside those of other fuels in a carbon-constrained world, we project that an onshore wind-dominated renewable system could remain competitive in 2050 even when it provides 75% or more of all power, while a solar-dominated one may also be competitive at around 40%.

Back-up options for renewables

Many options exist to back up renewable energy and the technology selected often depends on how flexible it can be. As well as conventional power generation, such as gas or nuclear plants, being brought online, stored energy can be released from batteries or hydro-electric dams. Water can also be pumped back up into dams for later release – known as pumped hydro. Compressed air energy storage (CAES) involves compressing air in underground caverns and later releasing it to drive a turbine generator. Other measures include demand-side technologies used to move demand to better match peaks in intermittent renewable generation and interconnections between grids that enable them to supplement each other as demand requires.

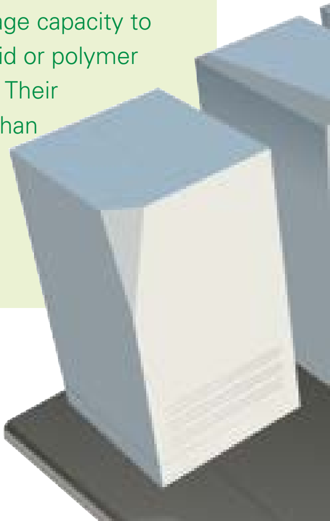
For shorter duration 'peaking' services, required at times of peak demand, lead-acid batteries and compressed air are the most economical options to store energy today, alongside pumped hyrdo, but lithium-ion and flow batteries are projected to be competitive well before 2050. Indeed, early examples of grid-scale lithium-ion battery storage are already in use.

For longer duration 'balancing' services, whereby power is stored at times of lower demand to be released when demand rises, pumped hydro is widely used today; gas-fired power, where available, is otherwise the most effective source of back-up. In the future, many types of new generation batteries should see growing use.

The 21st century battery

After decades of dominance by lead-acid batteries, new types of battery are developing rapidly, with great potential for power storage, electric vehicles (see section 2.3) and other applications. While there are uncertainties around the pace of change, high energy density lithium-ion batteries have seen costs fall significantly since 2010. Other new technologies include metal-air, flow and solid-state batteries. In metal-air batteries electricity is generated through a chemical reaction that oxidises a metal such as lithium or zinc using oxygen from the air. Flow batteries typically use two liquid electrolytes stored in external tanks to hold charge with energy released by pumping the charged fluids through an electrochemical cell. Because of their simple structure, it can be relatively cheap to add storage capacity to flow batteries. Solid-state batteries replace liquid or polymer electrolytes with a solid material such as glass. Their configuration allows for higher energy density than lithium-ion chemistries. Solid-state cells do not contain flammable electrolytes so also offer safety advantages.

See section 2.3



Right: A stylized grid-scale battery – batteries are becoming cheaper and more powerful as they take on key roles in the evolving 21st century energy system, including powering electric cars, backing-up renewable power and storing energy in grid networks to balance supply with demand.

Other options – hydrogen and distributed systems

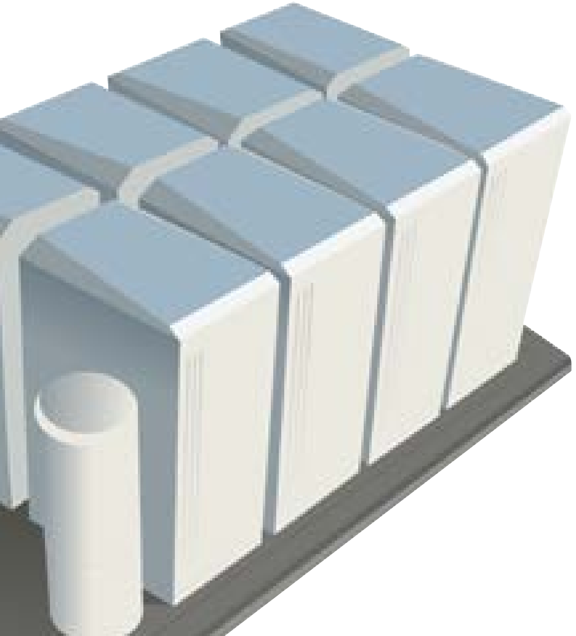
Hydrogen is a zero-emission energy carrier that could be used to provide power, as well as fuel for transport and heat, if costs could be reduced to competitive levels.

Hydrogen can be created from surplus renewable power by electrolysing water or produced by steam methane reformers. Once developed, hydrogen can be stored under pressure in caverns, pipelines or vessels. Studies suggest that it can be blended into some natural gas networks at levels of up to 10% by volume, without the need for system modification, and used for heat – both industrial and domestic – or power. For example, solar-generated power not needed during the summer could be converted to hydrogen and stored for heat or power in winter. Natural gas and hydrogen can be burned together in conventional plants to create electricity, providing an alternative form of lower-carbon back-up for renewable power. Hydrogen can also be used in fuel cells, including those in vehicles.

Our analysis indicates that the costs of producing, compressing, storing and transporting hydrogen would need to be reduced substantially and upgrades to existing gas infrastructure undertaken for it to be widely available and competitive with other fuels. However, with major investments in development and deployment, the global business-led Hydrogen Council has envisaged that hydrogen could account for around 20% of total energy consumed in 2050.

→ **See section 2.3**

Our analysis also examined distributed power systems and found that where extensive and interconnected networks already exist, a centralised power supply would continue to remain cheaper than distributed supply, for example using smaller-scale solar PV in combination with batteries.

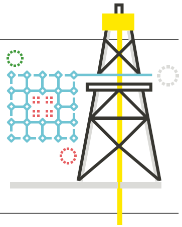


● = Hydrogen sources
— = Pipeline

Hydrogen pipelines and sources owned and operated by Air Liquide in Western Europe to supply transport charging points and industrial facilities. Such pipelines could be extended, with large volumes of hydrogen being stored for use in power generation and fuel cell-driven vehicles.

The changing future of power

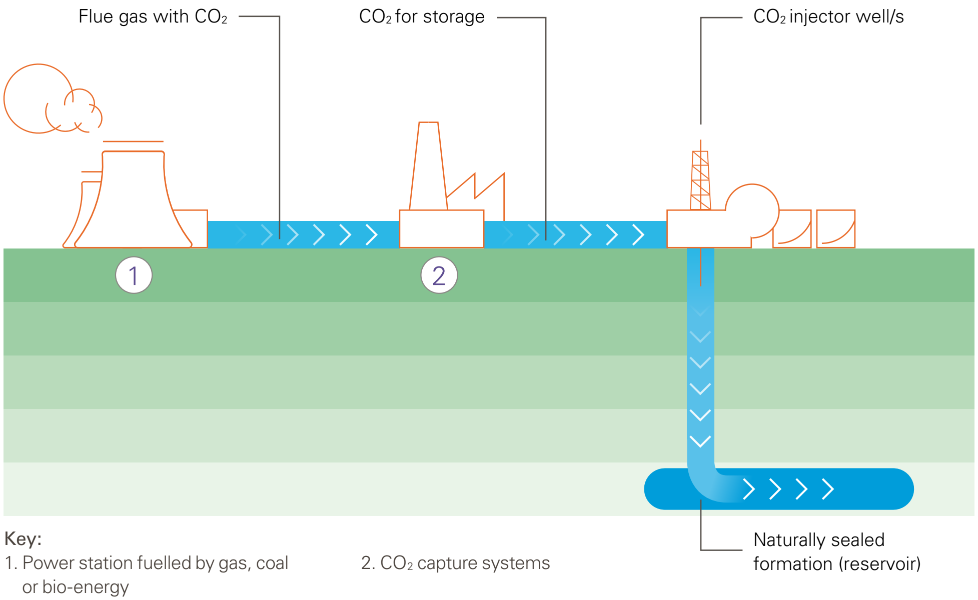
Digital technology could reduce net power demand by more than 25% by 2050.



Carbon capture use and storage (CCUS)

CCUS is widely recognised as a tool that could potentially be critical and cost-effective in reducing emissions and helping to meet the Paris Agreement goals. It can be applied at power stations burning gas, coal or biomass, or at energy-intensive industrial facilities, with the captured carbon dioxide either being used for commercial purposes, for example in enhanced oil recovery (EOR), or stored securely underground in suitable geological formations.

The relevant technologies are proven and ready but their scale-up needs to be accelerated if they are to achieve their full potential to deliver a low-carbon energy system with optimal use of hydrocarbons. CCUS is only set to become widely deployed in the power sector if it attracts targeted policy support to achieve greater cost reductions and carbon emissions are priced.



Key:
1. Power station fuelled by gas, coal or bio-energy
2. CO_2 capture systems

Carbon capture, use and storage (CCUS) can reduce carbon emissions from power stations and other industrial facilities to minimal levels by capturing carbon dioxide instead of venting it. The captured carbon dioxide can be used, for example being injected into oil fields to stimulate additional production, or stored, typically in underground geological formations.

Source: BP

Digital power

It is estimated that digital technology could reduce overall net electricity demand by more than 25% by 2050. Some digital innovations, such as use of data centres and intelligent cities, are projected to increase power demand but this rise may well be offset by digitally-enabled savings. The estimate of net savings also takes account of the impact of charging electric vehicles which is projected to add 5-10% to global demand for power by 2050.

