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- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
- Support global collaboration on energy technology to secure future energy supplies and mitigate their environmental impact, including through improved energy efficiency and development and deployment of low-carbon technologies.
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Foreword

Digital technologies permeate modern life, affecting everything from the way we work and travel, to the way we live and play. Digitalization holds great promise to help improve the safety, productivity, efficiency and sustainability of energy systems worldwide. But it also raises questions of security, privacy and economic disruption.

The International Energy Agency (IEA) has been focused on the interplay between digitalization and energy for many years. We formulated smart grid roadmaps in 2011 and 2017. We have tracked the progress of electric vehicles and smart charging, and analysed renewables integration and energy use by connected devices.

We are finding that digitalization is becoming increasingly important to a wide variety of energy sectors. Furthermore, with digital technologies changing so rapidly, there are many unknowns about how technology, behaviour and policy will evolve over time and how these dynamics will impact energy systems into the future.

To ensure a more systematic and co-ordinated approach to our efforts, I established a cross-agency Digitalization and Energy Working Group in 2016. Drawing on expertise from across the agency, we are now presenting this first comprehensive examination of digitalization and energy.

Our aim is to provide an accurate and balanced view of what is happening today. Using our analytical tools, we are also beginning to paint a picture of what could happen next. In addition to this report, a new interactive website complements our efforts and provides an alternative way to access our findings.

This effort has benefited from the guidance and feedback of IEA member, association and partner countries as well as energy and technology companies (including those of the IEA Energy Business Council). All of these governments and companies are seeking insights into the opportunities and challenges of digitalization across the whole energy system.

Our hope is that this report will be a clear and accessible step toward helping all global actors better navigate the rapidly changing digitalization and energy landscape.

Dr Fatih Birol
Executive Director
International Energy Agency

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The individuals and organisations that contributed to this study are not responsible for any opinions or judgments it contains. All errors and omissions are solely the responsibility of the IEA.

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We look forward to your continued feedback and partnership, including suggestions and guidance on further needed analysis.

More information about the report is available at: www.iea.org/digital.

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Executive summary

Over the coming decades, digital technologies are set to make energy systems around the world more connected, intelligent, efficient, reliable and sustainable. Stunning advances in data, analytics and connectivity are enabling a range of new digital applications such as smart appliances, shared mobility, and 3D printing. Digitalized energy systems in the future may be able to identify who needs energy and deliver it at the right time, in the right place and at the lowest cost. But getting everything right will not be easy.

Digitalization is already improving the safety, productivity, accessibility and sustainability of energy systems. But digitalization is also raising new security and privacy risks. It is also changing markets, businesses and employment. New business models are emerging, while some century-old models may be on their way out.

Policy makers, business executives and other stakeholders increasingly face new and complex decisions, often with incomplete or imperfect information. Adding to this challenge is the extremely dynamic nature of energy systems, which are often built on large, long-lived physical infrastructure and assets.

This report seeks to provide more clarity for decision makers on what digitalization means for energy – shining a light on both its enormous potential and most pressing challenges. It is the first effort from the International Energy Agency (IEA) to comprehensively depict how digitalization is reshaping the energy sector. It is also intended to serve as a springboard for future work.

Digitalization: A new era in energy?

The energy sector has been an early adopter of digital technologies. In the 1970s, power utilities were digital pioneers, using emerging technologies to facilitate grid management and operation. Oil and gas companies have long used digital technologies to model exploration and production assets.

Recent technological advances and trends are truly astounding. Data are growing at an exponential rate – internet traffic has tripled in only the past five years. There are now more mobile phone subscriptions than people in the world.

Advancing technology, falling costs, and ubiquitous connectivity are opening the door to new models of producing and consuming energy. Digitalization holds the potential to build new architectures of interconnected energy systems, including breaking down traditional boundaries between demand and supply.

The impact of these tremendous digital advances and their rapid deployment across the energy landscape raise the fundamental question of whether we are on the cusp of a new digital era in energy and, if so, what are the emerging trends. This report attempts to answer these questions.

All energy demand sectors are feeling the effects

Digital technologies are already widely used in energy end-use sectors, with the widespread deployment of potentially transformative technologies on the horizon, such as autonomous cars, intelligent home systems and machine learning. While these technologies could improve efficiency, some could also induce rebound effects that increase overall energy use.

In the **transport** sector, cars, trucks, planes, ships, trains and their supporting infrastructure are all becoming smarter and more connected, improving safety and efficiency. Digitalization could have its biggest impact on road transport, where connectivity and automation (alongside further electrification) could dramatically reshape mobility. Meanwhile, the overall net impacts on energy use are highly uncertain. Over the long term, under a best-case scenario of improved efficiency through automation and ride-sharing, energy use could halve compared with current levels. Conversely, if efficiency improvements do not materialise and rebound effects from automation result in substantially more travel, energy use could more than double.

In **buildings**, our analysis shows that digitalization could cut energy use by about 10% by using real-time data to improve operational efficiency. Smart thermostats can anticipate the behaviour of occupants (based on past experience) and use real-time weather forecasts to better predict heating and cooling needs. Smart lighting can provide more than just light when and where it is needed; light-emitting diodes (LEDs) can also include sensors linked to other systems, for example, helping to tailor heating and cooling services.

In **industry**, many companies have a long history of using digital technologies to improve safety and increase production. Further cost-effective energy savings can be achieved through advanced process controls, and by coupling smart sensors and data analytics to predict equipment failure. 3D printing, machine learning and connectivity could have even greater impacts. For example, 3D printing can be used to make aircraft lighter, reducing both the materials to build the plane and the fuel to fly it.

Energy suppliers will reap greater productivity and improve safety

The **oil and gas** industry has long used digital technologies, notably in upstream, and significant potential remains for digitalization to further enhance operations. Widespread use of digital technologies could decrease production costs between 10% and 20%, including through advanced processing of seismic data, the use of sensors, and enhanced reservoir modelling. Technically recoverable oil and gas resources could be boosted by around 5% globally, with the greatest gains expected in shale gas.

In the **coal** industry, digital technologies are increasingly being used in geological modelling, process optimisation, automation, predictive maintenance, and to improve worker health and safety. Specific examples include driverless trucks and tele-remote equipment operated from the control room. Digitalization's overall impact, however, may be more modest than in other sectors.

In the **power** sector, our analysis shows that digitalization has the potential to save around 80 billion United States dollars (USD) per year, or about 5% of total annual power generation costs. This can be achieved by reducing operation and maintenance costs, improving power plant and network efficiency, reducing unplanned outages and downtime, and extending the operational lifetime of assets. One example of this is the use of drones to cheaply monitor thousands of kilometres of transmission lines over rough terrain.

Digitally interconnected systems could fundamentally transform electricity markets

The greatest transformational potential for digitalization is its ability to break down boundaries between energy sectors, increasing flexibility and enabling integration across entire systems. The electricity sector is at the heart of this transformation, where digitalization is blurring the distinction between generation and consumption, and enabling four interrelated opportunities:

- **"Smart demand response"** could provide 185 gigawatts (GW) of system flexibility, roughly equivalent to the currently installed electricity supply capacity of Australia and Italy combined. This could save USD 270 billion of investment in new electricity infrastructure that would have otherwise been needed. In the residential sector alone, 1 billion households and 11 billion smart appliances could actively participate in interconnected electricity systems, allowing these households and devices to alter when they draw electricity from the grid.
- Digitalization can help **integrate variable renewables** by enabling grids to better match energy demand to times when the sun is shining and the wind is blowing. In the European Union alone, increased storage and digitally-enabled

demand response could reduce curtailment of solar photovoltaics (PV) and wind power from 7% to 1.6% in 2040, avoiding 30 million tonnes of carbon dioxide emissions in 2040.

- Rolling out **smart charging technologies for electric vehicles** could help shift charging to periods when electricity demand is low and supply is abundant. This would provide further flexibility to the grid while saving between USD 100 billion and USD 280 billion in avoided investment in new electricity infrastructure between 2016 and 2040.
- Digitalization can facilitate the development of **distributed energy resources**, such as household solar PV panels and storage, by creating better incentives and making it easier for producers to store and sell surplus electricity to the grid. New tools such as blockchain could help to facilitate peer-to-peer electricity trade within local energy communities.

Direct energy consumption of digital technologies

Digital technologies that make all these potential benefits possible also use energy. As billions of new devices become connected over the coming years, they will draw electricity at the plug while driving growth in demand for – and energy use by – data centres and network services. However, sustained gains in energy efficiency could keep overall energy demand growth largely in check for data centres and networks over the next five years.

Data centres worldwide consumed around 194 terawatt hours (TWh) of electricity in 2014, or about 1% of total demand. Although data centre workload is forecast to triple by 2020, related energy demand is expected to grow by only 3% thanks to continued efficiency gains.

Data networks, which form the backbone of the digital world, consumed around 185 TWh globally in 2015, or another 1% of total demand, with mobile networks accounting for around two-thirds of the total. Depending on future efficiency trends, by 2021 electricity consumption from data networks could increase by as much as 70% or fall by up to 15%. This large range highlights the critical role of policy in driving efficiency gains.

Beyond the next five years, providing credible assessments of energy use by digital technologies is extremely difficult. Direct energy use over the long run will continue to be a battle between data demand growth versus the continuation of efficiency improvements.

Building digital resilience to prepare for inevitable cyber-attacks

While digitalization can bring many positive benefits, it can also make energy systems more vulnerable to cyber-attacks. To date, the disruptions caused to energy systems by reported cyber-attacks have been relatively small. However, cyber-attacks are becoming easier and cheaper to organise. Moreover, the growth of the Internet of Things (IoT) is increasing the potential "cyber-attack surface" in energy systems.

Full prevention of cyber-attacks is impossible, but their impact can be limited if countries and companies are well-prepared. Building system-wide resilience depends on all actors and stakeholders first being aware of the risks. Digital resilience also needs to be included in technology research and development efforts as well as built into policy and market frameworks.

International efforts can also help governments, companies and others to build up digital resilience capabilities. A variety of organisations are involved, each contributing its comparative strengths, including to share best practices and policies as well as to help mainstream digital resilience in energy policy making.

Managing privacy concerns and impacts to jobs

Privacy and data ownership are also major concerns for consumers, especially as more detailed data are collected from a growing number of connected devices and appliances. For instance, data on energy use in households collected by smart meters can be used to tell when someone is home, using the shower, or making tea. At the same time, aggregated and anonymised individual energy use data can improve understanding of energy systems, such as load profiles, and help lower costs for individual consumers. Policy makers will need to balance privacy concerns with these other objectives, including promoting innovation and the operational needs of utilities.

Digitalization is also affecting jobs and skills in a variety of energy sectors, changing work patterns and tasks. This is creating new job opportunities in some areas while causing losses in others. Policy makers in the energy field should participate in broader government-wide deliberations about these effects and how to respond to them.

Government policy design is critical

Policy and market design are vital to steering digitally enhanced energy systems onto an efficient, secure, accessible and sustainable path. For example, digitalization can assist in providing electricity to the 1.1 billion people who still lack access to it. New digital tools can promote sustainability, including satellites to verify greenhouse gas emissions and technologies to track air pollution at the neighbourhood level.

Policy-making processes can also benefit from more timely and sophisticated collection and publication of energy data that greater access to digital data could facilitate. Emerging low-cost digital tools, such as online registries, web-crawled data and quick response codes, can lead to more targeted and responsive policy regimes.

While there is no simple roadmap to show how an increasingly digitalized energy world will look in the future, the IEA recommends ten no-regrets policy actions that governments can take to prepare:

- Build digital expertise within their staff.
- Ensure appropriate access to timely, robust, and verifiable data.
- Build flexibility into policies to accommodate new technologies and developments.
- Experiment, including through "learning by doing" pilot projects.
- Participate in broader inter-agency discussions on digitalization.
- Focus on the broader, overall system benefits.
- Monitor the energy impacts of digitalization on overall energy demand.
- Incorporate digital resilience by design into research, development and product manufacturing.
- Provide a level playing field to allow a variety of companies to compete and serve consumers better.
- Learn from others, including both positive case studies as well as more cautionary tales.

Chapter 1

Digitalization: A new era in energy?

Highlights

- Digitalization describes the growing application of information and communications technologies (ICT) across the economy, including energy systems.
- The trend toward greater digitalization is enabled by advances in data, analytics and connectivity:
  - increasing volumes of data thanks to declining costs of sensors and data storage
  - rapid progress in advanced analytics, such as machine learning
  - greater connectivity of people and devices as well as faster and cheaper data transmission.
- Digitalization encompasses a range of digital technologies, concepts and trends, such as artificial intelligence, the "Internet of Things" (IoT) and the Fourth Industrial Revolution.
- Some of these digitalization trends are truly astounding – 90% of the data in the world today were created in just the past two years, and there are now more mobile phone subscriptions in the world than there are people.
- Digital technologies have been helping to improve energy systems for decades, but the pace of their adoption is accelerating. For example, global investment in digital electricity infrastructure and software has been increasing by 20% annually in recent years.
- These digitalization trends raise the fundamental question of whether we are entering a new era of digitalization in energy.