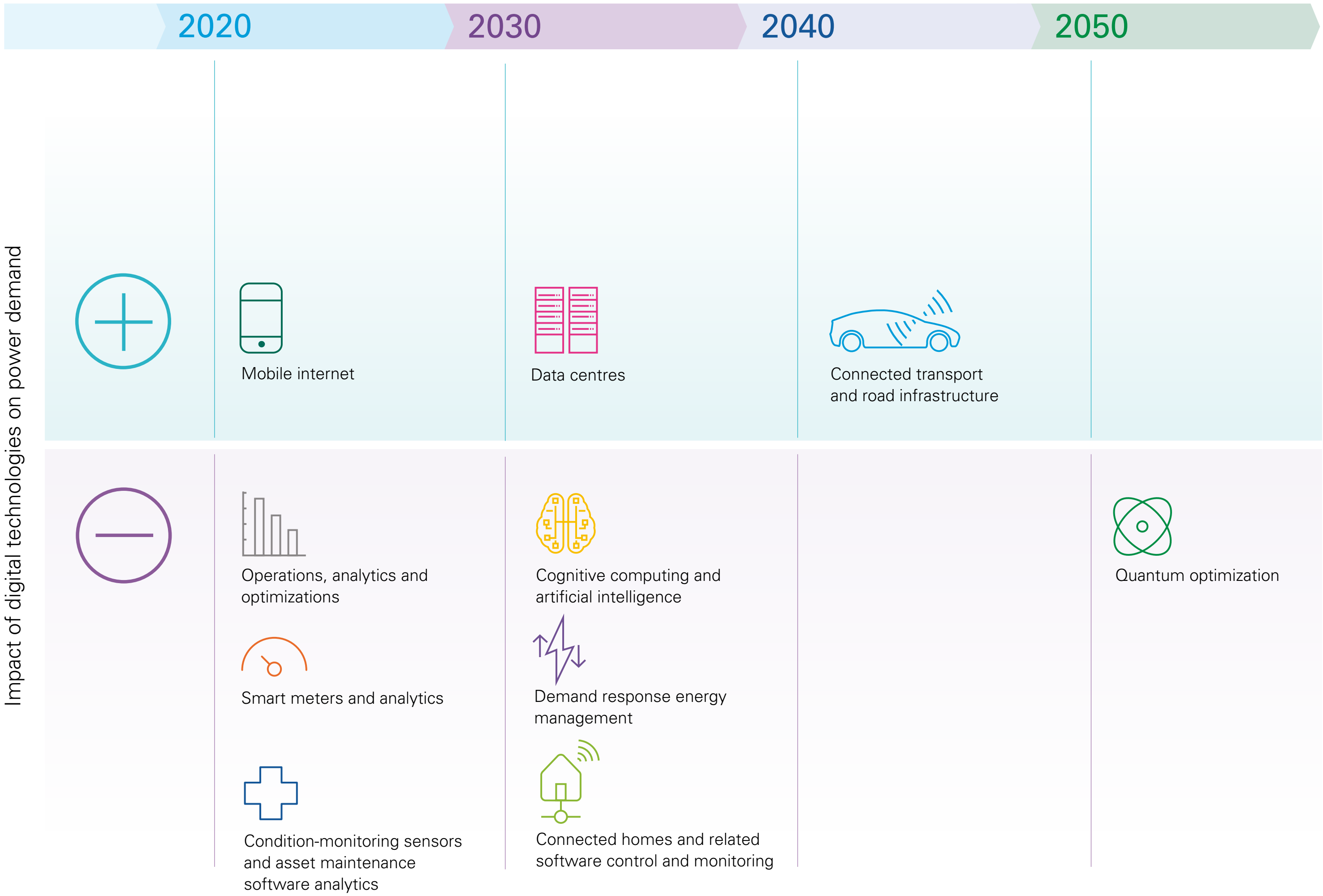
Until 2025, the main efficiency benefits leading to cost savings are projected to be on the supply side, as generators and operators use digital technology to optimise operations and reduce energy wastage. After 2025, substantial demand-side savings could be made, particularly as homes and businesses progress from the use of smart meters to become fully connected to digital networks, using monitoring and control systems to minimise demand.

The greatest savings in energy use could occur in factories, offices and other industrial and commercial locations, which use significantly more electricity than homes.

Meanwhile, advances in digital, including artificial intelligence, are set to drive a further wave of savings within supply-side systems, as advanced computing enables operators to optimise grid operations.

How digital technologies could affect demand for power

Use of digital technologies is projected to result in a net reduction in power demand as increases in processing power requirements are offset by digitally-enabled efficiencies.



ⓘ The graphic shows when key digital technologies for digital power are projected to have their maximum impact.
⊕ Technologies resulting in increased power grid demand. ⊖ Technologies reducing power grid demand.

Source: BP

Phil Sheppard

Head of Network Strategy
UK National Grid

> With new forms of power generation, and with gas-fired power backing-up renewables, as well as providing energy directly to homes and industry, there is a strong case to treat the gas and electricity networks as an integrated system.

For more information on the UK National Grid visit: *www.nationalgrid.com/uk*

Transforming the UK's power network

Britain's grid is becoming greener. In 2017, 30% of electricity generated in Great Britain was from green sources and the level of carbon dioxide from generation has halved since 2012, from 508 to 237 grams of carbon dioxide per kilowatt hour (gCO_2/kWh). For a short period we were at 73 gCO_2/kWh, below even the 2030 target of 100 gCO_2/kWh. On the day of 21 April 2017 we ran without coal generation – a first since 1882.

This transformation is the result of policy and market changes. Over 16 gigawatts (GW) of fossil fuel generation has closed since 2010. Instead, we now have 16 GW of offshore and onshore wind, and over the last few years 12 GW of solar photovoltaic generation has been installed.

We expect the rate of change to rise. The remaining 13 GW of coal generation is expected to close by 2025 and there is real appetite to use batteries in conjunction with intermittent renewables. This approach provides participants with the ability to store energy during low price periods until the price is higher and to sell services to the system operator to help manage the system. Advancing technology and the ability to learn by doing is outpacing policy and regulation.

With further growth in renewable generation to address climate change, and as coal generation disappears, the market will increasingly turn to gas generation to balance the intermittency of wind and solar power.

The gas required is available as we carry three times as much energy in our gas transmission system than the electricity system, and it can be five times higher on the coldest days. However, with new forms of electricity generation including combined heat and power systems, and with gas-fired generation being used to back-up renewables as well as providing energy directly to homes and industry for heating and cooking, there is a strong case to treat the gas and electricity networks as a single integrated system. This approach will enable operators to understand and manage the trade-offs and interactions, and allow consumers to receive their energy at least cost and maximum convenience.

These changes require us to continue to innovate and collaborate, to integrate established and new technologies. We are exploring the use of artificial intelligence (AI) and looking at how we can improve data and optimise the whole electricity system, not just transmission. Though our System Needs and Product Strategy we are providing real transparency of our future needs. We are working to co-develop services to ensure that all types of technology and any provider can compete in the market.

As the National Grid System Operator we must continue to provide our customers with a stable and secure system, facilitate a low-carbon society and provide consumers with value for money.

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How might technology change the future of transport?

Technology is set to transform transport over the coming decades, as vehicles powered partly or fully by electricity, become cost-competitive with those solely using internal combustion engines. At the same time, major growth is projected in autonomous, or self-driving, vehicles and ride-sharing. Trucks may see changes in the types of fuel used, and some may be electrified, for example for use in built-up areas. Planes and ships are less well suited to electrification, but are also set to see changes in the types of fuel they use.

Use of biojet is set to grow as the airline industry seeks to cap its greenhouse gas emissions.

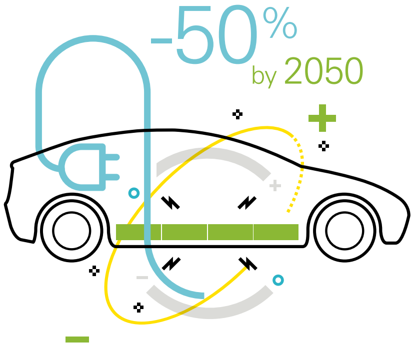
Charging up – mobile rapid charging systems, such as those provided by BP's partner FreeWire, are set to become familiar as numbers of electric vehicles grow.

Demand for travel remains central to society, with transport accounting for around 20% of primary energy use globally. Our current projections suggest that the world's total number of cars, vans and light trucks – the global 'light duty vehicle fleet' – could grow to around 2.6 billion vehicles in 2050 from 1.2 billion in 2015.

Today's vehicles

Giving way – after a century on the world's roads, vehicles powered by internal combustion engine are being joined by millions of electric and hybrid vehicles.

Today, the global transport fleet mainly consists of internal combustion engine (ICE) based vehicles, using gasoline, diesel, biofuels, compressed natural gas (CNG) and liquefied petroleum gas (LPG), with just 1% of the light duty sector comprising electric vehicles (EVs) or hybrids as of 2015.



Battery electric car costs could fall by around 50% per kilometre travelled by 2050 – to just under those of hybrid and conventional ICE-based cars.

Today, electric vehicles are relatively expensive compared to others, although policies and incentives can make them attractive to buyers. Vehicle manufacturers are planning to compete in this market at scale with a range of technologies.

- Hybrid electric vehicles (HEVs) combine an internal combustion engine with one or more electric motors and a battery pack. They include:
  - 'mild' hybrids, in which electric motors act to support the combustion engine, but cannot move the vehicle independently; and
  - 'full' hybrids, in which the engine and motor operate interchangeably or together with a limited electric drive range.
- Plug-in hybrid electric vehicles (PHEVs) use an ICE along with electric motors and a battery that can be charged from the grid.
- Battery electric vehicles (BEVs), or fully electric vehicles, only use a motor and are powered solely by energy from a battery charged from the grid.

Fuel cell vehicles (FCVs) provide another option for decarbonization and improved air quality. Their systems generate electricity as they convert hydrogen and oxygen into water, with the resulting power being used for propulsion. Both BEVs and FCVs produce no emissions from the tailpipe, although greenhouse gases may be generated further up the supply chain when the electricity or hydrogen is produced.

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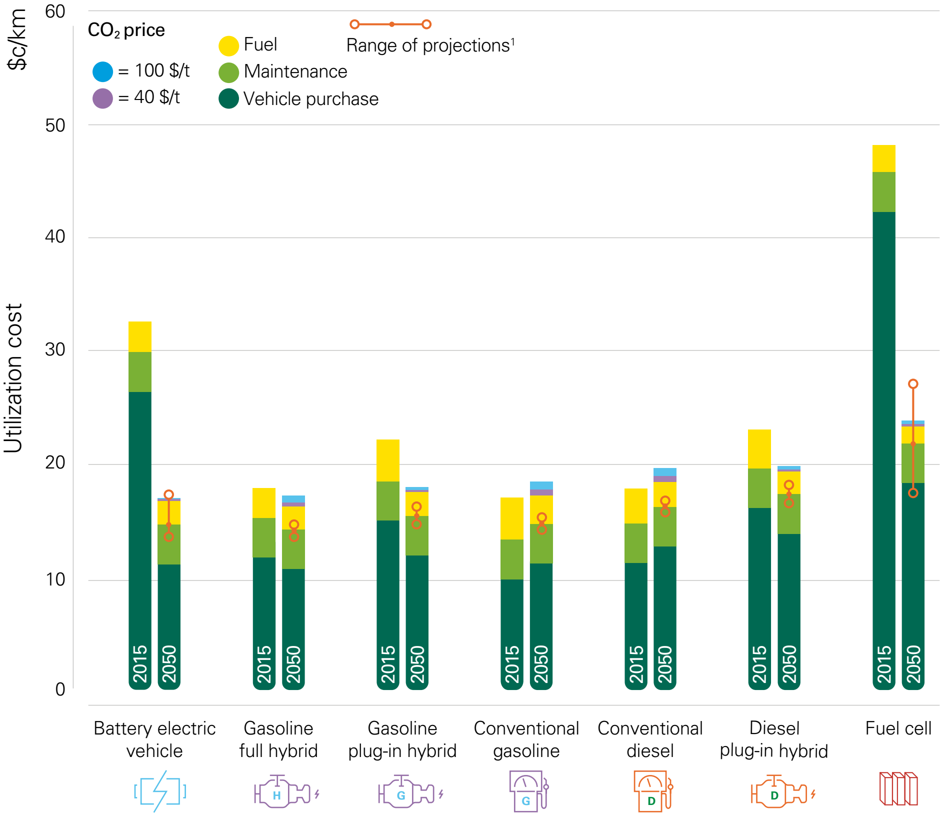
The converging costs of cars

Total costs of using a mid-sized car in Europe, 2015 and 2050

Electric, hybrid and conventional vehicle costs are likely to converge before 2050 – independent of any policy impacts.



Source: BP

Our analysis assumes: a 200 mile range battery electric vehicle with a 60 kWh battery; 20,000 km/year mileage; and 10-year vehicle life. CO_2 cost has been based on 'well-to-wheel' full lifecycle emissions.

[1] Includes range of projections for vehicle purchase and maintenance costs.

~17 $c/km

The cost at which conventional cars, hybrids and electric vehicles are projected to converge by 2050.

Converging costs

In our analysis, the costs of buying, running and fuelling electric and hybrid cars in Europe fall to become competitive with those of ICE-driven models before 2050. The model shows the average lifetime costs of a BEV decreasing by around 50% by 2050, to just under those of a hybrid or a conventional ICE-based vehicle.

FCVs, almost three times as expensive to purchase as an ICE car today, could see their overall costs more than halve, but appear to remain uncompetitive with other mid-sized car types owing to their relatively high capital costs.

With BEVs, PHEVs and ICE vehicles becoming potentially so closely competitive, it may be that factors other than technology-related costs, particularly government policies, play a decisive role in determining the shape of the vehicle fleet of 2050. Indeed, tailpipe CO_2 emissions targets are already encouraging vehicle manufacturers to sell more battery and plug-in electric vehicles, while action to improve urban air quality also favours electric vehicles.

The transformation of transport

Uncertainties over electrification

There is a wide range of uncertainty associated with electrification of transport, with estimates of the number of BEVs ranging between hundreds of millions to more than one billion by 2050. There are various factors contributing to this uncertainty, including:

- battery costs
- distances driven
- the impact of additional electricity demand from vehicle-charging
- the scale of environmental benefits
- the effect of growing car and ride-sharing.

The influence of policies such as legislative targets, which are not factored into these techno-economic projections, could be felt in any of these areas.

Battery costs

Our calculations take account of our latest estimates for falling battery costs, partly based on data from major vehicle manufacturers. Full electric vehicle battery costs per kilowatt hour (kWh) are projected to fall from more than 200 $/kWh today to around 50 $/kWh by 2050 for 60 kWh packs. Batteries are being improved to have shorter charging times, higher storage capacity (for improved range) and reduced mass. Our calculations assume a step change in performance, for example if lithium-ion chemistries are followed by solid-state or metal-air battery designs.

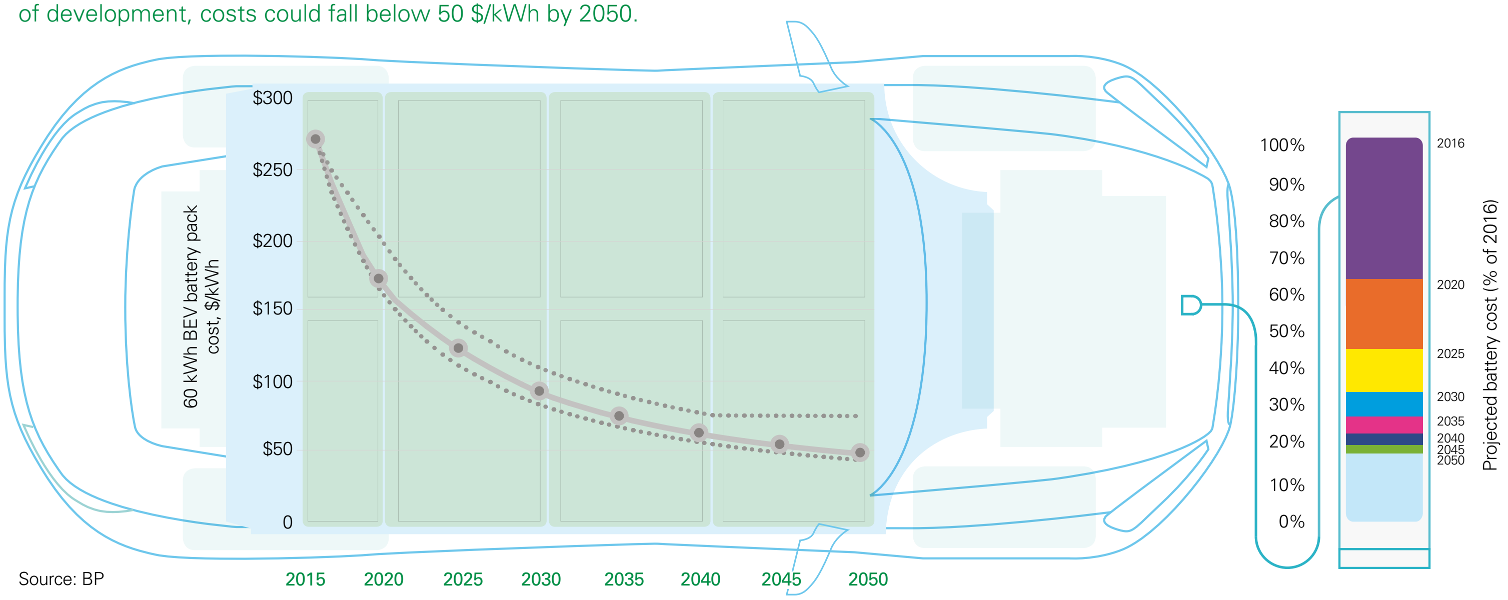
See section 2.2

Distance driven

Higher purchase prices for EVs are offset by their lower fuel costs, so the cost per kilometre of using the vehicle falls as the distance driven increases. Their low running costs are suited to shared car applications that increase the miles travelled by a vehicle.

Projected battery cost curve 2015-2050

Projected battery pack costs for cars and small vans – at current rates of development, costs could fall below 50 $/kWh by 2050.



Source: BP

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Vehicle charging

Electrification of vehicles is anticipated to have a significant impact on the energy system, both in terms of the increasing demands placed on the world's power grids by charging millions of vehicles and the costs and types of infrastructure used in the grids.

In the UK, for example, charging electric vehicles could increase demand by around 19 terawatt-hours (TWh) in 2030 and by around 70 TWh in 2050 – potentially 5-10% of power demand at that date – depending on usage of electric vehicles.

Not only are the numbers of such vehicles increasing the challenge that must be dealt with by the grid, but manufacturers are also increasing battery capacity to offer extended ranges. To achieve a range of around 500 km, a battery with 70-120 kWh of storage capacity might be used, and charging such a battery would take around 10-17 hours using a 7 kW, domestic charger. This additional load may be balanced, and possibly offset, by 'smart charging' and other digital methods to reduce demand at peak times. Other solutions for meeting the additional demand include repurposing second-life EV batteries as mobile charging stations and ultra-fast forecourt or 'destination-based' charging.

See section 2.2

Half of all vehicle kilometers travelled by passenger cars could be autonomous by 2050.

Environmental benefits

Hybrids typically achieve higher levels of fuel economy and therefore lower emissions than ICE vehicles. However, the environmental benefits of electric vehicles are largely tied to that of the power grid from which they are charged. EV technology itself can provide appreciable efficiency improvements over traditional vehicles, but further reductions in transport-related emissions depend on the degree to which the power system is decarbonized. Meanwhile, HEVs have lower exhaust emissions of particulates and nitrogen oxides than conventional ICE vehicles, and BEVs have zero exhaust emissions, which can help to improve local air quality in urban areas. (Air quality is also discussed in section 3.0)

See section 2.2 and 3.0

Digital transport

Digital technology is also anticipated to have a major effect in the transport sector, particularly through autonomous – or self-driven – vehicles and various forms of connected shared mobility.

Today millions of people use satellite navigation to guide their journeys, drawing on data stored in mobile networks. More fully 'connected cars' with connectivity that includes vehicle-to-vehicle (V2V) communication systems and vehicle-to-other (V2X) systems that interact with traffic infrastructure, smart phones and other devices are at advanced stages of development. Simple connectivity could become standard by 2020.

Such systems enable the exchange of data on factors such as speed, direction, location, braking and the activation of stability control mechanisms. The benefits include better traffic management, warnings of changing road conditions and the ability to optimize energy use over a journey.

The connected car is likely to evolve in the short term so that features available in some models today become commonplace.

From the early 2020s, however, more profound change is anticipated, with autonomous vehicles, or AVs, reaching the market and gaining scale over the following decade. Some elements of autonomy are available now, such as collision avoidance, lane assist and assisted parking, but over the next three decades the world's roads are set to see millions of AVs – 'autonomous' being defined here as vehicles with high levels of automation – including fully self-driving models (or Levels 4 and 5 – see opposite). While ICE vehicles can be automated, many AVs are also likely to be electric vehicles as BEVs have a simple powertrain that is well suited to automation.

Research shows that barriers to AV uptake include concerns over safety, liability and the time taken to develop and harmonize regulations. AV developers are responding by creating standards and deploying high-profile demonstrators designed to show that AVs can judge distance and speed better than humans, thereby avoiding road accidents, injuries and fatalities. The ability of AVs to dampen braking and accelerating rates using forward looking control systems, and to enable trucks and other vehicles to proceed safely in convoys, known as 'platooning', also helps reduce energy usage.