What is digitalization?

Digitalization describes the growing application of ICT across the economy, including energy systems. Consider, for instance, the many digital technologies in play when hailing a ride through an app – your smartphone and its mobile internet connection; the global positioning system (GPS) that pinpoints your location; and the real-time traffic data and advanced analytics that direct your driver.

Digitalization can be thought of as the increasing interaction and convergence between the digital and physical worlds. The digital world has three fundamental elements:

- **Data:** digital information
- **Analytics:** the use of data to produce useful information and insights
- **Connectivity:** exchange of data between humans, devices and machines (including machine-to-machine), through digital communications networks.

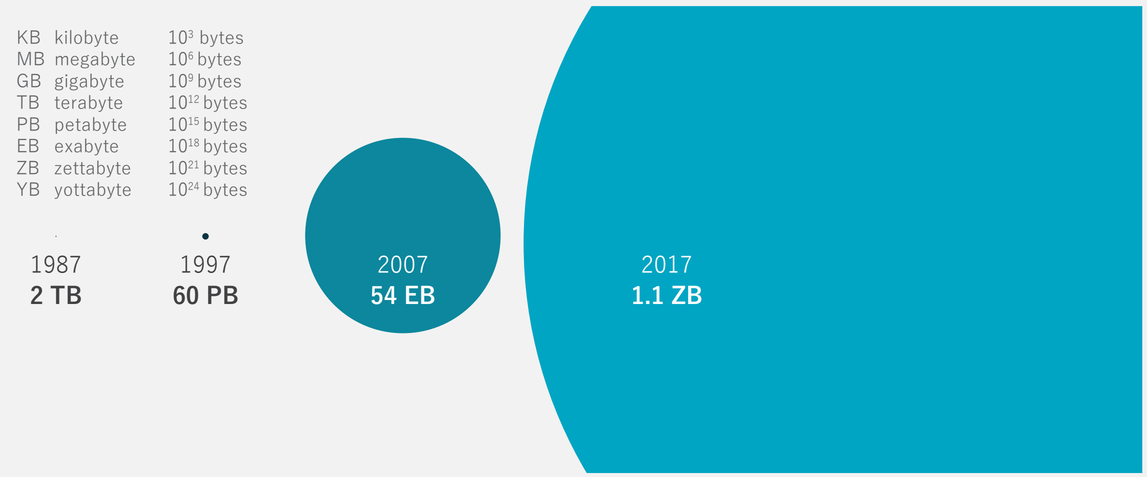
The trend toward greater digitalization is enabled by advances in all three of these areas: increasing volumes of data thanks to the declining costs of sensors and data storage, rapid progress in advanced analytics and computing capabilities, and greater connectivity with faster and cheaper data transmission.

How pervasive is digitalization?

Around 90% of the data in the world today were created over the past two years (IBM, 2017). This exponential growth has led to the use of increasingly large units of measurement. For example, global annual internet traffic surpassed the exabyte threshold in 2001 and is expected to pass the zettabyte threshold by 2017. (One exabyte is 1 000 000 000 000 000 000 bytes, or 10^{18} bytes, and one zettabyte equals 1 000 exabytes, or 10^{21} bytes [Figure 1.1].) Internet traffic has tripled over the past five years (Cisco, 2017a).

Advances in computing power and efficiency have enabled more powerful and sophisticated analytics, such as artificial intelligence (AI) and automation. For example, AI and the ability for machines to process large and complex data are bringing us closer to fully automated cars and trucks. Advanced analytics also enable the creation of digital replicas of physical assets ("digital twins") that can be used to simulate and optimise industrial design and oil and gas drilling. Analytics also enable sophisticated control of building and industrial process equipment, and are ushering in a new wave of automation in manufacturing, including robotics and 3D printing.

Figure 1.1 Global internet traffic

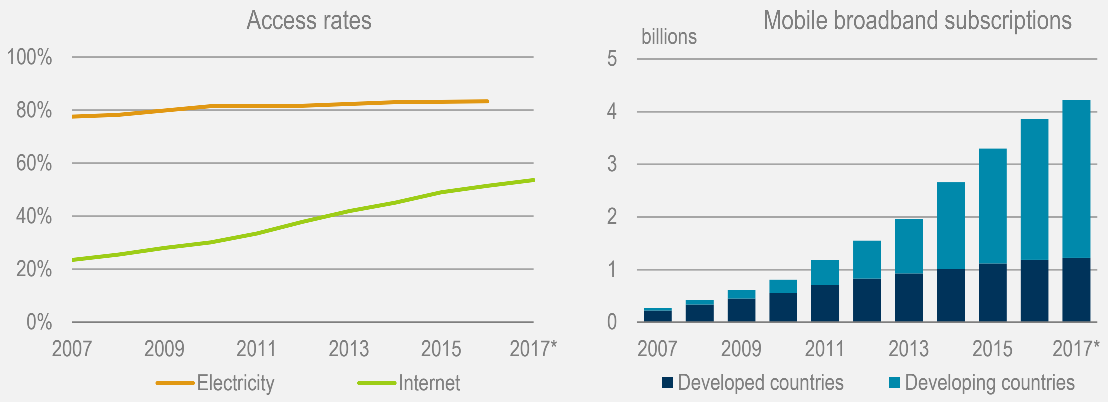


Key message: The world is witnessing an explosion in data, with internet traffic expected to enter the zettabyte era in 2017.

Sources: IEA calculations based on Cisco (2017b) and Cisco (2015).

People and devices are also becoming connected in ever-increasing numbers. More than 3.5 billion people, or nearly half the global population, now use the internet – up from only 500 million in 2001 (ITU, 2017). About 54% of households now have internet access at home (Figure 1.2, left). In the last five years, global mobile broadband subscriptions increased threefold and surpassed 4 billion active subscriptions in 2017, while mobile phone subscriptions reached 7.7 billion. The developing world is leading the more recent growth in connectivity, accounting for almost 90% of the total growth in mobile broadband subscriptions over the past five years (Figure 1.2, right).

Figure 1.2 Global trends in connectivity



Key message: Connectivity is increasing rapidly, particularly in the developing world.

Notes: * denotes estimate for 2017; "Internet access" is defined as households with internet access at home; developed/developing country classifications are based on the UN M49.

Sources: ITU (2017), *ICT Facts and Figures 2017*; IEA (2017), *Energy Access Outlook: From Poverty to Prosperity*.

Everyday objects such as watches, home appliances and cars are being connected to communications networks – the "Internet of Things" (IoT)[1] – to provide a range of services and applications, such as personal healthcare, smart electricity grids, surveillance, home automation and intelligent transport. The number of connected IoT devices is forecast to grow from 8.4 billion in 2017 to over 20 billion by 2020 (Gartner, 2017).

Financial markets, investment trends and digital disruption in other sectors also signal the pervasiveness of digitalization and the greater interactions between digital and energy worlds. The five largest publicly traded companies by market capitalisation currently are all ICT companies with businesses that either depend on digital technologies or provide related services (Figure 1.3). Energy companies, on the other hand, remain global leaders by revenue: six of the top 10 companies are in the energy sector, with the sole digital company – Apple – in 9th place (Fortune, 2017).

Figure 1.3 Largest companies by market capitalisation

Key message: Digital technology companies have become global leaders by market capitalisation, though energy companies still lead in revenues.

Notes: Rankings are for publicly traded companies; market capitalisations calculated at the end of Q2; circle sizes are relative to market capitalisation.

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[1] At the most basic level, IoT is the concept of connecting everyday objects to networks to provide a range of services or applications. IoT encompasses both machine-to-machine (M2M) communication (where devices interact and share data without the direct involvement of people) and connecting "things" to networks to enable people to remotely control processes or manage their devices (IEA, 2014).

Investments and acquisitions by ICT companies in energy-related companies signal the sector's increasing interest in energy (e.g. Google/Nest; Oracle/Opower). ICT companies are also investing more in energy, notably renewables, accounting for more than half of total corporate power purchase agreements (PPAs) for renewables over the past two years (see Box 5.2).

While the rapid rise of Airbnb and Uber might show how quickly digital disruption could occur, there is considerable variability in disruption potential across sectors. For instance, some have less of a "tether" to the physical world (e.g. media), while others (e.g. agriculture) fundamentally involve the production and supply of physical goods, even though digital technologies can have a significant impact on the way business is conducted.

A new era of digitalization in energy?

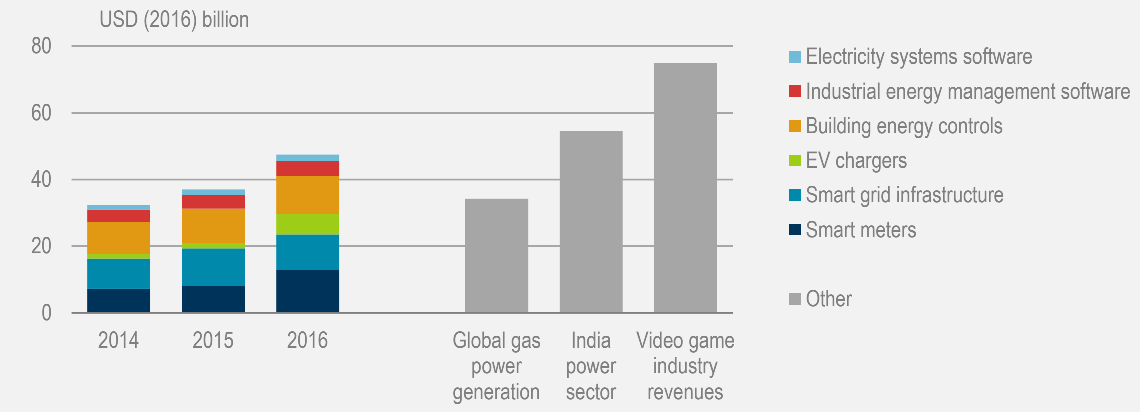
Digital technologies have been helping to improve energy systems for decades. In fact, the energy sector has often been an early adopter of large information technology (IT) systems. In the 1970s, power utilities were digital pioneers, using IT to facilitate management and operation of the grid. Electricity markets are now monitored and controlled in real time over vast geographical areas serving large numbers of customers.

Oil and gas companies have long used digital technologies to model exploration and production assets, including reservoirs and pipelines. The industrial sector has used process controls and automation for decades, particularly in heavy industry, to maximise quality and yields while minimising energy use. Intelligent transport systems are using digital technologies in all modes of transport to improve safety and efficiency.

The pace of digitalization in energy is increasing. Investment in digital technologies by energy companies has risen sharply over the last few years. For example, global investment in digital electricity infrastructure and software has grown by over 20% annually since 2014, reaching USD 47 billion in 2016 (Figure 1.4). This digital investment in 2016 was almost 40% higher than investment in gas-fired power generation worldwide (USD 34 billion) and almost equal to total investment in India's electricity sector (USD 55 billion).

The astounding advances in digitalization and their rapid deployment across the energy landscape raise the fundamental question of whether we are on the cusp of a new digital era in energy. The remainder of this report attempts to answer this fundamental question.

Figure 1.4 Investments in digital electricity infrastructure and software



Key message: Investment in digital electricity infrastructure and software grew over 20% annually between 2014 and 2016, overtaking global investment in gas-fired power generation.

Notes: Global gas power generation and India power sector are 2016 investments; EV = electric vehicle.

Sources: Calculations for investment in digital infrastructure and software based on MarketsandMarkets (2016), *Internet of Things in Utility Market*; BNEF (2016), *Digital Energy Market Outlook*.

Purpose and structure of report

This report describes the status of digitalization in energy, how it is affecting energy systems, what might happen in the future and what all this means for policy makers, companies and consumers. Digitalization and energy is a complex and constantly evolving topic. As such, this report is not intended to be a definitive, exhaustive analysis. Rather, it seeks to shed light on how the energy and digital worlds interact and to serve as a springboard for further analysis by the International Energy Agency (IEA).

The rest of this report is structured as follows:

- Chapter 2 analyses the current and potential impact of digitalization on energy use in the three main demand sectors – transport, buildings and industry.
- Chapter 3 looks at the impact of digital technologies on energy supply, focusing on oil and gas, coal and electricity.
- Chapter 4 explores the more transformational potential of digitalization to break down individual energy silos, to blur the boundaries between energy demand and supply, and to help create a highly interconnected electricity system.
- Chapter 5 assesses the direct use of energy by digital technologies themselves, including data centres, data networks and connected devices.
- Chapter 6 considers the main cross-cutting risks of digitalization – cybersecurity, privacy and economic disruption.