BP's projections suggest that AVs could account for nearly 20 trillion vehicle kilometres travelled per year globally, or more than 40% of the total, by 2050. There are signs that drivers around the world are accepting the change, with 78% of Americans in a recent survey saying that they believe AVs could make life easier.

Shared cars

There are many ways in which cars and journeys can be shared – taxi rides, individual or shared, hailed on the street or ordered online; self-driven car rentals, short- or long-term; all using different types of vehicle.

We define 'shared cars' as those that provide mobility services to individuals, including conventional cabs and private hire cars as well as vehicles used by ride-hailing apps. They also cover short-term hiring and sharing of cars by groups of people as an alternative to car ownership, typically in cities, using systems whereby cars can be picked up and left anywhere within a specified area. In time, we expect to see AVs operating as shared cars, being hired or hailed by individuals or small groups. With billions of people moving into cities around the world, the economic benefits of shared services are becoming manifest.

We estimate that in 2016 there were around 10 million such vehicles in use globally covering around 500 billion vehicle kilometres.

Our current estimates are that by 2050 around 25% or 10 trillion of the 40 trillion kilometres travelled by all cars will be accounted for by shared cars.

The impact of shared mobility on total numbers of vehicles and demand for fuel is uncertain. Lower costs and increasing ease of travel are set to encourage more journeys, including some where the vehicle is in transit between users, while more efficient vehicles and driving approaches may optimize vehicle kilometres travelled and reduce fuel use.

Electrification, autonomy and ride-sharing are likely to complement one another, for example by increasing EV utilization and thereby reducing running costs. Early analysis has shown that autonomy has the potential to improve efficiency by around 10% for EVs or 20% for ICE-based vehicles.

Trucks, ships and planes

For heavy trucks, liquefied natural gas (LNG) could grow in use as it represents a cost-effective, lower-carbon alternative to diesel. Electric vehicle technology is another option, with some manufacturers already building demonstrators today. Electric power is also projected to be the most cost-effective option for medium-duty trucks by 2050.

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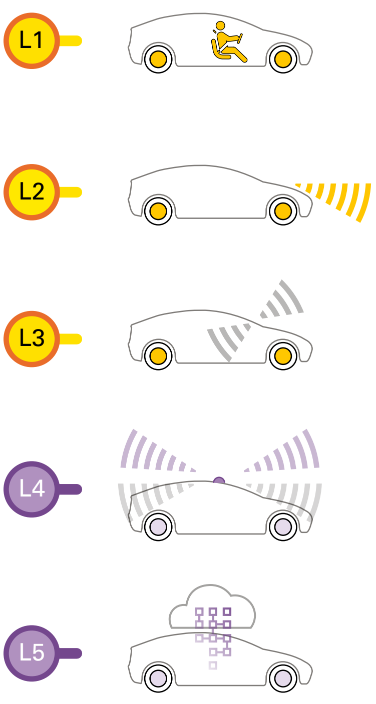
Arriving soon: The self-driving car

Millions of self-driving vehicles are set to appear on the world's roads during the next decade

Autonomous cars are a novelty today but vehicles with varying levels of automation are expected to be used widely by the early 2020s and common by the 2030s. Car sharing could complement autonomous vehicles – for example by increasing utilization and thereby reducing running costs.

Automation level



Function-specific automation.
Most functions controlled by driver and some by the car system, e.g. park assist.

Combined function automation.
At least two functions are automated, e.g. cruise control, lane-centering.

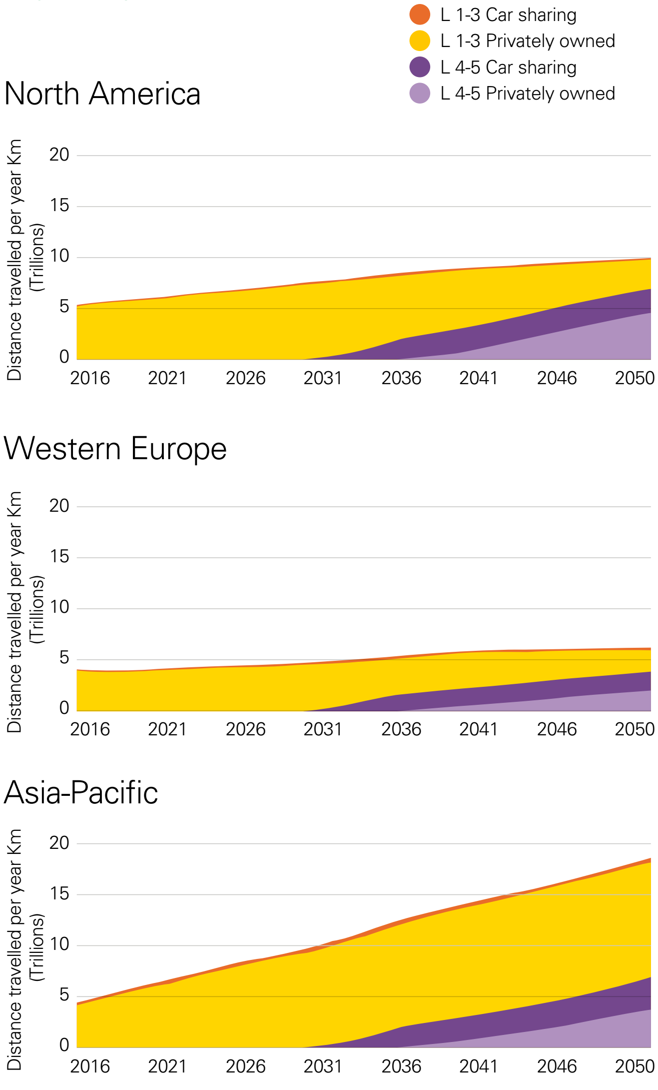
Limited self-driving automation.
Safety critical functions are shifted to the car system, driver is not required to monitor the situation at all times.

High automation.
Approaching 'fully autonomous', the vehicle designed to perform all safety-critical driving functions.

Full automation.
Level 5 vehicles will be fully autonomous with no option for human driving.

Right: forecasts for numbers of self-driving vehicles vary widely. This BP projection suggests that, in these three regions, autonomous vehicles could account for roughly a quarter of the distance travelled in the mid-2030s and a half by 2050.

Source: BP



LNG is also a growing competitive option for shipping, although LNG-fuelled ships currently only make up around 0.2% of the global fleet. Opportunities to improve the energy efficiency of ships include using novel kinds of kites and sails, hull design advances, propeller optimization and waste heat recovery.

In aviation, high-energy-density hydrocarbons are hard to replace, cost-effectively and practically. However, the aviation industry has committed to cap emissions in 2020 and halve them by 2050. These targets encourage use of bio-jet fuel as it presents a viable low-carbon alternative to conventional fuels. By November 2017, more than 100,000 commercial flights had been undertaken using bio-jet blends.

Section 3.0 has further coverage of transport in the context of reducing carbon emissions.

→ **See section 3.0**

Competition among liquid fuels

While increasing numbers of vehicles run on electricity, millions of hybrids and ICE-based vehicles are set to remain at least partially powered by liquid fuels. Efficiency improvements in these vehicles allow them to drive further for each litre of fuel. Our analysis indicates that the costs of biofuels made from various biological crops, wastes and oils could fall sharply by 2050. In our modelling, the production costs of ligno-cellulosic (LC) ethanol – made from crops such as grasses – fall 60% by 2050 to bring them close to those of gasoline and diesel. However, with a carbon price of 100 $/tCO$_2$ applied to the combustion of fuel in an ICE vehicle, the biofuel alternative would become cheaper than the conventional fuels.

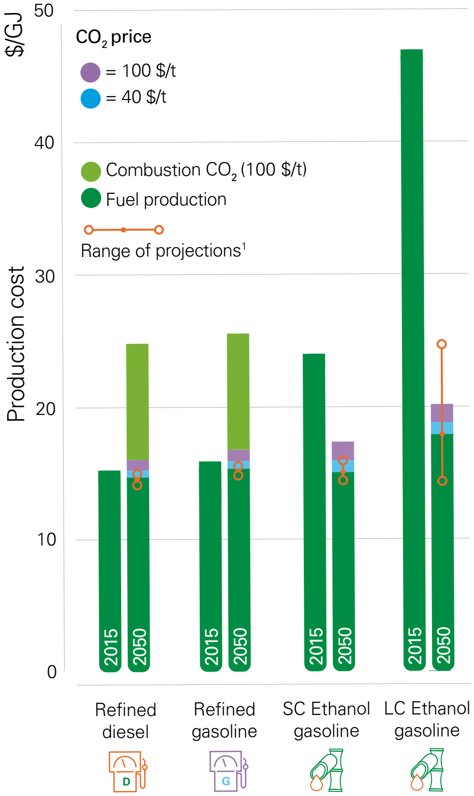
With a carbon price of 100 $/tCO$_2$ sugarcane ethanol, which is prevalent in Brazil today, is modelled to be the most economical fuel in 2050, where sufficient volumes of the crop can be grown.

There are a number of biological alternatives to diesel fuel, or bio-distillates, of which those made from vegetable oil are nearly competitive with conventional products today.

Today's biofuels can be blended into fuel at low concentrations, typically up to 10%, enabling them to be used in conventional vehicles. If biofuels continue to become more competitive, there may be more investment in flexible-fuel vehicles that can run on higher blends, up to 85%, along with the accompanying refuelling infrastructure.

Biofuels come of age

Biofuels are projected to become competitive with fuels made from crude oil by 2050, particularly if carbon emissions are priced.



Source: BP

[1] Includes range of projections for fuel production costs.

The chart shows production costs in dollars per gigajoule of energy ($/GJ).

SC: Sugar Cane

LC: Lignocellulosic

Gilles Normand

Senior Vice President, Electric Vehicle
Groupe Renault

> By the middle of the next decade, technology will solve the problems that were barriers to the wider adoption of EVs, such as range anxiety, charging times and cost.

How will technology facilitate the mass adoption of electric vehicles

Perceptions change quickly. At the time of BP’s first Technology Outlook report three years ago, electric vehicles (EVs) remained a technical curiosity – of interest to keen environmentalists but holding little appeal for the vast majority of drivers.