- Chapter 7 focuses on the critical role of government policy – how digitalization can help achieve policy goals and improve the policy-making process, and the importance of integrated policy frameworks and market design. It concludes with a set of no-regrets recommendations for policy makers.

Due to the cross-cutting nature of digitalization, certain subjects are covered in multiple chapters. For instance, the impact of digitalization on electricity systems is discussed in both Chapters 3 and 4. Similarly, policy implications related to particular energy sectors (e.g. transport) are addressed, respectively, in Chapters 2, 3 and 4, while cross-cutting policy issues are discussed in Chapters 6 and 7.

This report is also complemented by a new, interactive website – www.iea.org/digital – which will provide a dynamic means to access the information in this report.

Many terms and concepts are introduced and discussed in this report, some of which may be unfamiliar to either energy sector or digital experts, respectively. While concepts are explained as they arise, a full list of terms is also available in the glossary at the end of this report.

This report utilises a variety of IEA analytical tools, including both existing and new IEA analysis. It draws on various IEA models, including the World Energy Model, the Energy Technology Perspectives Model and the Mobility Model (MoMo). The report contains references to an IEA Central Scenario, which is used in this report to describe the pathway for energy markets and technological progress based on the continuation of existing energy and climate policies and measures, and to a certain extent announced commitments and plans. It is broadly in line with the *World Energy Outlook* New Policies Scenario (NPS) as well as the 2017 *Energy Technology Perspectives* Reference Technology Scenario (RTS). The Central Scenario should not be interpreted as a forecast.

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Chapter 2

Impact of digitalization on energy demand in transport, buildings and industry

Highlights

- Digitalization is having a major impact on transport, buildings and industry. How significant this will turn out to be in the future will differ for each sector and particular application.

- **Transport** is becoming smarter and more connected, improving safety and efficiency. In road transport, connectivity is enabling new mobility sharing services. Combined with advances in vehicle automation and electrification, digitalization could result in substantial but uncertain energy and emissions impacts. Over the longer term, road transport energy use could either drop by about half or more than double, depending on the interplay between technology, policy and behaviour.

- Digitalization could cut total energy use in residential and commercial **buildings** by around 10% to 2040. These efficiency gains are largest in heating and cooling, particularly through the use of smart thermostats and sensors. Smart lighting allows for potentially substantial cuts in lighting electricity demand. However, new services and comforts brought about by digitalization – as well as greater use of standby power by idle devices and appliances – could offset potential savings.

- **Industry** has been using digital technologies for a long time to improve safety and productivity. Digitalization could lead to further significant energy savings with short payback periods through improved process controls within industrial plants and beyond the plant fence. Three-dimensional (3D) printing, machine learning and enhanced connectivity could have an even bigger impact.

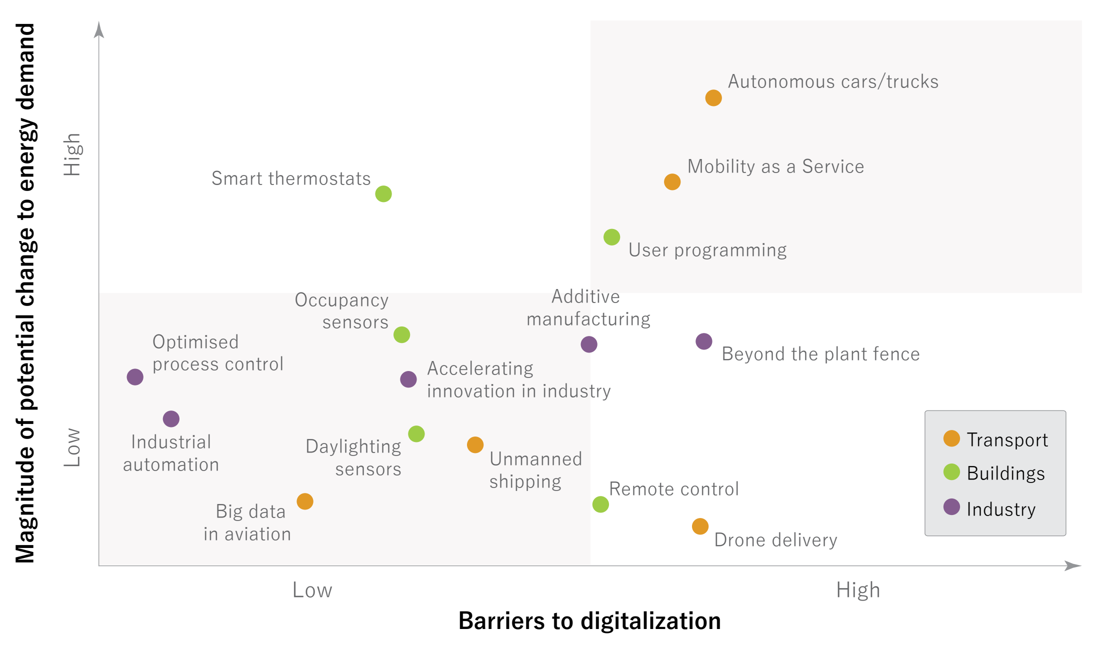
- Sector-specific and cross-sectoral policies are needed to maximise benefits made possible by digital technologies and to address challenges, including cybersecurity, data privacy and job losses.

Introduction

Digitalization can be a powerful means for increasing efficiency, productivity and energy savings in transport, buildings and industry. This chapter explores specific impacts of digitalization within each of these demand sectors.[1] The magnitude of potential impacts – and associated barriers – varies greatly depending on the particular application (Figure 2.1).

Broader systemic implications, including digitalization's ability to break down boundaries between various demand and supply sectors leading to even more potentially transformative impacts, are discussed in Chapter 4. Cross-cutting risks such as cybersecurity, data privacy and job losses are discussed in Chapter 6.

Figure 2.1 Digitalization's potential impact on transport, buildings, and industry



Key message: Digital technologies and applications face a variety of barriers to adoption and use, and their impacts on energy use differ across demand sectors.

Notes: The digitalization trends/strategies included in this figure are not intended to be exhaustive. "Magnitude of potential change to energy demand" indicates the potential impact of digitalization on energy demand in absolute terms, which may be positive or negative. "Barriers to digitalization" include technological, regulatory and public perception components. The quadrants are illustrative only and intended to give a sense of relative magnitude.

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[1] Digitalization outside the energy sector, such as e-commerce, e-materialisation (e.g. e-books, DVDs to streaming video), and teleworking, could also change energy use patterns through a range of efficiency, substitution, and rebound effects. Relevant examples are discussed in this chapter. See Horner, Shehabi, and Azevedo (2016) for a detailed discussion around the challenges in quantifying the direct, indirect, structural, and behavioural effects of digitalized products and services.

Transport

Cars, trucks, planes, ships, trains and their supporting infrastructure are becoming "smarter" and more connected, improving safety and efficiency across the transport system. The most revolutionary changes could come in road transport, where ubiquitous connectivity and automation technologies could fundamentally transform how people and goods are moved. Thus, this chapter focuses mostly on road transport, with passing reference to other transport subsectors.

Deployment of digital technologies in transportation

The digitalization of transport essentially describes the concept and development of "intelligent transportation systems" (ITS). ITS involve: the deployment of sensors for data collection; use of communications technologies to enable remote control; and application of advanced analytics to improve system operations, safety, efficiency and service, as well as to lower costs (US Department of Transportation, 2016).

Everyday examples of ITS include in-road traffic detectors to control traffic lights, radio-frequency identification (RFID) to automatically collect tolls, and the use of the global positioning system (GPS) and telecommunications for roadside assistance. The three main trends shaping the future of ITS are connectivity, shared mobility and automation.

Smarter and more connected vehicles and infrastructure

Smarter and more connected vehicles and infrastructure are collecting and analysing large volumes of data in order to make individual vehicles as well as the broader system operate more efficiently. Connected vehicles, equipped with internet access, cellular radio, dedicated short-range communications (DSRC)[2] and other means of sensing and connectivity, are increasingly able to interact with nearby vehicles, infrastructure or both (Li et al., 2012; Narla, 2013).

Across all transport modes, digital technologies are helping to improve energy efficiency and reduce maintenance costs. In aviation, the latest commercial aircraft are equipped with thousands of sensors, generating almost a terabyte of data on an average flight (Airbus, 2017). Big data analytics optimise route planning and can help pilots make in-flight decisions and reduce fuel use. Ships are also being equipped with

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[2] DSRC enables wireless communication using signals in the very high to super high frequency range (75 megahertz to 5.9 gigahertz in the United States) for vehicle safety and mobility applications (including vehicle-to-vehicle [V2V] and vehicle-to-infrastructure [V2I]). For more on DSRC, see *Dedicated Short Range Communications (DSRC); The Future of Safer Driving*, US Department of Transportation, 2016, www.its.dot.gov/factsheets/pdf/JPO-034_DSRC.pdf.

more sensors, helping crew take actions to optimise routes, while advances in satellite communications are enabling greater connectivity. Better communication between ships and ports could optimise ship speed to meet requirements on port arrival timing, yielding significant fuel savings from slow steaming. In rail, sensors are being used to monitor everything from engine temperature to vibrations, while cameras collect visual data on the condition of the tracks.

In road transport, real-time information on location and routing can help optimise vehicle and fleet operations. Connectivity also enables the execution of a wide range of other operations, from checking the status of battery charging for electric vehicles (EVs) to platooning of freight trucks.[3] Connected transport systems also foster the development and adoption of shared mobility services and platforms.

Shared mobility

Shared mobility emerged in major cities in the early 2000s with the arrival of car-sharing services from providers such as ZipCar, whereby members could borrow cars on a short-term (hourly) basis (Clewlow, 2016). Many of these services are now accessed through smartphone apps, allowing users to locate and unlock vehicles, and making one-way journeys possible.[4] Worldwide membership of car-sharing services could grow from more than 7 million globally in 2015 to around 36 million by 2025 (Frost and Sullivan, 2016).

Bike-sharing services based on similar technologies and platforms are now available in over 1 000 cities worldwide. Such services have exploded in popularity in the People's Republic of China (hereafter, "China"). The number of active users has more than doubled within only one year (2016) and is expected to top 50 million by the end of 2017. Shanghai alone has an estimated 450 000 shared bikes, compared with 21 000 in Paris. "Dockless" systems (widely deployed in China) and electric bicycle systems (e.g. Copenhagen, Madrid) could further increase the popularity of these services globally.

App-based ride-hailing services are also beginning to have a major effect on urban mobility. With the widespread adoption of smartphones equipped with GPS and the availability of digital road maps through APIs (application program interface),[5] the uptake of such services is growing rapidly, including in emerging economies. Didi Chuxing operates in over 400 cities in China, with 20 million rides per day.

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[3] Platooning refers to the practice of driving vehicles (primarily heavy-duty tractor-trailers or rigid trucks) in a single line with small gaps between them to reduce drag and thereby save fuel during highway operations. V2V and V2I communication technologies can enable trucks to drive in very close proximity without sacrificing safety or manoeuvrability.

[4] One-way car-sharing systems like car2go allow users to pick up a vehicle at one location and drop it off at another.

[5] An API is a list of commands that allows software programs to communicate with each other and use each other's functions.

Singapore-based GrabTaxi operates in 50 cities across Southeast Asia. With growing internet access and a large population of young people who are concerned about pollution and open to ride-sharing, some analysts believe India could soon become one of the largest markets for shared mobility in the world (Morgan Stanley, 2017). App-based ride-hailing services are beginning to apply advanced algorithms to co-ordinate and match users along routes, making possible truly “shared” mobility services, such as UberPool and LyftLine.

Mobility as a Service (MaaS) platforms aim to simplify the range of shared mobility services by offering a unified routing and payment platform.[6] MaaS platforms allow users to subscribe to an all-inclusive, multi-modal “mobility package” and access a variety of shared mobility services,[7] including bicycles, buses, trains, cars, taxis and ride-hailing services. The world’s first such service, Whim, was introduced in Finland in 2016.

Automated driving technologies

Automated driving technologies aim to improve safety and driving convenience through advanced sensing and automated decision-making capabilities that can assist or replace human control. While recent attention has focused on passenger cars, automated driving technologies are already widely deployed in the railway business, primarily on rapid transit and urban lines, and in aviation, where unmanned flight is already common in military applications. The use of drones for delivery services are being tested in some cities (Box 2.1).

Despite a host of technical, regulatory and other policy-related hurdles, prospects for the deployment of connected automated vehicles in road transport are promising due to rapid advances in key technologies[8] as well as their large potential cost savings and safety benefits.[9] Commercial applications, particularly where labour costs are proportionately high (e.g. buses and ride hailing) or where automation could enable higher vehicle utilisation (e.g. trucks), are well-suited to be targeted first (Wadud, 2017). Major automakers have announced plans to introduce highly automated

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[6] Various names and acronyms have been applied to describe MaaS. In the United States, the Federal Transit Administration has adopted the term “Mobility on Demand”: www.transit.dot.gov/research-innovation/mobility-demand-mod-sandbox-program.html.