EVs still account for only a small percentage of the global auto market (less than 1% in 2017), even for a European leader such as Renault which has been developing the technology, training its employees and preparing its dealer network for EVs since 2009. However, there has been a revolution in understanding over the past couple of years, as the dramatically improving capabilities of EVs have captured the public imagination, resulting in impressive segment growth.

By the middle of the next decade, technology will solve the problems that were barriers to the wider adoption of EVs, such as range anxiety, charging times and cost. For example, Renault ZOE, Europe’s best-selling EV, already has a real driving range of 300 km. Within a few years, EVs will be capable of 600 km between charges, effectively eliminating any remaining concerns.

Predictable improvements in battery technology and the benefits of production at scale will, by 2025, make the total cost of owning and running an EV cheaper than an equivalent internal combustion engine car – even for large vehicles.

Auto manufacturers and battery suppliers are already examining new solutions such as solid-state batteries, which offer more capacity at lower cost than today’s lithium-ion batteries.

Changing patterns of energy usage, and the increasing reliance on renewables, will require better technology for energy storage. EVs and car batteries will also be able to contribute to home electricity consumption and grid management, further reducing operating costs.

But while new technology is a requirement for the mass adoption of EVs, it is not the only one. We also need to develop the ecosystem and infrastructure to make them easy to use, and to build awareness and trust. The commitment of a wide variety of players, including energy companies, cities and governments will make this happen way before 2050.

For more information on Groupe Renault visit: *https://group.renault.com/*

How can technology change heating and cooling?

Heating and cooling make up a significant share of overall demand for energy; for example accounting for almost half of European demand for energy today. While homes and offices use a range of heaters and air-conditioners, industrial facilities process materials such as oil, chemicals, steel and cement at extremely high temperatures.

Right: Rooftop air-conditioning units. Nine in ten new US homes have air-conditioning installed.

Our analysis of buildings in Europe and the US, suggests that heating and cooling will continue to be provided by a variety of appliances from familiar gas-fired and electric heaters to newer technologies such as pumps which extract heat from air, ground or water and combined heat and power (CHP) systems. Our study of heat use in industry in China, Europe and North America showed potential for major energy savings if technology reaches its full potential.

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Industrial heating

In energy-intensive industries, such as iron and steel, cement, petrochemicals and refining, the way heat is generated and used has a large bearing on business efficiency and profitability. This study shows there is scope in each of these sub-sectors for significant energy efficiency improvements.

Industrial heat varies from region to region. In China, coal dominates, having provided 54% of demand in 2013. Gas had the largest share in North America (around 30%), with electricity (27%) followed by gas (25%) in Europe.

Our analysis suggests that there are technically and economically viable routes to cut overall industrial energy demand by approximately 10-20% by 2050, in a large part through a mixture of production process improvements.

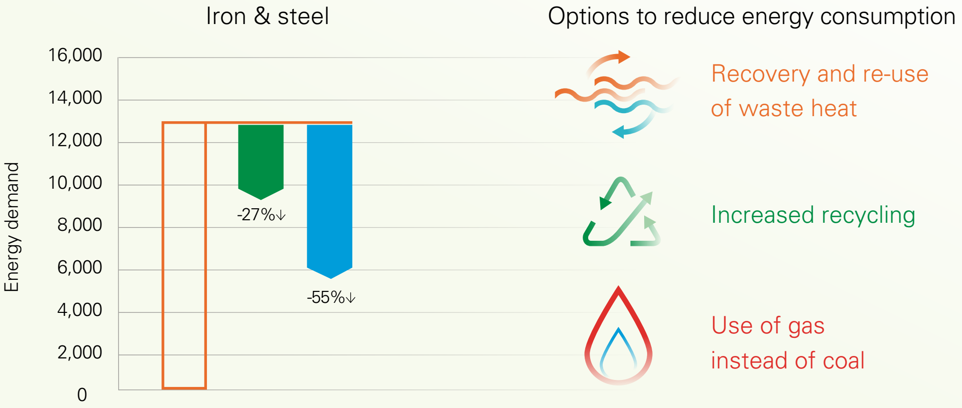
Iron and steel production has the highest potential for reducing energy demand by 2050 from production process improvements, saving up to 55% current energy usage. These changes include producing iron by reducing iron ore directly using natural gas instead of smelting with coke in a blast furnace.

Right: Industry is a significant user of heat – including iron & steel manufacture.

Changing demand for heat in industry

Factories and heavy industry use vast volumes of heat. However technological and efficiency gains could limit and in some cases lower demand by 2050. The iron and steel sector has the highest potential to reduce demand.

○ = 2015 Baseline
🟢 = 2050 Business as usual + 40 $/tCO_2$
🔵 = 2050 Ultimate technology potential + 80 $/tCO_2$



ⓘ Our analysis modelled two possible futures for industrial heat, reflecting differing levels of action to reduce emissions. In one, technology development continued on a 'business as usual' basis with a carbon price of 40 $/tCO_2$. In the other, technology achieved its ultimate potential alongside a carbon price of 80 $/tCO_2$.

Source: Marakon & BP

Today's heating systems

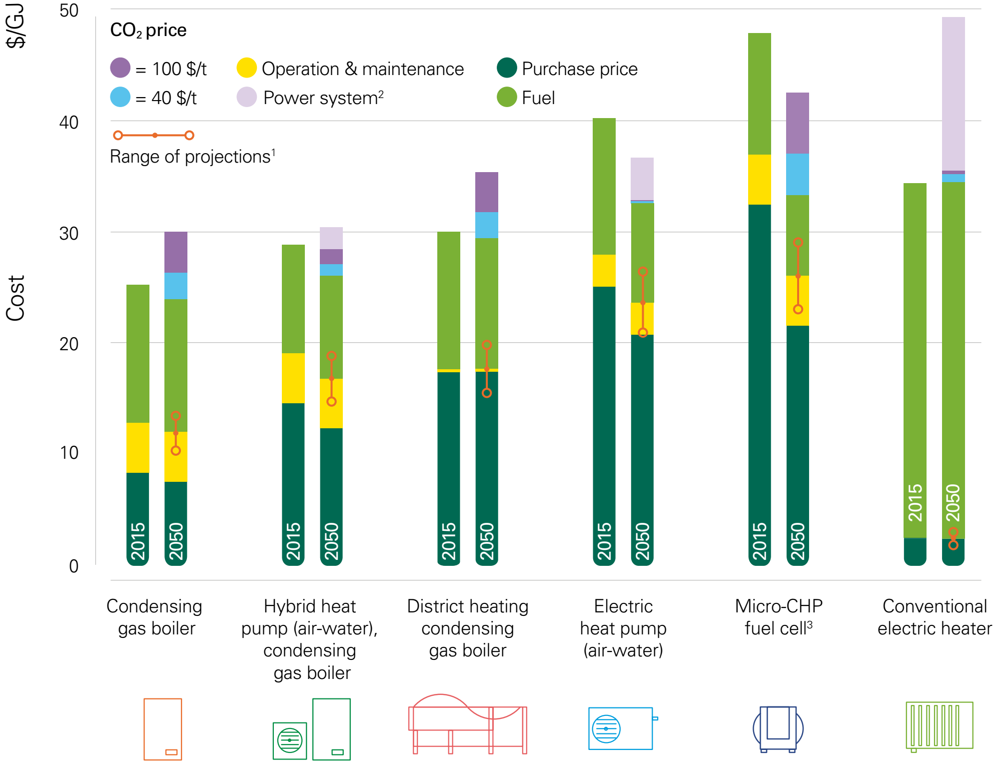
For homes, gas-fired appliances are typically the most competitive sources of heating in Europe and the US today. Many modern gas-fired appliances use condensing heat exchangers, which recover heat from the exhaust gases that would otherwise be wasted, making them highly efficient with comparatively low levels of carbon emissions.

In Europe, gas-fired condensing boilers are followed in economy by hybrid systems combining heat pumps and a gas boiler for use on very cold days, and then electric heaters and heat pumps. District heating systems that use centralised equipment to serve multiple buildings provide some European populations with economical heat. For example, more than half of the citizens of Denmark, Estonia, Finland, Latvia, Lithuania, Poland and Sweden are served by district heating.

The US residential heating sector primarily uses gas furnaces (that heat air as opposed to water), followed by electric heaters and heat pumps. One-quarter of the largest commercial buildings in the US use district heating systems. The southern US states require less heating and more cooling and the most common air-cooling technologies are driven by electricity.

Cost of heating a large house in Western Europe – 2015 and 2050

Condensing gas boilers may be the cheapest way to heat a home today, but by 2050, with a 100 $/tCO$_2$ carbon price, they are projected to be matched in cost by hybrid systems that consist of an electric pump extracting heat from the air supplemented by a condensing gas boiler. Both of these systems are modelled to be cheaper than gas-fired district heating, electric heat pumps and micro-combined heat and power systems. Costs of conventional electric heaters are projected to be relatively high as they could be increased by higher electricity prices resulting from investment in lower-carbon power infrastructure.



[1] Includes uncertainty in operation & maintenance and purchase price.

[2] Potential additional fuel costs to cover capital spending in power sector on lower carbon infrastructure, assuming a 100 $/tCO$_2$ carbon dioxide price.

[3] Net micro-CHP fuel costs could be reduced by around 5 $/GJ if electricity price increases in line with a cost on carbon of 100 $/tCO$_2$, assuming gas price is held at 2015 levels.

CHP – Combined heat and power   Source: BP

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Building refurbishment or heating system replacement?

Most European homes are fitted with some energy-saving measures, but the average energy efficiency falls far below the highest possible levels, as represented by the 'Passivhaus' or 'passive house' performance standard. By 2050 half of Europe's buildings are anticipated to have similar insulation properties to today, the other half having even been newly built to modern standards, or refurbished – at a projected rate of 1%–1.4% per year.

In Europe, our modelling indicates that in the near term, for the majority of existing buildings, replacing a domestic boiler with a higher-efficiency unit is usually a more cost-effective way to save energy and reduce heating costs than major works to upgrade the building fabric and insulation.

By contrast, the building stock in the US is somewhat newer than in Europe although significant geographical variations exist. The number of houses built in the warmer South and West has far exceeded those built in the cooler North and East regions in the last few decades. High levels of thermal insulation and efficient cooling systems can be found in these new buildings, whereas the older buildings in the North and East typically have issues similar to those in Europe.

Changes by 2050

By 2050 for large houses in Europe, our modelling projects that with a carbon price of 100 $/tCO$_2$, heating systems using gas continue to play a key role. Overall usage costs of condensing gas boilers could be matched by those of hybrid systems – consisting of an electric heat pump that extracts heat from the air supplemented by a condensing gas boiler. Both of these systems are projected to be cheaper than gas-fired district heating and electric heat pumps. The costs of micro-CHP systems using fuel cells to produce power and heat from gas – are also projected to fall. However, a carbon price would increase fuel costs for these CHP units. The purchase costs of electric heaters are projected to change little by 2050, but the competitiveness of these systems also depends on the price of electricity, which is projected to rise to cover the costs of investing in lower-carbon infrastructure in the power sector. Solar heating for water is competitive in Southern Europe now and could become competitive across Europe by 2050.

In the US, gas furnaces are projected to remain leaders in providing domestic heating by 2050, with high-efficiency gas-fired condensing furnaces remaining competitive with conventional models over the 2015-2050 period. Micro-CHP units may also emerge as competitive options, particularly for larger buildings.

Where there is a demand for summer cooling and also a small amount of winter heating such as the South and West of the US, reversible heat pump technology, which can flexibly provide either heating or cooling, may be preferred.

Impact on air quality

Emissions of nitrogen oxides (NO$_x$) from burning gas in commercial and residential heating systems may be progressively reduced by applying low-NO$_x$ burners and selective catalytic NO$_x$ reduction to their exhaust systems to deliver air quality improvements. In many developing countries, the use of gas for heating (and other domestic activities such as cooking) could also improve indoor air quality and public health.

See section 3.0

A UK town in winter – demand for heat depends on climate, building quality and the efficiency of heating equipment.

Greg Jackson

CEO, Octopus Energy

> The potential for sensors to monitor the warmth of individuals and to deliver directed heat to them, rather than heating space, may become a reality.

For more information on Octopus Energy visit: *https://octopus.energy*

Will consumers warm to electric heating?

Domestic heating is a major focus of government decarbonisation programmes, and it is already seeing digital innovation – with smart thermostats, smart radiator valves, smart boilers and smart diagnostics all playing a part in helping consumers enjoy more comfortable homes with lower energy bills. Are these innovations enough, and what's next?

Smart control systems have had relatively low customer uptake, despite advertising campaigns claiming significant benefits. It seems that householders may be less interested in 'gadget-driven' change when it comes to heating – as it is with power. After all, many could save up to £300 on their energy bills just by switching provider – a quick job – but do not get around to it. So it's easy to see why they may rarely get new heating equipment installed just for similar savings.

So it appears unlikely that consumer-driven digital change will deliver revolutionary efficiency on its own. Instead, the real action may be driven on the supply side, with new technologies such as enhanced, digitally controlled, electric heating.

Electricity is currently typically several times more expensive than gas per unit of heat generated, but the cost difference can be dramatically reduced with digital technologies.

In Northern European countries, peak demand for electricity is in the early evening. Grids have to meet the needs of companies which are still operating whilst many workers are arriving home and using electricity for heating, entertainment, lighting and cooking.

Electric heating devices such as heat pumps and storage heaters allow the time of consumption and the time of heat delivery to be separated. Increasingly, room-level temperatures can be monitored and thermodynamics modelled by smart kit. Combining this ability with the technology to read or forecast intra-day grid prices and react accordingly, allows electricity to become highly viable for heating and a price on carbon could tip the balance further toward electric heating. Devices which also monitor when individual rooms are in use, both predictively and in real time, could deliver dramatically more efficient heating – with the dynamism of electricity potentially outcompeting other fuel sources.

Further out, the potential for sensors to monitor the warmth of individuals and to deliver directed heat to them, rather than heating space, may become a reality – reducing energy demand significantly.

The transition to new, lower-carbon heating systems may generate enormous short-term opportunities through new technology developments and create long-term value by providing end-to-end solutions, from generation to consumer.

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The environmental perspective

How might the energy system adapt to meet environmental goals?

So far, this Outlook has focused largely on how advances in technology could reduce the costs and increase the competitiveness of different forms of energy in the years to come.

However, other critical questions include the extent to which such changes will support the transition to a low-carbon economy and address further environmental issues such as air pollution in cities, as well as how the different sectors of power, transport, industry and heating interact.

The Amazon river and jungle – a natural carbon sink that helps offset emissions of greenhouse gases.

Addressing the threat of climate change means limiting emissions of greenhouse gases, as governments from around the world pledged to do following the signature of the 2015 Paris Agreement at the UN's 21st Conference of the Parties (COP21). The aim of the Agreement is to keep the rise in average temperatures to well below two degrees Celsius compared with pre-industrial levels.

Improving air quality, meanwhile, involves reducing levels of nitrogen oxides, ozone and particulates arising from vehicles, industry and other sources.

Our analysis examined the role of energy technologies in addressing both of these sustainability challenges.

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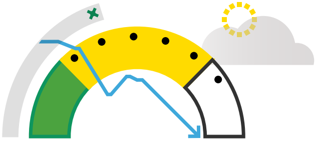


Our modelling explored the key technologies involved in the transition to a low-carbon economy.

Modelling a low-carbon future

To examine ways of limiting carbon emissions, we used a well-established model called TIAM World (see box, right) to identify the mix of technologies that might provide energy in different circumstances.

The model does not create precise forecasts, but provides generalized insights to show which technologies are the most economical in various situations.

The modelling examined the power, transport and heat sectors in the three regions of China, Europe and North America between 2015 and 2050. The projections were based on inputs such as technology costs, demand levels, regional price variations and, in some cases, constraints on carbon emissions.

We looked at different pathways or ‘cases’ to understand the contrast in the technology mix between a future in which carbon emissions are constrained and one where they are not.

Initially we modelled an ‘unconstrained’ pathway in which technologies competed purely on cost.

We also examined pathways where carbon emissions were constrained in various ways. In particular, one pathway looked at the broad mix of technologies that might supply energy if the world reduced emissions in line with limiting the rise in global average temperature to 2°C. This assessment was based on projections from the International Energy Agency (IEA) (Energy Technology Perspectives 2016) in which such a ‘two degree world’ would require carbon dioxide emissions to be reduced by more than 70% by 2050 from 2015 levels across the three regions.

TIAM

- The TIAM-World model used to examine alternative futures is based on the TIMES (The Integrated MARKAL-EFOM System) Integrated Assessment Model, developed under a Technology Collaboration Programme of the International Energy Agency (IEA). TIAM-World is distinctive in creating models that span the energy system, including power, transport and heat, for example indicating where carbon emissions can be reduced at lowest cost, in whatever sector.

The 2015 Paris Agreement, which pledges to limit the global temperature rise to well below two degrees Celsius above pre-industrial times, has been ratified by 175 countries.

This modelling of a two-degree future was based solely on achieving such emissions reductions – and the parts played by different technologies in reducing them – rather than on assumptions about specific policies. Both this and the unconstrained model therefore provide insights into the potential impact of technology, aside from policy and other factors.

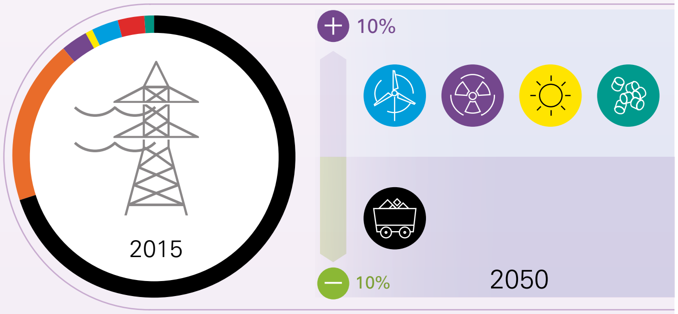
Also, the modelling did not factor in carbon offsets, whereby emissions are compensated for by projects that reduce emissions elsewhere, such as planting trees or reducing methane emissions from landfill sites. The 2015 Paris Agreement on climate change provided for new mechanisms to promote financing and trading of carbon offsets and these are increasingly being offered to customers by businesses such as airlines and energy providers.

China's technology mix – in 2015 and a 'two-degree' future

Analysis indicates that a 'two-degree' future requires a major transformation. Here we see the technologies providing power, transport and heat today and those that are projected to grow to supply more than 10% of all energy or fall below that threshold by 2050.

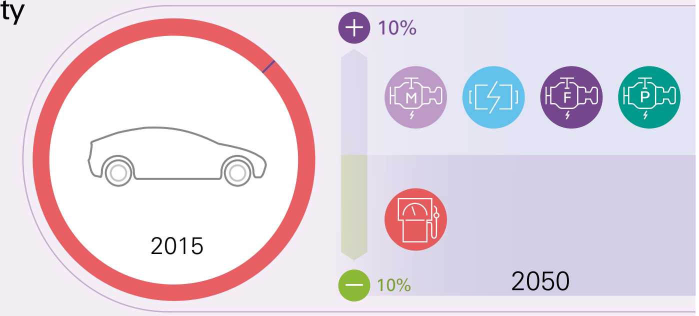
Power sector

- ● Coal
- ● Hydro
- ● Nuclear
- ● Solar
- ● Wind
- ● Gas
- ● Biomass (CCUS)



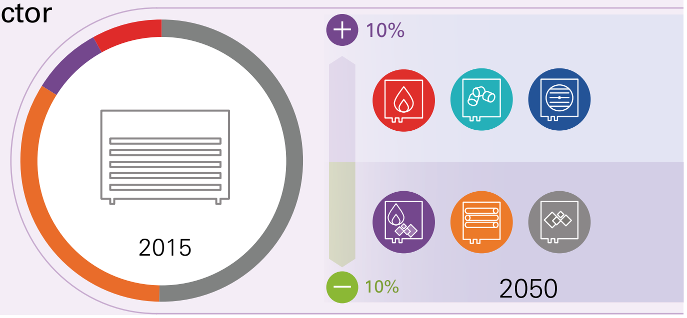
Transport – Light duty sector

- ● Battery electric vehicle
- ● Plug-in hybrid
- ● Full hybrid
- ● Mild hybrid
- ● Internal combustion engine



Heat – Residential sector

- ● Condensing gas-fired heater
- ● Electric heat pump (air)
- ● District heating biomass
- ● District heating coal-fired
- ● Coal-fired heater
- ● Wood-fired heater



Source: BP

- ⊕ Technologies increasing beyond 10% of the energy mix
- ⊖ Technologies falling below 10% of the energy mix

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Observations across the three regions

In the unconstrained future, largely determined by the progress of technology and resulting increased efficiencies and cost reductions, emissions from energy consumption rose by around 15% between 2015 and 2050 across the three regions. This growth is significantly less than the 70% increase experienced over the previous 35-year period (1980-2015) but very different from the fall of more than 70% by 2050 envisaged in the IEA's scenario for a two-degree world.