[7] Such platforms could integrate services from both public and private operators, as well as public-private partnerships and other hybrid business models, relying on data sharing via APIs.

[8] Including machine vision and 3D cameras, laser-imaging detection and ranging (LIDAR) and advanced GPS, and artificial intelligence software.

[9] With over 90% of crashes attributable to human error or choice (US Department of Transportation, 2015), an automated, connected, electric and shared (ACES) mobility system could significantly reduce the number of road fatalities and injuries, while also improving mobility access for the growing number of seniors, as well as children and the disabled.

passenger vehicles as early as 2020,[10] with some experts predicting its widespread adoption in the period 2025-40 (Arbib and Seba, 2017; Fulton, Mason and Meroux, 2017; Gartner, 2016; Milakis et al., 2015; Wadud, 2017).

Box 2.1 Drones

The use of unmanned aerial vehicles, or drones, for civilian and commercial purposes is at an early stage. Delivery by drones is being tested in cities in China, India and California, but prospects for mass deployment are uncertain. Capacity limitations are expected to restrict the use of drones as substitutes of road vehicles to deliver the massive volume of commodities circulating throughout cities and the economy (IEA, 2017a). Under reasonable assumptions for loading, unloading and flight times, it would take about 15 drones operating around the clock to deliver the same number of products as a single light commercial vehicle does in a typical eight-hour shift (McKinnon, 2015). In addition, the per-kilometre costs of drone delivery are likely to remain higher than those of conventional trucks in the medium term.

Life-cycle analysis shows that the potential energy and emissions advantages of drones are likely to be limited and highly context dependent (Goodchild and Toy, 2017). Safety, security, liability and noise considerations are further barriers to the widespread use of drones, and their viability in goods delivery markets is likely to depend on the regulatory context. Nonetheless, drones have proved their utility in a variety of specific applications, such as delivering high-value goods in cities, vaccines to remote communities, or essential supplies for disaster relief.

In the energy supply sector, drones carrying cameras or multiple sensors (e.g. GPS, radar, sonar) have an array of applications such as performing inspections of corrosion on oil rigs and wind turbine blades. They can also conduct surveys of environmental conditions and wildlife at potential offshore wind sites, which may be difficult or expensive to reach by other means. Drones equipped with thermal imaging cameras have been used to conduct aerial thermography to detect power losses and failure risks in solar photovoltaic plants. Specially equipped drones can also perform basic maintenance of electricity grids; for instance, a flame-throwing drone can burn off rubbish entangled around wires.*

* "Flame-throwing drone removes net entangled in China power line": https://youtu.be/iOqWfLZT8OM.

The investment and financial implications of the roll-out of connected automated vehicles and mobility services are enormous. With the market for automated driving technologies expected to grow to almost USD 200 billion by 2030 (Archambault et al.,

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[10] Here "highly automated" refers to automated monitoring and control of the vehicle, corresponding to Levels 4 and 5 of the hierarchy defined by the Society of Automotive Engineers (SAE) International Standard J3016 (SAE International, 2016). The SAE Standard defines six levels of automation, from no automation (Level 0) to full automation (Level 5). A key distinction of levels occurs between Levels 2 and 3, depending on whether a human (Levels 0-2) or car (Levels 3-5) monitors the environment. Vehicles with high or full automation (Levels 4-5) are commonly referred to as "autonomous", "driverless", or "self-driving" (although Level 4 allows "driverless" mode only under certain conditions, e.g. highway).

2015),[11] automakers, technology companies and app-based ride-hailing service providers are all vying to control the key technologies that will underpin the market, pouring billions into research, strategic partnerships, and acquisitions.[12] High-profile legal battles (e.g. Waymo v. Uber) over proprietary automated driving technologies have ensued (Abuelsamid, Alexander and Jerram, 2017). Tesla, whose vehicles are now equipped with the necessary hardware for fully automated driving (Tesla, 2016), has announced plans to release an electric truck with automated capabilities. Tesla's market capitalisation recently surpassed that of Ford, GM and, most recently, BMW, despite selling fewer than 80 000 vehicles and spending USD 770 million more than it earned in 2016 (Mitchell, 2017).

Implications for energy use and emissions: Focus on road transport

Transport currently accounts for 28% of global final energy demand and 23% of global CO_2 emissions from fuel combustion (IEA, 2017b). In the IEA Central Scenario,[13] final energy consumption for transport grows by almost half to 165 exajoules in 2060, with most of the demand coming from road freight vehicles (36%) and passenger light-duty vehicles (28%). The dynamics and net effects of automated, connected, electric and shared (ACES) mobility will play a key role in shaping the future energy and emissions trajectory of the overall transport sector.

Digitalization can affect road transport energy demand in many ways. Highly automated vehicles reduce driver stress and allow for more productive use of travel time, making private car travel more attractive. Automation will also make road freight transport cheaper. Both of these factors could encourage more travel activity, resulting in increased congestion and energy demand. On the other hand, shared and autonomous transport could facilitate vehicle right-sizing[14] and accelerate EV

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[11] This market refers to "sales of autonomous vehicle components for road vehicles". By comparison, this figure is slightly less than Toyota's consolidated global net revenues in fiscal 2016, which totalled about USD 240 billion (Toyota, 2016).

[12] Recent acquisitions of automated driving companies include Intel (Mobileye, USD 15.3 billion), Ford (ArgoAI, USD 1 billion), GM (Cruise Automation, 1 billion) and Uber (Otto, USD 680 million). Major investments in shared mobility platforms include Apple (Didi Chuxing, USD 1 billion), GM (Lyft, USD 500 million) and Volkswagen (Gett, USD 300 million). For a more complete listing of automobile manufacturer investments in connected and automated vehicle technologies and shared mobility businesses, see Table 3 of Slowik and Kamakaté (2017).

[13] As defined in Chapter 1, the Central Scenario describes the pathway for energy markets and technological progress based on the continuation of existing energy and climate policies and measures, and to a certain extent announced commitments and plans. It is broadly in line with the *World Energy Outlook* New Policies Scenario (NPS) as well as the 2017 *Energy Technology Perspectives* Reference Technology Scenario (RTS). This should not be interpreted as a forecast.

[14] Increased use of shared and autonomous transport could help optimise the size of vehicles to match utilisation patterns, resulting in improved energy efficiency.

adoption, reducing energy use and emissions.[15] High utilisation rates of automated and shared vehicles spurring more rapid vehicle (and fleet) turnover could favour and accelerate the uptake of highly efficient technologies including EVs, reducing the emissions intensity of travel (Johnson and Walker, 2016).

The successful integration of shared and automated mobility services with mass public transit, walking and cycling could also help to reduce energy use.[16] For instance, feeder services provided by shared and automated vehicles could foster the use of high-capacity public transport. In cities with high population density and good public transport networks, digitalization could contribute to a shift away from the traditional paradigm of vehicle ownership towards the provision of MaaS. The challenge for local authorities is to find the right mix of fiscal instruments and transport and urban planning to ensure that autonomous and shared vehicles strengthen, rather than take over, public transport.

The consequences of ACES mobility for energy and emissions are highly uncertain. They will depend on the combined effect of changes in consumer behaviour, policy intervention, technological progress and vehicle technology. Analyses of extreme scenarios developed for the US Department of Energy find that automated vehicles in some cases could reduce fuel consumption by more than 90% or increase it threefold under a "perfect storm" of inefficient behavioural response compared with central projections (Brown, Gonder and Repac, 2014).

Several recent studies consider a range of ACES mobility development scenarios, most of which focus on passenger vehicles (Brown, Gonder and Repac, 2014; Fulton, Mason and Meroux, 2017; Greenblatt and Saxena, 2015; Stephens et al., 2016; Wadud, MacKenzie, and Leiby, 2016). Two of these studies, in particular, demonstrate the range of implications of possible developments in vehicle autonomy, sharing and electrification for energy use and emissions:

- Wadud, MacKenzie and Leiby (2016) examine the mechanisms by which connected and automated vehicles may lead to a wide range of outcomes with respect to energy use. The study explores a range of possible technological and societal developments in the United States, and finds that road transport

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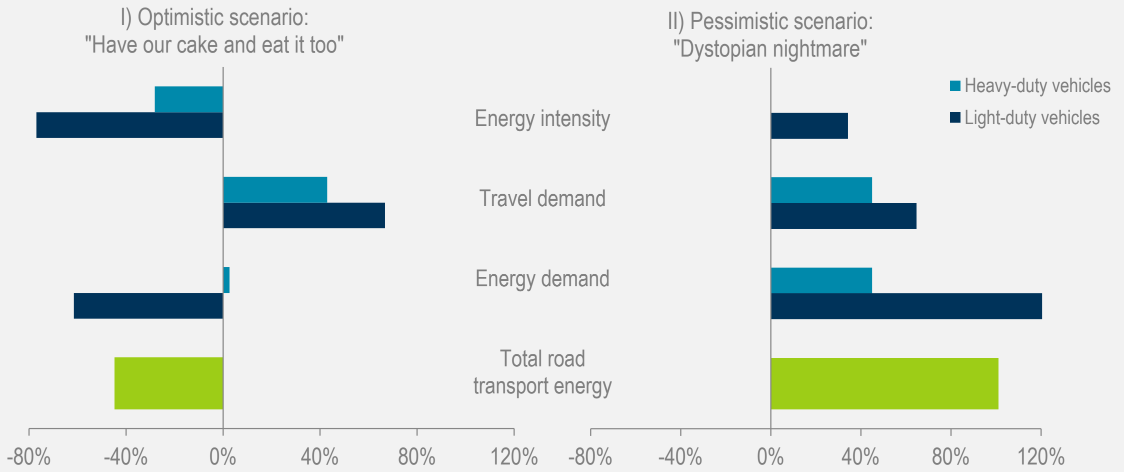
[15] The coupling of connectivity and automation with EVs could help diversify energy use, reduce pollutant emissions and, if the electrical grid is progressively decarbonised, also result in lower greenhouse gas emissions.

[16] Public transport authorities and transit agencies across several municipalities in the United States have integrated app-based ride sharing into their portfolio of services, promoting and in some cases even subsiding Uber, Lyft and conventional taxi rides that connect to and from public transit stations, or that serve underprivileged populations (Slowik and Kamakaté, 2017). Nevertheless, early evidence from New York City suggests that Uber and Lyft may be displacing mobility that would otherwise have taken place on public transport (Schaller, 2017). Similar results were found in a recent survey in seven major US cities including New York, Chicago and Los Angeles (Clewlow and Mishra, 2017).

energy demand could be reduced by almost half under an optimistic scenario, or more than double in a pessimistic scenario (Figure 2.2). The study also finds that even at low levels of automation, prioritising system-level connectivity and co-ordination among vehicles over individual vehicle automation could result in significant gains in energy efficiency.

- Fulton, Mason and Meroux (2017) explore the global energy and carbon dioxide (CO_2) emissions implications of automation, electrification and shared mobility. The findings suggest that technological innovation in electrification and automation alone may result in increased greenhouse gas emissions. Sharing of trips and vehicles, MaaS and strong support for public transit are needed to steer the transformation of urban mobility in a way that leads to lower emissions.

Figure 2.2 Range of possible energy impacts from vehicle automation in the United States



Key message: US road transport energy demand is reduced by almost half under an optimistic scenario, but more than doubles in a pessimistic scenario.

I) In this scenario, virtually all of the potential benefits of automation are realised, including smoother traffic flow, fewer accidents (vehicles become smaller/lighter) and the widespread adoption of eco-driving and platooning.

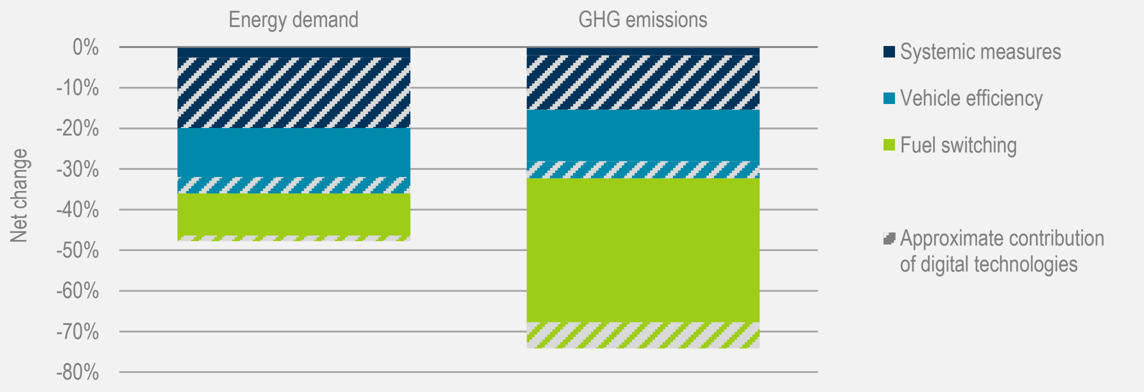
II) In this scenario, broad adoption of higher levels of automation is coupled with strong increases in demand for travel, and no efficiency benefits materialise (e.g. no platooning or eco-driving).