The modelling therefore suggests that currently expected technology advances alone would not deliver the carbon reductions needed for a 'two-degree world' and that further action would be required, particularly policy measures such as putting a price on carbon emissions as well as consumers making lower-carbon choices.

Modelling least-cost pathways, system-wide, shows that the greatest emissions reductions can be made in the power sector because it has the cheapest decarbonization options. This model, like other integrated simulations, suggested that in a two-degree world: the power sector would become carbon-negative by using bioenergy with carbon capture and storage (BECCS); transport emissions would be reduced by the use of electric cars and hybrids; and the heat sector would have the highest remaining emissions.

BECCS power stations were favoured because they potentially offer negative lifecycle emissions by using as feedstock crops that absorb carbon dioxide from the atmosphere when growing, yet emit none when burned for power as the carbon is captured. However, concerns over the technology include whether enough cropland would be available and the extent of the benefit given the carbon released during cultivation and harvesting processes.

Overall, the modelling identified CCUS as a major component of the least-cost two-degree world, while being absent from the most economical unconstrained pathway. As with the power sector analysis (section 2.2), this result suggests that technology advances alone will not make CCUS competitive enough to attract major investment, and that targeted policy support and effective carbon pricing would be required.

Relative natural gas prices appeared as an important factor in shaping the energy mix, with gas prevalent in North America, where prices are low, but less so in China, where they were assumed to be higher – as they are today.

Regional variations

The modelling showed significant variations between the three regions studied.

In **China**, coal continued to dominate power generation in an unconstrained pathway, while being phased out by around 2040 in a two-degree world. In the two-degree model, nuclear capacity grew from a small share of the 2015 system to dominate in 2050, supported by wind, solar and other sources. In residential heating, the two-degree case showed electric heat pumps taking a larger share of the market instead of gas heaters and coal-fired district heating.

In **Europe**, renewables made up most of the 2050 power sector in many of the pathways studied, supported by coal and gas in an unconstrained case, and BECCs in a two-degree case. In a two-degree world, by 2050, hybrids of gas boilers and electric heat pumps were favoured along with district heating.

In **North America**, wind and decarbonized gas using CCUS led the power sector in the two-degree world, compared to gas without CCUS in the unconstrained case. Gas also led the heat sector in both cases.

In all regions, hybrids made up most of the fleet in an unconstrained pathway, whereas battery electric vehicles took a larger share in the two-degree alternative.

Air quality

Messages from the models

While modelling is an approximation, and these insights do not provide forecasts, several messages about the potential capability of technology emerged:

- A ‘two-degree world’ would need a major transformation of the energy system. Technology advances alone appear unable to deliver such a future and stronger policy intervention would be needed.
- Renewables are important technologies to transform the power sector – particularly wind and solar which are seeing strong growth today.
- The power sector offers greater scope for least-cost emissions reduction than transport or heat.
- Carbon capture use and storage (CCUS) is critical in reducing emissions at the least cost.
- There are major variations between regions in the least-cost routes to emissions reduction.
- Natural gas has an important role in a two-degree world, being used in power, transport and heat, with potential for even greater use if plentiful shale resources are further developed.

Air quality

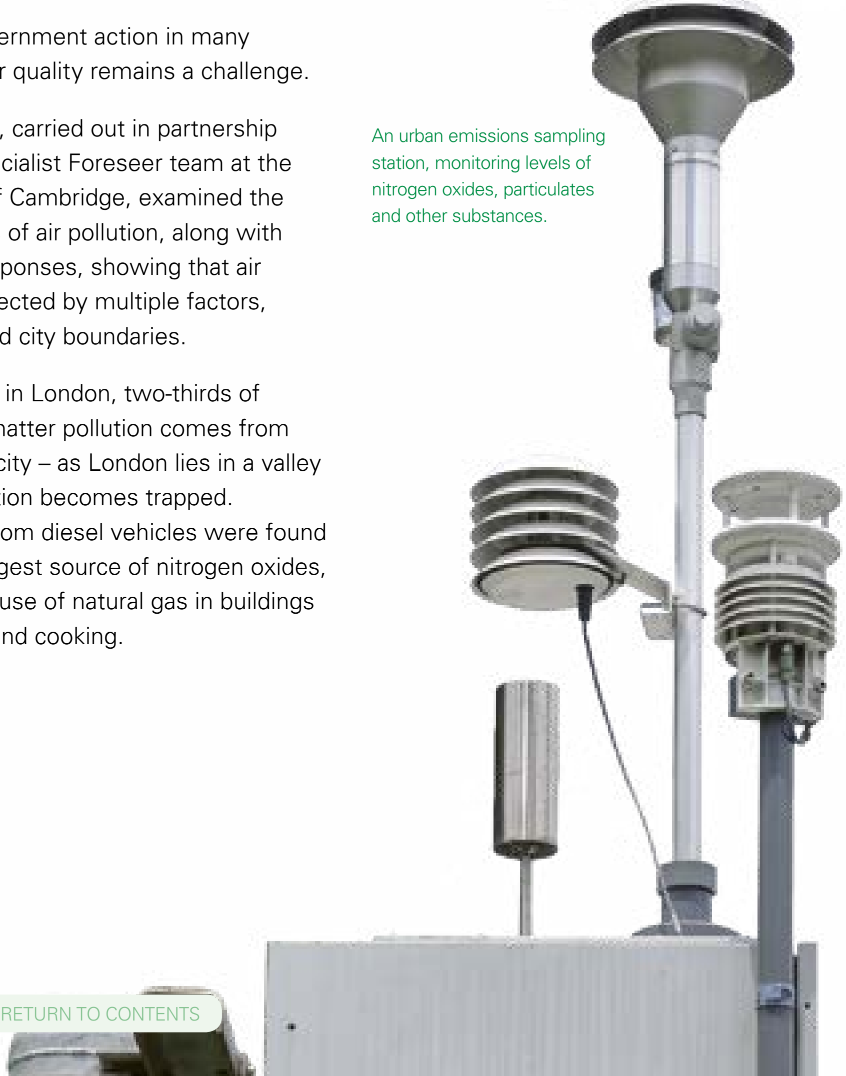
Our examination of air quality issues focused on London, Los Angeles and Beijing, which have some of the highest urban pollution levels in the three regions examined. Air quality is particularly affected by nitrogen oxides (NO_x) ozone and fine particulate matter known as $PM_{2.5}$ – on which this study focused.*

Despite government action in many countries, air quality remains a challenge.

Our analysis, carried out in partnership with the specialist Foreseer team at the University of Cambridge, examined the main causes of air pollution, along with potential responses, showing that air quality is affected by multiple factors, many beyond city boundaries.

It found that in London, two-thirds of particulate matter pollution comes from outside the city – as London lies in a valley where pollution becomes trapped. Emissions from diesel vehicles were found to be the largest source of nitrogen oxides, followed by use of natural gas in buildings for heating and cooking.

In Los Angeles, local sources accounted for 80% of NO_x and $PM_{2.5}$ emissions, with contributions spread between vehicles, buildings and sources such as soil, dust and sea salt. Of the cities studied, Los Angeles had the highest levels of ozone, a pollutant formed from the reaction between nitrogen oxides, carbon monoxide and volatile organic compounds in sunlight.



An urban emissions sampling station, monitoring levels of nitrogen oxides, particulates and other substances.

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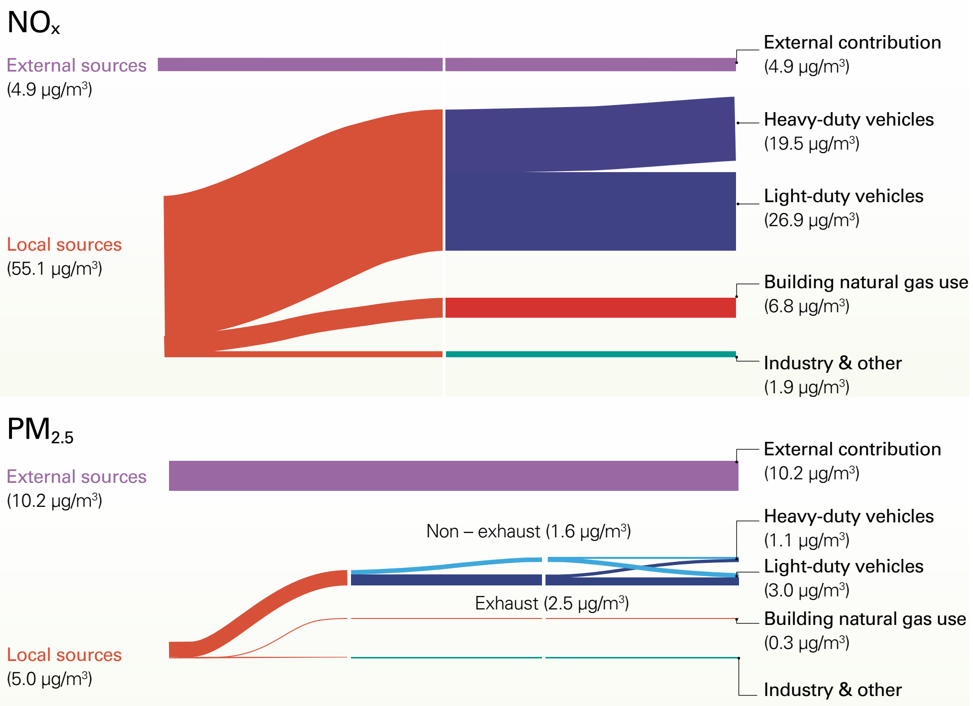
What affects Central London's air quality? Where nitrogen oxides and particulates come from



Data sources: Clean Air for all, 2015; Cambridge Environmental Research Consultants, 2011.