Note: This figure only shows two of the four scenarios from the study. One of the other scenarios describes a world with limited automation and minimal impact on energy use, while the other assumes large improvement in fuel efficiency as well as increased travel demand, resulting in a moderate net reduction in energy use.

Source: Wadud, MacKenzie and Leiby (2016), “Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles”.

The IEA recently considered the energy and CO_2 emissions implications of digitalization in freight transport (IEA, 2017a). In a Modern Truck Scenario, digitally enabled changes[17] to improve supply chain and logistics operations contribute about one-third of the cumulative greenhouse gas reduction potential in the road freight sector to 2050 relative to the IEA Central Scenario (Figure 2.3). Such efforts could culminate in new paradigms for goods delivery, such as the "physical internet",[18] reducing the number of trucks and traffic needed to deliver goods. Connectivity and automation can improve the operational efficiency of road haulage through eco-driving, shifting operations to less congested times and routes, and platooning. Finally, smarter charging of plug-in electric trucks can both improve the economics of electrification and reduce the carbon intensity of electricity sourced.[19]

Figure 2.3 Digitalization's impact on energy use and emissions reductions in road freight



Key message: Digital technologies can play a key role in reducing energy demand and greenhouse gas emissions in road freight, notably by facilitating horizontal and vertical collaborations among companies to streamline supply chains and logistics.

Notes: Greenhouse gas emissions are measured on a well-to-wheels basis; systemic measures include platooning, the retiming of urban deliveries and driver training, among others; fuel switching includes both the use of advanced biofuels and the adoption of alternative powertrains running on low-carbon energy carriers, such as electricity and hydrogen; GHG = greenhouse gas.

Source: IEA (2017a), *The Future of Trucks – Implications for Energy and the Environment*.

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[17] Examples include: GPS coupled with real-time traffic information for route optimisation; on-board monitoring and feedback that enhances eco-driving performance; vehicle connectivity that can safely reduce gaps between platooning trucks to improve fuel efficiency; and data sharing between companies across the supply chain to ship more goods with fewer trips.

[18] The "physical internet" describes an open, shared global logistics system inspired by the movement of data on the internet, in contrast with the proprietary logistics systems that are common today. Currently, nearly all logistics service providers and carriers maintain proprietary assets, both physical (e.g. warehouses and trucks) and operational (e.g. information on routes, customers and markets) (Wible, Mervis and Wigginton, 2014).

[19] For example, charging at times when renewable electricity generation exceeds demand, supplying power to the grid during peak demand times and providing other ancillary grid services. See Chapter 4 for a discussion on the potential interactions between EVs and the grid as a result of digitalization.

Energy use and emissions in the road transport sector and other transport modes could also be affected by digitalization beyond the sector itself.[20] For instance, lower transport demand as a result of more teleworking could reduce travel and energy demand, although empirical studies suggest that the actual impact on mobility and energy use are mixed. In fact, teleworking may result in an overall increase in energy use in many contexts, for instance, by increasing energy use at home and changing overall travel decisions (Choo, Mokhtarian and Salomon, 2005; Kim, Choo and Mokhtarian, 2015; Larson and Zhao, 2017; Melo and de Abreu e Silva, 2017; Ory and Mokhtarian, 2006).

Additive manufacturing, commonly known as 3D printing, could reduce demand for long-distance shipping of goods. 3D-printed components could also lead to lighter aircraft (Huang et al., 2016) and improve turbine efficiency, thereby reducing in-flight fuel use (see Box 2.3). Digitalization could also pave the way for a variety of systemic cross-sectoral interactions and opportunities. For instance, digitally-enabled smart charging and vehicle-to-grid (V2G) technologies could play an important role in integrating higher shares of variable renewables into electricity supply (see Chapter 4).

Barriers to digitalization and policy considerations

Government policies and regulations will play an important role in the deployment of digital technologies in transport, as well as steering developments towards lower energy and emissions pathways.

Addressing barriers and risks

As transport becomes increasingly digitalized, questions about vehicle and software certification, liability, cybersecurity,[21] data privacy, and employment (see Box 6.5) will need to be addressed (Hern, 2017).

Connected and automated vehicles, in particular, face a variety of technical, regulatory and other[22] hurdles that could impede their widespread deployment. Real-world testing, learning and data collection are vital to improving technology and instilling public confidence in automated driving technologies. Regulators should consider

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[20] For example, the move from DVDs to streaming video could cut energy use from DVD production and transport, while increasing energy use by data centres and networks. The convenience of such e-services could also result in rebound effects that encourage greater use of these services, resulting in higher energy use overall. See Horner, Shehabi, and Azevedo (2016) for other examples.

[21] Ensuring cybersecurity becomes more difficult once vehicles are connected to each other (V2V) and to infrastructure (V2I) (Perlroth, 2017).

[22] For example, ethical and moral considerations. The German government recently released a report on ethical aspects of automated cars (BMVi, 2017).

getting rid of outdated regulations and introduce new ones to encourage competition and facilitate trials.

Harmonising and standardising communications and data protocols will also be important in permitting cross-border travel of connected automated vehicles. For example, the European Union is working with member states, automakers, telecom companies and other industrial stakeholders toward legislation to ensure interoperability.[23]

Public policy can also help promote innovative mobility services and foster multi-modality[24] by establishing platforms for sharing and maintaining high-quality databases to be easily queried and integrated with APIs (Shaheen et al., 2016).[25] Such publicly accessible databases would need to be well maintained to ensure the data are accurate and the data made available in such a way as to ensure personal privacy.

In road freight, sharing of data, assets and services across the supply chain can enable dramatic improvements in freight logistics (IEA, 2017a). Governments can also promote the reporting of aggregated information (such as vehicle- and tonne-kilometres taking place in a given area and at a given time) making it possible for authorities to monitor the impact of public policies without compromising confidentiality. All datasets need to meet high standards of cybersecurity (see Chapter 6).

Toward smart and sustainable mobility

Policy can help steer developments in automated and connected mobility towards lower energy use and emissions. For example, the gradual introduction of distance-[26] and congestion-based pricing could moderate potential rebound effects[27] stemming from high levels of automation. Other measures could help to direct consumer interest

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[23] For more on the European Commission's priorities in shaping legislation on "co-operative, connected and automated mobility" under the framework of its Digital Single Market strategy, see: https://ec.europa.eu/digital-single-market/en/cooperative-connected-and-automated-mobility-europe.

[24] "Multimodality" refers to seamless trip-making across multiple transport modes (e.g. walking, cycling, bus, urban rail and cars).

[25] For example, the approach being pursued under the Finnish Transport Code is to establish public entities as repositories of mobility databases and data exchange hubs (Ministry of Transport and Communications, 2016), making data easily accessible to app developers and to the public at large. Shared mobility operators in Washington, DC, Boston and San Francisco have shared data with public agencies, either voluntarily or by mandate (Shaheen, Cohen and Zohdy, 2016). Collaboration between Rio de Janeiro's public transport app Moovit and Google Waze resulted in the integration of real-time road traffic and public transport data (Olson, 2014).

[26] Distance-based pricing should be differentiated on the basis of vehicles' fuel efficiency and/or pollutant emissions performance.

[27] Rebound effects occur when energy savings resulting from improved efficiency (resulting in lower energy costs) can stimulate increased energy consumption and general expenditures that counteract the technical potential savings. For example, high levels of automation could improve energy efficiency, but could also result in greater overall driving activity due to reduced costs.

and spending towards shared mobility to curb energy use and emissions. This might be especially effective in markets with rising car ownership, such as China, India and other emerging economies. In road freight, global standardisation of truck sizes and pallets could boost fuel efficiency in the same way that the adoption of standardised containers enabled vast operational efficiency gains in maritime freight.

Policy can also adapt to leverage the synergies between sharing, automation, and electrification as a means to accelerate EV adoption. The European Commission's "Europe on the Move" strategy seeks to overhaul existing legislation and set up new initiatives to promote "clean, competitive and connected mobility" (European Commission, 2017). App-based ride-hailing service providers such as Lyft have already set goals to provide services using only electric, autonomous vehicles powered by 100% renewable energy (Zimmer, 2016; Zimmer and Green, 2017).

Buildings

Digitalization of the provision of energy services

There is significant potential for digitalization to improve energy services and user comfort in buildings, while also reducing overall energy use. Smart energy management can:

- Help ensure that energy is consumed when and where it is needed, by improving the responsiveness of energy services (e.g. by using lighting sensors) and predictively with respect to user behaviour (e.g. through learning algorithms that auto-programme heating and cooling services).
- Enable demand response to reduce peak loads (e.g. shifting the time of use of a washing machine), to shed loads (e.g. adjusting temperature settings to lower energy demand at a particular time) and to store energy (e.g. in thermal smart grids) in response to real-time energy prices or other conditions specified by the user.
- Predict, measure and monitor in real time the energy performance of buildings, allowing consumers, building managers, network operators and other stakeholders to identify where and when maintenance is needed, when investments are not performing as expected or where energy savings can be achieved.

The energy loads of a building can be displaced or turned on and off using active control systems that collect, process and adapt to real-time data using sensors, and which can be managed using a single front-end dashboard (e.g. smart phone or tablet app). Active controls can also integrate and intelligently link building energy services with information from the grid, allowing for better management of supply and demand.

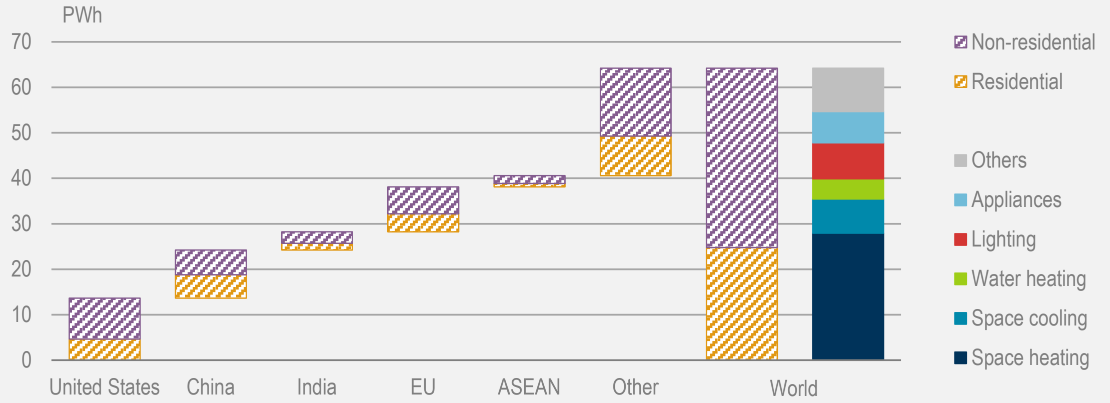
Such integration, paired with algorithms and market information, can help to drive down transaction costs between electricity generators and consumers. In retail markets, aggregating distributed energy loads across multiple end-users enable demand shaping, both reactively (e.g. using price signals) or proactively (e.g. using input on consumer preferences) (see Chapter 5).

Energy implications of digitalization in buildings

Buildings account for nearly one-third of global final energy consumption and 55% of global electricity demand. Electricity demand growth in buildings has been particularly rapid over the last 25 years, accounting for nearly 60% of total growth in global electricity consumption. In some rapidly emerging economies, including China and India, electricity demand in buildings grew on average by more than 8% per year over the last decade. In the IEA Central Scenario, electricity use in buildings is set to nearly double from 11 petawatt hours (PWh) in 2014 to around 20 PWh in 2040, requiring large increases in power-generation and network capacity.

Improving the operational efficiency of buildings by using real-time data could lower total energy consumption between 2017 and 2040 by as much as 10% compared with the Central Scenario, assuming limited rebound effects in consumer energy demand (Figure 2.4). Cumulative energy savings over the period to 2040 would amount to 65 PWh – equal to the total final energy consumed in non-OECD countries in 2015.

Figure 2.4 Cumulative energy savings in buildings from widespread digitalization



Key message: The widespread deployment of active controls, assuming limited rebound effects, would save up to 65 PWh cumulatively to 2040, or twice the energy consumed by the entire buildings sector in 2017.

Notes: Non-residential includes buildings used for wholesale and retail trade, storage, education, health, hospitality and commercial activities, as well as offices and public buildings; EU = European Union; ASEAN = Association of Southeast Asia Nations.

The largest potential savings are in heating, cooling and lighting, which together represented more than 60% of total final energy demand in buildings in 2015. For instance, smart thermostats can improve management of heating and cooling loads, allowing for improved and even remote control of temperatures throughout a building. This can ensure thermal comfort when and where it is needed while also maintaining and increasing energy savings when heating and cooling are not needed. Increasingly, learning algorithms in smart thermostats are taking this one step further, automatically pre-heating or pre-cooling a building space relative to expected occupant presence, user preferences, forecast weather conditions and other input information (e.g. energy prices).

Smart controls and connected devices, including even simple occupancy and photo sensors, consume energy in order to maintain connectivity, even when on standby (see Chapter 5 for a discussion on the direct use of energy by digital technologies, including connected devices). Standby power in buildings applications alone can be significant. For example, it ranges from 0.15 watts (W) to over 2.71 W for smart lighting, potentially consuming as much as 25 kilowatt hours (kWh) per light fixture or bulb if running 24 hours per day year-round (Kofod, 2016). Consequently, some connected lamps can consume more energy per year in standby mode than when actually in use, cutting their net energy efficiency by more than half.

The potential for energy demand growth from connected devices in buildings, whether they are smart or not, is already noticeable in many markets. For instance, the number of household appliances that are connected to communication networks, ranging from televisions and washing machines to doorbells and security cameras, has taken off in recent years, with their overall energy use amounting to an estimated 360 terawatt hours (TWh), or 13% of total household electricity consumption for appliances and other small plug loads in 2015 (Figure 2.5). In the IEA Central Scenario, 50% of household electricity demand for appliances by 2040 is expected to come from connected devices, presenting opportunities for smart demand response[28] but also increasing the need for standby power.

Economies of scale and continued product improvement are expected to halve the energy intensity of active control devices over the next 25 years, from an average of around 2 kWh per square metre (m^2) per year in 2010 to 1 kWh/m^2/year in 2040 (Figure 2.6). Globally, active controls are projected to consume 275 TWh in 2040 – accounting for 0.7% of buildings energy use in the IEA Central Scenario. This is far less than the 4 650 TWh potentially saved by those smart controls in 2040 (IEA, 2017b).

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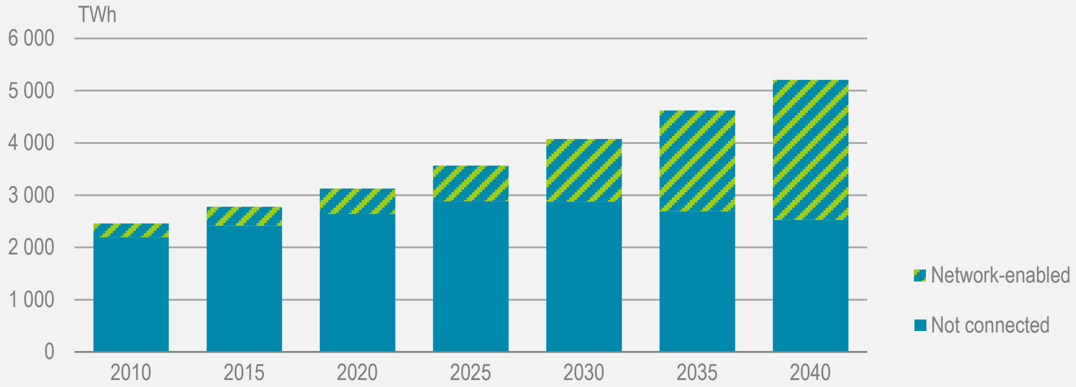
[28] Smart demand response refers to the possibility for consumers, smart controls and connected devices to adjust electricity consumption in response to time-based rates or other forms of financial incentive.

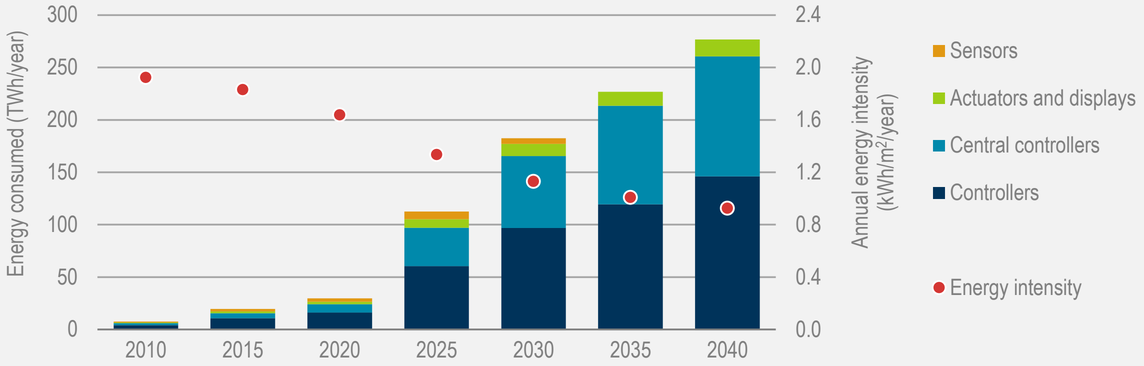
Figure 2.5 Household electricity consumption of appliances and other small plug loads



Key message: The share of connected "network-enabled" appliances in total household electricity consumption is set to grow rapidly, presenting opportunities for smart demand response but also increasing the need for standby power consumption.

Note: In the case of televisions, only "smart TVs" are considered to be network-enabled; those with connections to cable television or other broadcasting networks are not included.

Figure 2.6 Global energy use and average energy intensity of active controls in buildings



Key message: The energy intensity of active controls is expected to improve to 2040, consuming far less than the potential energy savings achieved by smart controls in buildings.

Notes: Sensors include occupancy and daylighting sensors; central controllers collect data from an entire dwelling or building and monitor operating units; controllers only operate on a specific zone of the building.

In addition to the energy efficiency savings, connected devices and active controls in buildings can offer greater comfort to consumers and bring important social and health-related benefits. For instance, around 11% of the population in the European Union is not able to heat their households adequately at an affordable cost (Pye and Dobbins, 2015). As many as 15% of households in IEA member countries suffer from energy poverty (IEA, 2017c). Optimisation of heating and cooling loads through active controls (with appropriate financing tools and support schemes for technology deployment) would help to reduce buildings energy demand, allowing healthier temperatures when and where occupants are present and reducing overall household spending on heating and cooling.

Smart thermostats

Smart thermostats are programmable connected devices that can help households monitor and regulate their heating and cooling loads. Potential savings range between 15% and 50% depending on the building and control technology (Grözinger et al., 2017). Smart thermostats can also automatically learn, enabling improved energy demand management in a building (or even by zone or room) using information on presence, occupant routine and even weather forecasts through online data. Better prediction of heating and cooling loads can enable improved equipment and/or network operation (e.g. optimised compressor working cycles and greater utilisation of heat exchangers). At the same time, smart thermostats can enable utilities to deploy demand-side response in buildings, where peak heating and cooling loads can have significant impact on the grid.

In the United States, purchase of smart thermostats doubled from 3% of total residential thermostat sales in 2014 to 6% in 2016 (Wilczynski, 2017). Globally, revenue from the sale of connected smart thermostats and their software and services is projected to increase from USD 1.1 billion in 2016 to USD 4.4 billion in 2025 (including USD 1.6 billion in North America, USD 1.3 billion in Asia-Pacific and USD 1.1 billion in Europe) (Navigant Research, 2016).

Major heating and cooling equipment providers, such as Johnson Controls, Danfoss and Honeywell, are offering products that can be scheduled and controlled remotely by smartphone apps or Bluetooth. Nest Labs, one of several newcomers to the market, offers Wi-Fi-enabled thermostats that use self-learning algorithms and sensors to improve heating, cooling and hot-water management in households. Based on field studies, Nest claims its thermostats achieve average energy savings of 10-12% for heating and 15% for cooling (Nest, 2015).

Some utility companies, including British Gas, Engie and Scottish and Southern Energy, are also offering their own smart thermostats. The entry of these non-traditional product suppliers into the smart thermostat market reflects a growing business opportunity, which can also help to secure competitive advantage for utility providers offering better controls to customers. Encouraging the use of smart thermostats could also help to reduce their need to invest in additional power generation capacity.

Certain utilities in the United States are exploiting the potential for demand-side management that smart thermostats present by rewarding customers who adjust their temperature settings during peak heating or cooling periods (National Grid, 2017). Data collected by smart devices could similarly be used by utilities to identify opportunities for launching energy-efficiency programmes or even to offer new services (e.g. through an energy service company [ESCO]), driving up spending on energy-efficiency improvements such as insulation or the replacement of heating/cooling appliances with more efficient ones. Other business models, such as WattTime, incorporate software in certain smart thermostats that adjusts the amount of electric heating and cooling (e.g. on-off cycles of air conditioners) according to the availability of renewable energy using real-time data from power grid operators.

Governments are starting to play an important advisory role in the roll-out of smart thermostats. For example, the United States Environmental Protection Agency is endorsing devices that demonstrate verified minimum savings for heating and cooling through the Energy Star Program, with seven thermostats recognised to date (Energy Star, 2017).

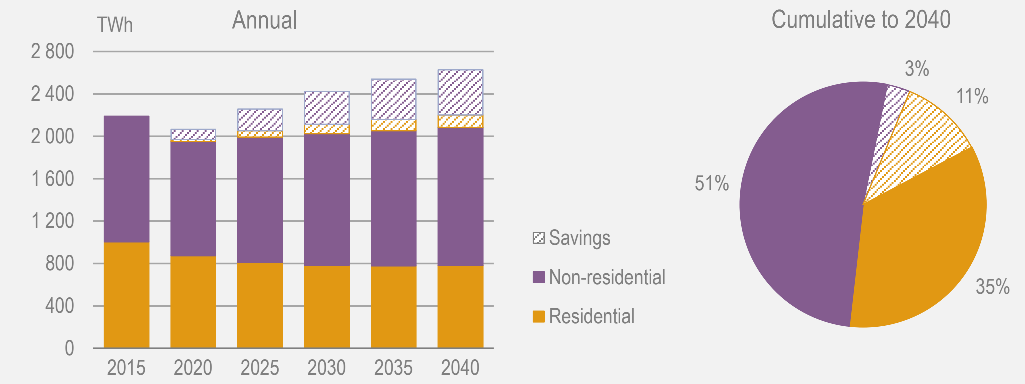
Smart lighting

The global lighting market is changing rapidly with the growing adoption of light-emitting diode (LED) technology. LED sales reached around 30% of the global residential market alone in 2016 (IEA, 2017b). This shift could reshape lighting services and energy demand, particularly as the luminous efficacy of LED technology (measured in lumens per Watt [lm/W]) continues to improve. New LED products coming onto the market are now able to produce 150 lm/W (compared with a standard compact fluorescent lamp at 50-70 lm/W) for residential use and up to 200 lm/W for commercial applications.

Smart lighting (e.g. high-performance LEDs connected to building control systems) can process user preferences along with information such as daylight conditions and building occupancy. This offers an opportunity to provide greater lighting quality and building energy services while also achieving substantial energy savings. The IEA estimates that smart lighting could save nearly 8 PWh of cumulative electricity demand between 2017 and 2040 compared with the IEA Central Scenario, or 14% of total final lighting energy consumption during that period, in addition to the savings already brought by expected shifts to LEDs. More than three-quarters of the additional savings from smart lighting come from commercial buildings (Figure 2.7).

Smart lighting in buildings can also help reduce energy consumption for other end uses, such as heating and cooling, while also helping to increase the quality and value-added of other building services. For instance, LEDs equipped with sensors can directly interact with a building's energy management system, improving information on heating and cooling needs relative to occupancy, activity or daylight. Recent LED technologies can also be directly integrated into the building's ethernet, turning lighting into a building services and information tool (e.g. using location-based data that point to a specific room or position within a building) (Box 2.2).

Figure 2.7 Potential electricity savings from smart lighting in buildings to 2040



Key message: Smart lighting could cut global electricity needs for lighting in buildings by more than 20% in 2040.

Note: The electricity savings potential from smart lighting, including sensors and digital controls, is calculated as the energy use reductions beyond the estimated savings from expected deployment of LED lighting already estimated in the IEA Central Scenario.

Box 2.2 LEDs as a value-added tool for energy services

Recent developments in LED technologies are rapidly reshaping the lighting market as a potential tool for value-added services in buildings. For instance, French retail giant Carrefour and the United Arab Emirates mall Aswaaq are using LEDs to make shopping easier for customers using light-positioning technology (Philips, 2015). Light fidelity (or Li-Fi) modulates light at frequencies imperceptible to the human eye, allowing a unique digital signal from an LED. This signal, captured by a smart phone, can be used for product searches or store mapping to provide location-based information for shoppers.

Light-positioning data can also be used to provide energy services tailored to the needs of individuals, for example, by allowing individualised heating, cooling or light settings for a particular space in an office building. The Edge building in Amsterdam, which incorporates "Power-over-Ethernet" (PoE, using a single cable to provide both data connection and electric power) and LED technology, is one example of this type of service. Integrated light sensors connected to the building's information technology network provide information on occupancy patterns and energy usage, which can help the building manager to provide services more efficiently and effectively, such as by optimising cleaning schedules, use of space and ventilation.