ⓘ 'Local' emissions are those produced within the city boundary
Data shows annual mean concentrations.

In Beijing, particulate levels were more than four times those of London and Los Angeles, with around half originating outside the city, from regions several hundred kilometres away. The main source of PM$_{2.5}$ in Beijing was coal use in industry, power plants and heating, while sources of NO$_x$ were dominated by transport, followed by industry.

In all three cities, a substantial share of the particulate emissions from transport arose from brake, tyre and road wear, alongside those from exhaust gases.

Messages from the air quality analysis

The research into air quality showed how the same challenge has diverse causes in different cities. Achieving a decisive solution would therefore need a range of actions.

- Measures need to address both local and regional sources of emissions, as many cities are affected by NO$_x$ and PM$_{2.5}$ originating some distance away.
- Emissions need to be mitigated across several fronts. Transport has often been the main focus for change, frequently via a focus on diesel vehicles as they generate both NO$_x$ and PM$_{2.5}$, with solutions including incentives for electric and hybrid vehicles as well as tougher tailpipe emission standards. However, reductions in emissions from industry and buildings would also be needed in some locations, especially in relation to particulates.
- In transport, addressing PM$_{2.5}$ from exhaust emissions is only part of the solution. Non-exhaust emissions from tyre, brake, and road wear are also significant contributors, although the exhaust emissions can generate more of the smaller particulates.

* PM$_{2.5}$: Particles less than 2.5 microns in size that can travel deep into the respiratory tract and cause health problems.

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> New government policies and business practices are necessary to change the rules of the game, and to foster a more cost-effective and productive transition to a low-carbon future.

Building a low-carbon future

As others before me have observed, energy is at the heart of the environment challenge, and environment is at the heart of the energy challenge. Carbon dioxide emissions from the combustion of fossil fuels are the largest source of greenhouse gases, and direct methane emissions from natural gas production add to the total. It is not possible to effectively confront the threat of climate change without transformation in how we produce and consume energy.

Likewise, the energy industry will be fundamentally challenged in its growth if it cannot find ways to advance the low-carbon energy solutions consumers and society are demanding. The 2015 Paris Agreement, now ratified by 175 countries, set a clear goal of limiting temperature rise to well below 2°C from pre-industrial levels, and this implies that global GHG emissions must peak and begin to decline in the next decade, with steep reductions by 2050.

The first obvious solution to the energy-environment challenge is technological innovation. Decoupling economic growth from emissions like particulate matter and greenhouse gases can be achieved through the development and deployment of cleaner energy technologies. Energy efficiency technologies like LED lightbulbs deliver the same lighting services as incandescent lightbulbs but consume a quarter of the energy. Their slightly higher upfront costs are quickly recouped and deliver long run savings. Low-carbon renewable sources of electricity like solar, wind, and geothermal are now competitive with fossil fuels in some markets. Other technological solutions that are still not currently competitive in the marketplace, such as carbon capture and storage, could become so with policies that create a cost for carbon pollution.

Although the costs of many cleaner energy technologies are falling rapidly, they do not compete on a level playing field. Conventional fossil fuels enjoy incumbency, which means that most of the existing rules and infrastructure were created to support them and not the cleaner alternatives. New government policies and business practices are necessary to change the rules of the game, and to foster a more cost-effective and productive transition to a low-carbon future. Government must enhance support for low-carbon energy research, development and demonstration, and then create a coherent and consistent policy approach to support the commercialization of clean energy technologies in a way that enhances equitable access to energy for all.

For more information on the Climate Policy Lab visit: *www.climatepolicylab.org*

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Insights

What are the key points that emerge from the Technology Outlook?

This Technology Outlook has covered key sections of the energy system – from the production of natural resources through to the use of energy in homes, workplaces, vehicles and heating. In the course of that examination a number of key themes have emerged. Some are linked to specific uses of energy, for example in power or transport, while others have an impact in many areas, for example digital innovation. In this final section, we set out our top ten insights for the energy world and those who have an influence on it, in government, business, academia and beyond.

1 Meeting the Paris goals is technically and economically feasible but would require profound change.

Technology advancement can deliver the 70% plus emissions reductions thought necessary to keep the global temperature rise to 2˚C or less, but the analysis suggests that its progress would need to be accelerated beyond currently projected trends. Many of the technologies required, such as renewable power sources, hybrid and electric cars and digital innovations, are growing. However, the analysis strongly suggests that such a future will not come about without significant policy intervention, for example in the form of carbon pricing. This analysis shows some of the many potential mixes of technologies available and confirms that the power sector appears to have the lowest cost options for decarbonization.

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Shanghai, China – fast growing cities are at the forefront of change in energy technology.

2 Wind and solar power are set to grow rapidly and become a major source of electricity world-wide by 2050.

Our analysis suggests that onshore wind power could become the most economical source of electricity for many regions by 2050 as its costs continue to fall rapidly, driven by advances in turbine technology as well as economies of scale. Solar power is also increasing in efficiency and projected to become competitive in many situations.

3 There are significant integration costs when a high proportion of grid demand is provided by wind and solar power.

If and when wind and solar power account for proportions of more than 40% of total electricity generated, considerable costs are projected to manage their intermittency. Options include storing and releasing energy, for example using batteries, managing demand or using back-up power from gas or coal – possibly with CCUS – or nuclear. Solar, which cannot be captured at all during the night, incurs higher integration costs than wind.

4 Energy storage options are developing rapidly.

Technologies for storing electricity are progressing fast, particularly advanced batteries. These technologies are set to lower the costs of electric vehicles and increase the range over which they can be driven. Advanced batteries also provide new options for storing energy in electricity systems, alongside the use of pumped hydro-electric schemes. While lead-acid batteries have been most cost-effective for grid-scale storage to date, by 2050 competitive options could include compressed air energy storage and lithium-ion, metal-air, solid-state and flow batteries. Hydrogen could also offer an important energy storage option.

5 Transport is set to see transformative change, led by electric vehicles.

Electric vehicles are projected to account for a large number of the 2050 fleet of cars and other light vehicles, alongside hybrids. Electric car batteries are projected to fall to a quarter of today’s costs by 2050. A large proportion of vehicles is projected to become self-driving while car and ride-sharing could change car purchase habits and, potentially, fuel consumption. Liquefied natural gas is projected to become a competitive fuel for trucks and some ships. Bio-jet remains a viable solution to help achieve the aviation industry’s emissions targets, along with carbon offsets.

6 Much of the world’s heating is projected to continue to be provided by gas-fired appliances although action to reduce carbon emissions could favour electric systems and hybrid appliances using heat pumps with gas.

Gas-fired heaters are projected to continue to play a major role to 2050. If carbon emissions are reduced in line with the IEA’s scenario for keeping the global temperature rise to two degrees, electric heat pumps are projected to become more widely deployed in China and North America, as are district heating and hybrid heat pump and gas boiler systems in Europe.

7 Decarbonized gas technologies are important to resolving the dual challenge of reducing greenhouse gas emissions while meeting growing demand for energy.

The importance of decarbonizing gas using CCUS is underlined by its major presence in the modelling of the most economical energy system consistent with keeping the global temperature rise to two degrees, where it accounts for a significant share of power generation in North America and Europe. Without such deployment of gas with CCUS, such a future low-carbon system would be more expensive.

8 Digital technology is the most significant source of system-wide efficiency improvement, although its full power is unknowable.

Digitization is already transforming energy through innovations such as smart grids and 'connected cars'. Oil and gas production is becoming much more cost-effective as a result of advances in areas such as seismic and production optimization. Further changes seem assured as artificial intelligence evolves. Many developments are set to involve digital technology taking on new functions rather than simply increasing the speed and efficiency of operations.

9 Gas and oil are set to play a continuing role.

Gas is projected to play a significant role in the transition to a lower-carbon economy as a source of power, heat and transport fuel, with oil continuing to be used for transport and other sectors. Investment of more than $600 billion per year is estimated to be needed to fund new projects to offset natural oil and gas field decline and meet growing demand. By 2050, technology has the potential to reduce projected average lifecycle costs for both oil and gas by around 30%.

10 Energy efficiency offers massive potential to reduce emissions and save energy.

Our BP-commissioned study identified potential to save around 40% of current primary energy use and up to 13.5 billion tonnes of carbon dioxide emissions by making use of the best technologies, recognising that many of these efficiency improvements require significant investment. Leading technology areas where savings can be made are in everyday uses of energy. They include improving vehicle efficiency, improving building design, increasing use of heat pumps and moving to LED lighting.

These conclusions all demonstrate the over-arching message of this Outlook: that technology has huge potential to improve the way that the world finds, produces, processes and consumes energy. Technology is not only supporting sustainability, but also providing consumers with more choices. What is unknown is the extent to which the potential of energy will be fulfilled, as can be seen by the contrasting futures set out in some of the modelling for this analysis. While the precise shape of the future is unclear, we believe this analysis is nonetheless useful in showing the potential direction of change. For example, we can be confident that renewable energy and electric vehicles will grow significantly, while the analysis suggests that large-scale CCUS and step changes in energy efficiency may need a greater push from policy-makers.

While many questions remain, the most encouraging message from this Outlook is that, if harnessed, the technology of energy has the potential to deliver a more sustainable future.

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Appendix

5

Our approach

In the BP Technology Outlook 2018 we examine the potential of technology to change the way we produce energy and use it in power, transport and heat to 2050.

Acknowledgements

External perspectives were provided by Jonathan Cullen from the University of Cambridge; Mark James from Beyond Limits; James Haywood from Baker Hughes, a GE company; Adnan Amin from the International Renewable Energy Agency; Phil Sheppard from the UK National Grid; Gilles Normand from Groupe Renault; Greg Jackson from Octopus Energy; and Kelly Gallagher at Tufts University.

We greatly appreciate external perspectives such as the ones provided for the Outlook. The information and views set out in the external perspectives are those of the authors and do not necessarily reflect the opinion or views of BP p.l.c.

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Where could technology take us?

Over the coming decades, society faces a dual challenge – meeting the need for more energy, while at the same time reducing carbon emissions.

This publication examines the role of technology in meeting this challenge, drawing on research by BP and its partners into energy production, power, transport, heat and the shape of a future low-carbon economy.

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