LED lighting is also adding value beyond in buildings, such as in street lighting. For instance, Energy Efficiency Services Limited (EESL) has installed over 3.5 million LED street lights in India. Those lights, beyond the energy efficiency improvements and providing better visibility for drivers and improved safety for pedestrians, also communicate real-time individual data to help the electricity network monitor and control performance, address problems and ensure utility service delivery to the public.

While more efficient LEDs and smarter lighting services are expected to lead to overall energy savings, there may be some rebound effects, whereby the lower cost and improved quality of lighting increase demand for it. This may be particularly the case in the residential sector, where users will be offered a multitude of new lighting options ranging from customised ambiances to fully automated systems orientated more toward user control than energy management. By contrast, smart lighting services in commercial buildings appear to have much greater potential for saving energy, as lighting services tend to be more clear-cut (e.g. basic illumination of work spaces and meeting rooms) and there is a stronger incentive to lower operating and maintenance costs. Similarly, smart lighting in public places, notably street lighting, may also cut energy use beyond the direct energy savings from the use of LED lamps, for example by connecting streetlights to traffic lights and other traffic management tools. LEDs for public lighting could also improve local safety.

Barriers to further digitalization and policy considerations

Many obstacles lie in the path to realising the benefits of widespread digitalization in buildings. These range from concerns about privacy to technical and economic considerations, all of which affect the choice of whether to install and use sensors and devices that provide data and smart control to the building management system. There may be a case for utilities to offer financial incentives and introduce innovative tariff schemes to encourage building owners and occupants to adopt digital technologies, given the potential network cost savings from optimised energy use in buildings. Greater effort is also needed to communicate the benefits of digitalization to end users in the form of improved comfort and cost savings.

Standards for connected devices will be crucial to the prospects for digitalizing buildings. Policy makers and companies need to ensure that devices are able to provide and receive information using open source or compatible software to allow for interoperability across technologies. Common technical standards for connected devices will help ensure their interoperability at different levels (e.g. with other devices, with building management systems and with the grid). Standards could also help ensure user friendliness and product operability; design, interface and ergonomics can influence how well the devices are used and the amount of energy that can be saved as a result.

New business models for energy services could also help overcome barriers to digitalization in buildings. Large-scale deployment of smart building energy management tools and devices will call for a different approach to the provision of energy. Traditionally, building owners, operators and occupants purchased appliances and equipment such as boilers and light bulbs to provide a specific energy service, such as heat, in the same way that they purchased energy from a utility provider, typically through volume-based contracting. In the digital future, as building energy systems become more complex (and perhaps more expensive to install), new business models that provide a given set of energy services rather than an amount of energy may make more sense. Those new business models could also allow for broader energy efficiency delivery, perhaps requiring from the service provider (often easier to regulate) a minimum energy performance of the building.

The emergence of ESCOs or similar business models could also create opportunities for the provision of comprehensive energy packages, such as smart controls combined with heat pumping technologies and appropriate building renovation measures, aimed at delivering energy savings across a range of devices and end uses. Supportive policy frameworks, such as bulk procurement of energy-efficient technologies and white certificates,[29] can help in this regard by driving down costs of products and ensuring those technologies actually deliver on savings.

Industry

Industry has a long history of using digital technologies, originally to improve safety and increase production through automation. Additional benefits include less downtime, lower operating costs, reduced energy consumption and better product quality. This section focuses on manufacturing, construction and minerals extraction industries. Although industry contains many different subsectors, processes and outputs, many of the benefits from digitalization are similar. For example, increased data collection and analysis to optimise production process, to improve energy efficiency and to reduce waste apply to all production processes. Nonetheless, the usefulness of some technologies, such as 3D printing, where objects are created through a computer-controlled system by depositing consecutive layers of material, is greater in certain sub-sectors.

In 2014, industry was responsible for 38% of global final energy consumption and 24% of total CO_2 emissions (IEA, 2017a). With the expected continuing expansion of industrial production over the coming decades, particularly in emerging economies, the value of digitalization in improving the efficiency of energy and material use will only increase. While it is expected that digitalization in industry will continue in an incremental manner in the near term, some digital technologies may have far-reaching effects on energy use in certain areas, especially when they are applied in combination.

The degree to which a particular company or sector embraces or is affected by digitalization depends on several factors: the complexity of the production process (i.e.

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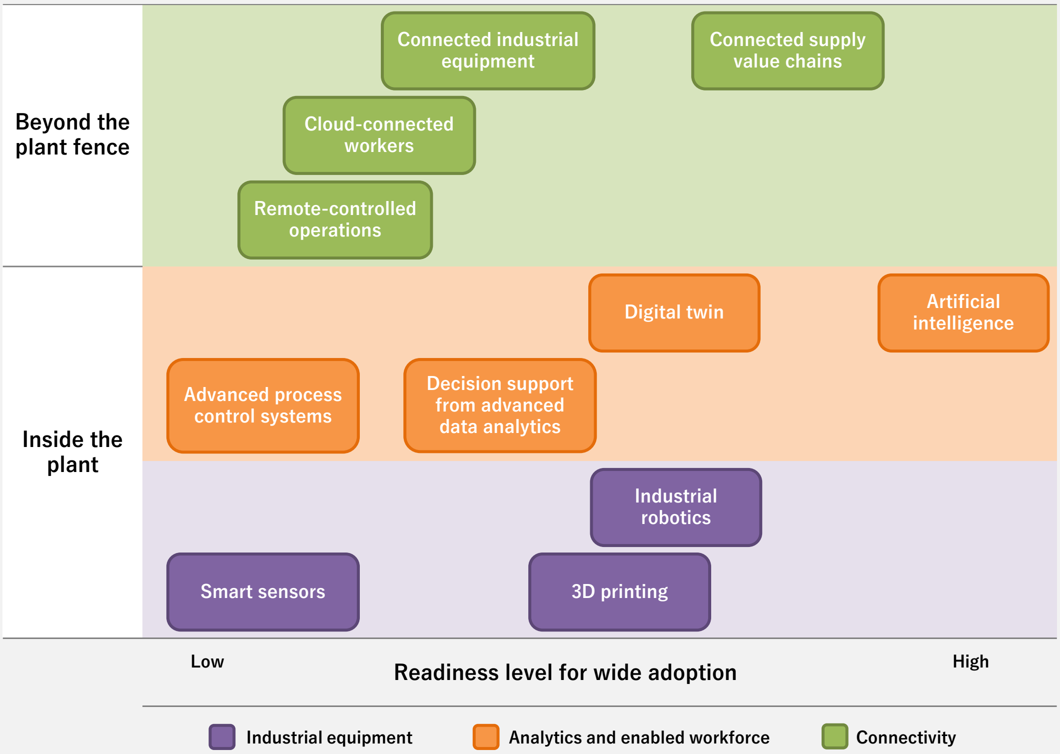
[29] A tradeable instrument issued by an authorised body guaranteeing that a specified amount of energy savings has been achieved, usually combined with an obligation on a utility to achieve a certain overall amount of energy savings.

the extent to which the process can be automated and how sensitive the process is to changes in operating variables); the financial capacity of the firm; its exposure to volatile energy prices; market competition; and the flexibility of its supply chains. Cultural factors, particularly the willingness of a firm to take on greater levels of risk by embracing a new technology or to change established operating practices, also influence the extent and pace of digitalization.

The human impact of digitalization, particularly the potential for digital technologies to reduce the number of employees required to operate and maintain a production process, is another factor which may limit its uptake. In addition, cybersecurity and data privacy concerns may also inhibit extensive digitalization in at least some industries (see Chapter 6).

The impact of digitalization on industry can be separated into the changes that take place *within* a particular plant and those that have implications *outside* the plant, or "beyond the plant fence" (Figure 2.8). These are each explored in turn.

Figure 2.8 Application of digital technologies and strategies in industry



Key message: Digitalization in industry can take diverse forms, ranging from automated equipment to connecting industrial operations based in different locations.

Notes: A digital twin results from virtually replicating a real industrial plant; enabled workforce refers to the enhancement of workers' skills through the use of digital technologies.

Sources: Based on World Economic Forum (2017a), *Digital Transformation Initiative: Chemistry and Advanced Materials Industry*, and World Economic Forum (2017b), *Digital Transformation Initiative: Mining and Metals Industry*.

Digitalization within industrial plants

The extent to which industrial process control is already digitalized varies across industries, reflecting the degree of automation (Figure 2.9). The introduction of more and smarter sensors to monitor various parameters, ranging from operating conditions to equipment status, allows for the identification and diagnosis of system inefficiencies and the development of operation and maintenance schedules that reduce downtime by predicting equipment failure. Current trends point to the development of "plug and play" and interoperable monitoring and optimisation software, which can be easily implemented and used in different industrial processes and firm sizes. Advanced data analytics can also support operators in making highly complex decisions by analysing vast amounts of data in short periods of time, helping troubleshoot equipment or even take corrective actions in emergency events.

Figure 2.9 Stages of digitalization in industrial process control

Offline open-loop control	Online open-loop control	Autonomous closed-loop control
Digital meters and sensors collect data on system performance, but control and optimisation is undertaken by human operators.	Digital meters and sensors collect data on system performance, with optimisation actions determined by control algorithms, but implemented manually by human operators.	Digital meters and sensors collect data on system performance, with optimisation actions determined by control algorithms and automatically implemented by digital systems.

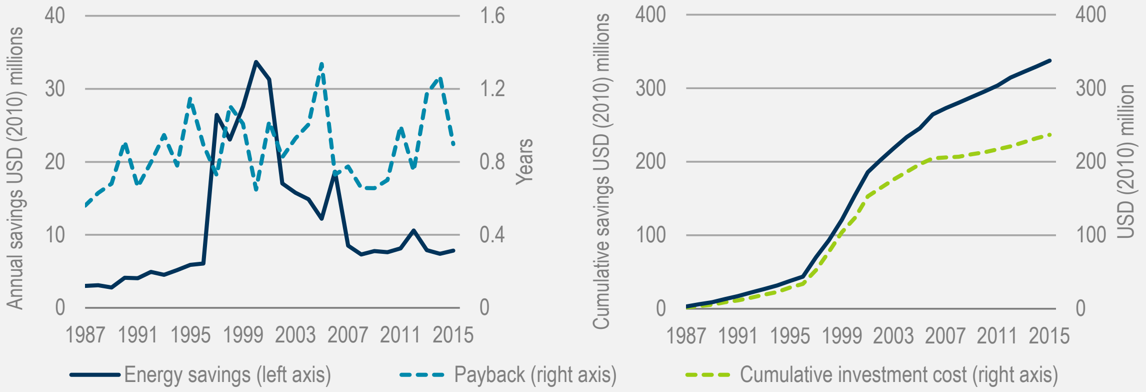
Key message: Increased digitalization enables greater autonomy of process controls.

Source: DRET (2013), *Case Studies in Systems Optimisation to Improve Energy Productivity.*

It is difficult to present a single figure for the energy savings that digitalization can yield in industry, as potential savings vary according to the type of activity, management systems, culture and the degree of integration along supply value chains. That said, real-plant data show that energy efficiency gains from the application of advanced digital process controls can yield significant savings at little or no net cost.

Two examples illustrate this potential. In the United States, improved process controls produced estimated energy savings of over USD 330 million in small and medium-sized manufacturers at a total investment cost of USD 235 million over the period 1987-2015 (Figure 2.10). The average payback from these measures was typically less than a year. Recommended measures and associated energy savings increased markedly during the late 1990s and early 2000s with advances in computing technology. The divergence between cumulative energy savings and investment cost that can be seen from the late 1990s reflects how technological advances have made it easier and cheaper to optimise process controls to improve energy efficiency.

Figure 2.10 Energy savings, payback and investment in digitally enabled optimisation of process controls in the United States



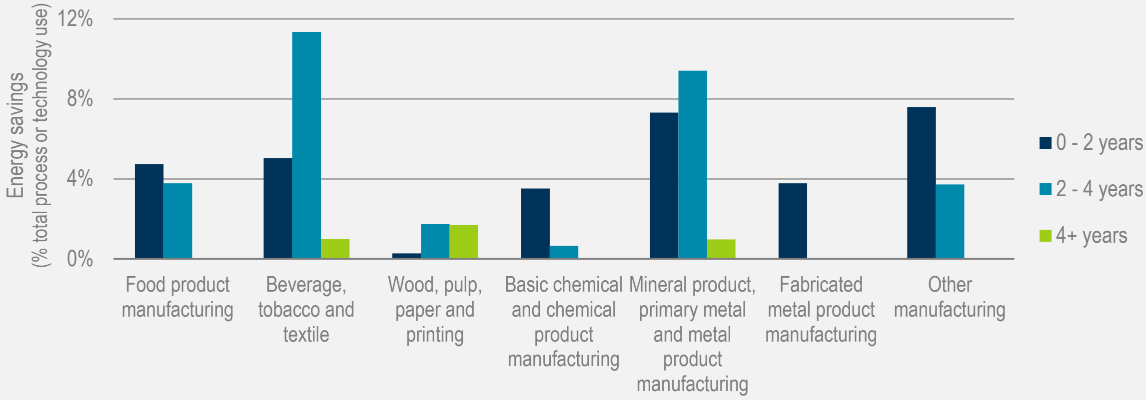
Key message: Improved process controls enhanced by digitalization can deliver substantial energy and cost benefits.

Notes: These measures were identified by audits funded by the US Department of Energy and undertaken by Industrial Assessment Centers (IACs). The energy savings identified are dependent on the number of audits undertaken in a given year, the number of recommendations identified and the companies in which the audits were conducted.

Source: IAC (2017), *IAC Database* (database).

A similar picture emerges from the results of an analysis of the potential energy savings from compliance with national industrial energy efficiency policies by optimising process control in Australia (Figure 2.11). The majority of the potential savings that were identified had payback periods of less than two years, with greater savings possible over longer periods.

Figure 2.11 Potential energy savings from improvements in process control enabled by digitalization by subsector in Australia, 2010-11



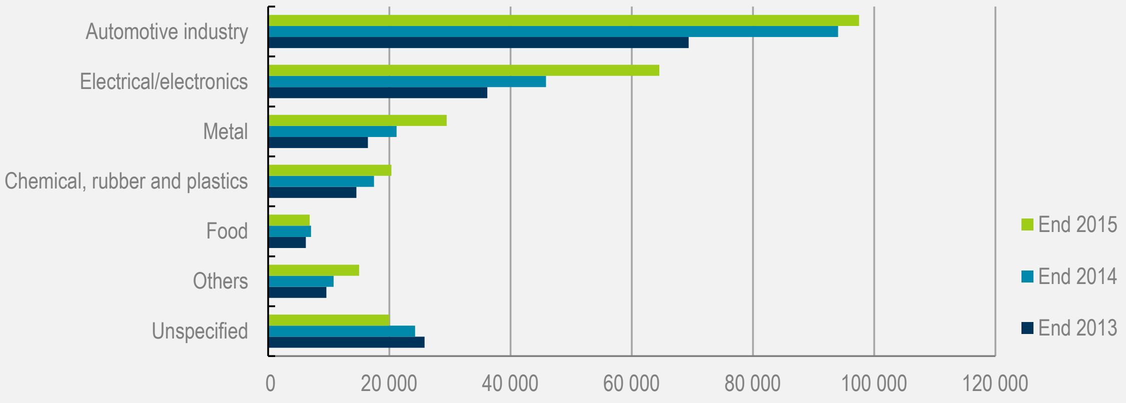
Key message: All industrial sectors analysed present opportunities with payback periods of less than two years for energy savings from improved process controls enabled by digitalization.

Source: ClimateWorks Australia (2013), *Industrial Energy Efficiency Data Analysis Project*.

Digital technology has also had an impact on the way products are manufactured. Technologies such as industrial robots and 3D printing are becoming standard practice in certain industrial applications. These technologies can help increase accuracy and reduce industrial scrap.

The worldwide supply of industrial robots has grown considerably in recent years (Figure 2.12). Since 2010, sales of industrial robots have grown on average by 16% per year, driven mainly by emerging economies, particularly China. China was responsible for 27% of the supply of industrial robots worldwide in 2015, with the automotive and electronics industries by far the largest sectors for deployment globally. Deployment of industrial robots is expected to continue to grow rapidly, with the total stock of robots rising from around 1.6 million units at the end of 2015 to just under 2.6 million at the end of 2019 (IFR, 2016).

Figure 2.12 Number of industrial robots worldwide by sector



Key message: The number of industrial robots in use continues to rise, driving productivity gains.

Source: IFR (2016), “Executive summary world robotics 2016 industrial robots”.

As industries continue to digitalize, 3D printing has emerged as one of the most visible process technologies and one most likely to transform certain industrial operations (Cotteller and Joyce, 2014). 3D printing can produce both plastic and metal parts in layer-by-layer fashion, on demand and directly from digital 3D files. It has several advantages compared with conventional manufacturing, including reductions in lead time, reduction of scrap materials, lower inventory costs, less manufacturing complexity, reduced floor space and the ability to deliver manufactured pieces with complex shapes and geometries (Huang, 2016). It can yield significant energy and resource savings under the right conditions. As an electricity-driven process, it also promotes the electrification of thermal forming processes such as metal casting and forging. This could lead to lower CO_2 emissions to the extent that power generation is decarbonised.

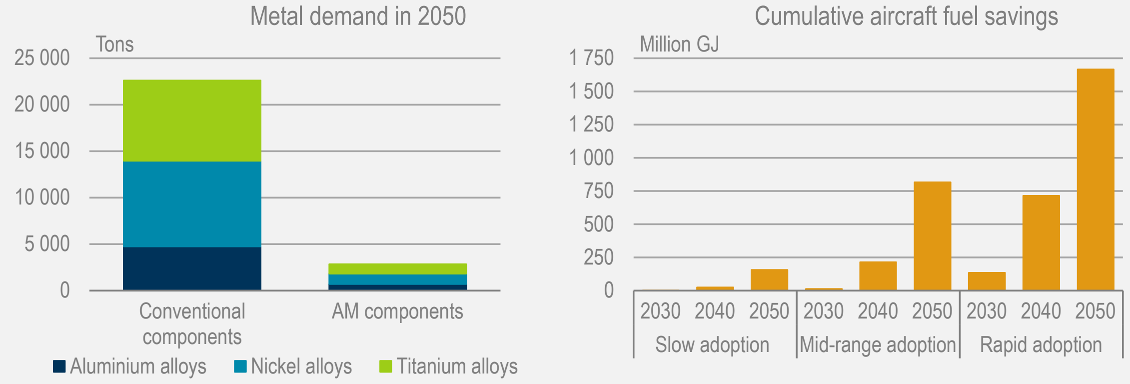
3D printing could also lead to the production of new objects with different or novel shapes, which could improve the function of final products and lead to energy savings beyond the industrial sector. For example, it is already being applied in the production of lightweight aircraft components by some aircraft manufacturers to reduce fuel consumption (Airbus, 2016).

3D printing markets have grown rapidly in recent years. In 2016, the worldwide industry grew by 17.4% to USD 6.1 billion and is expected to exceed USD 21 billion by 2020 (Wohlers Associates, 2017). However, the technology currently faces barriers that may limit widespread adoption, including high production costs, low throughput rates and difficulties in meeting the technical requirements for certain products (Huang, 2016; Huang et al., 2017). For these reasons, its use so far has been limited mainly to high-value applications in the aerospace (Box 2.3), medical and transport industries.

Box 2.3 3D printing in US aircraft manufacturing

Assessing the net energy and resource savings that can be achieved by 3D printing requires a life-cycle assessment approach. One recent study quantified the energy and resource impacts of selected lightweight metallic additive manufacturing components in the US aircraft fleet, under different adoption scenarios to 2050 (Huang et al, 2016). The assessment found that 9% to 17% of total typical aircraft mass could be replaced by lighter 3D printed components in the near term. This could deliver two environmental benefits. First, the reduced materials intensity of these alternative components could avoid nearly 20 000 tonnes/year of metal demand in 2050. Second, reduced aircraft mass could reduce the overall fuel use of the US aircraft fleet by up to 6.4% in 2050 if those components were fully adopted. Under a rapid adoption scenario of the selected 3D printed components, the resulting cumulative fuel savings by 2050 would be equivalent to 75% of the fuel consumption of US domestic aviation in 2015 (Figure 2.13).

Figure 2.13 Potential reductions in metals demand and fuel use in the US commercial aircraft fleet from the use of 3D printing



Key message: The use of 3D printed components in commercial aircraft could lead to significant material demand and fuel savings.

Notes: GJ = gigajoule; AM = additive manufacturing.

Source: Huang et al. (2016), *Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components*.

Digitalization can also accelerate innovation in industry. By virtually replicating real industrial plants – through the creation of a "digital twin" that accurately models the impact of changes to an existing production process – new manufactured products can reach the market earlier by saving time and resources in product design and in the development and optimisation of new production processes. Enhanced data collection and analytics can improve industry's understanding of consumer patterns and societal needs. When also combined with artificial intelligence or machine learning, automation and smart robots, virtual and autonomous experimentation becomes possible. Such experimentation greatly enhances industry's ability to innovate and to do so in a more rapid manner, as it avoids the costs associated with using physical industrial plants for testing, which requires downtime as well as the use of large amounts of energy and other resources. For example, chemicals manufacturers have used simulated experiments and optimisation techniques to reduce the batch time[30] for producing expanded polystyrene by as much as 30%. This has led to significant energy savings and substantially less production time and cost (World Economic Forum, 2017a).

The learning-by-doing phase of the innovation cycle, where industry improves operating practices and product design by capturing lessons from actual experience, can also be significantly shortened and made more economical through digitalization. Through continuous data collection and exchange, learning from plant operations can be integrated into new and revamped engineering designs in real time. Accelerating this learning-by-doing phase can translate into energy savings, as emerging industrial processes could reach their optimal energy performance level more rapidly.

Digitalization beyond the industrial plant fence

The impact of digitalization in industry is also moving beyond the plant fence. Digitalization opens up a wide range of opportunities when connecting a particular industrial facility to its surroundings. For example, digitalization can better connect producers along product value chains, thereby facilitating the reuse and recycling of materials.

Cloud-based collaborative platforms already exist to let manufacturers exchange information on available surplus raw materials, industrial by-products and waste. An example is the *Materials Marketplace* – an online platform that allows producers to find outlets for their traditional and non-traditional industrial waste streams.[31] Supply chains could be optimised by using inventories informed by real-time demand data from virtual suppliers' portals to maximise asset utilisation and minimise freight energy costs.

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[30] "Batch time" refers to the duration of a chemical process reaction.

[31] http://materialsmarketplace.org/.

By connecting industrial equipment to the network, companies can also benefit from identifying and providing real-time information on the availability of local waste streams, which can be captured and used to displace other forms of energy. Examples include excess heat, organic waste and off-gases, which can be captured and used to produce heat or electricity, thereby reducing both the cost of purchasing other forms of energy and the environmental footprint of the plant.

Within a firm, data analytics that benchmark energy performance across sites can be used to identify bottlenecks and opportunities for energy savings, while cloud-connected workers can benefit from a more dynamic exchange of lessons learned and experience. Minimising energy costs reduces a firm's exposure to price volatility and can provide a competitive advantage.

Autonomous closed-loop control (see Figure 2.9) can allow industrial processes at different facilities to be remotely controlled to adapt in real time to market needs and potential energy supply constraints, thereby reducing system inefficiencies. There are examples of large industrial complexes already being highly digitalized, involving firm-wide operations management systems that gather data from the production process, in real time, and update the plant status database remotely (World Economic Forum, 2017a).

Barriers to further digitalization and policy considerations

Lack of accurate information, shortcomings in technical expertise and cultural barriers may limit the potential for further digitalization within various industries. Informing stakeholders about digitalization can help overcome these problems. So far, technology and service providers have been the main source of digitalization information. Companies that lack technical expertise in the area can struggle to make sense of it and understand how they can take advantage of the new technologies available.

Governments may have a role to play by becoming more involved in providing advice, particularly for small and medium-sized enterprises that may not have had as much exposure to digital technology. Governments can also promote energy management systems that embrace advanced process controls to identify and monitor energy efficiency improvements. The adoption of energy management systems such as ISO 50001 – the global standard for energy management – is driven by government policies or incentives in many countries.

Government support for research and development (R&D) can also mitigate investment risks and boost private-sector industrial investment in digital technologies. Potential R&D opportunities include expanding the applicability of 3D printing and increasing the capacity of data analytics to solve complex problems and enable autonomous machine learning. Public-private partnerships can also be an effective framework to support demonstration and pilot projects involving the application of digital technologies in industry to reduce perceived risks and accelerate adoption.

Policies also need to encourage the participation of industry in electricity demand response, which digitalization makes possible through improved process controls and greater connectivity. Policy makers and regulators can make it easier for industrial firms to participate in demand response by reducing barriers for industrial sites to connect to electricity grids and district heating networks and harnessing innovative business models (see Chapter 4).

While improved connectivity can increase productivity across firms, supply chains and industrial sectors, to fully realise these benefits also requires policies and efforts related to cybersecurity and data privacy. Digitalization's impacts on jobs and skills, especially in the industrial sector, can also cause challenges (see Chapter 6).

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Chapter 3

Impact of digitalization on oil and gas, coal, and power supply

Highlights

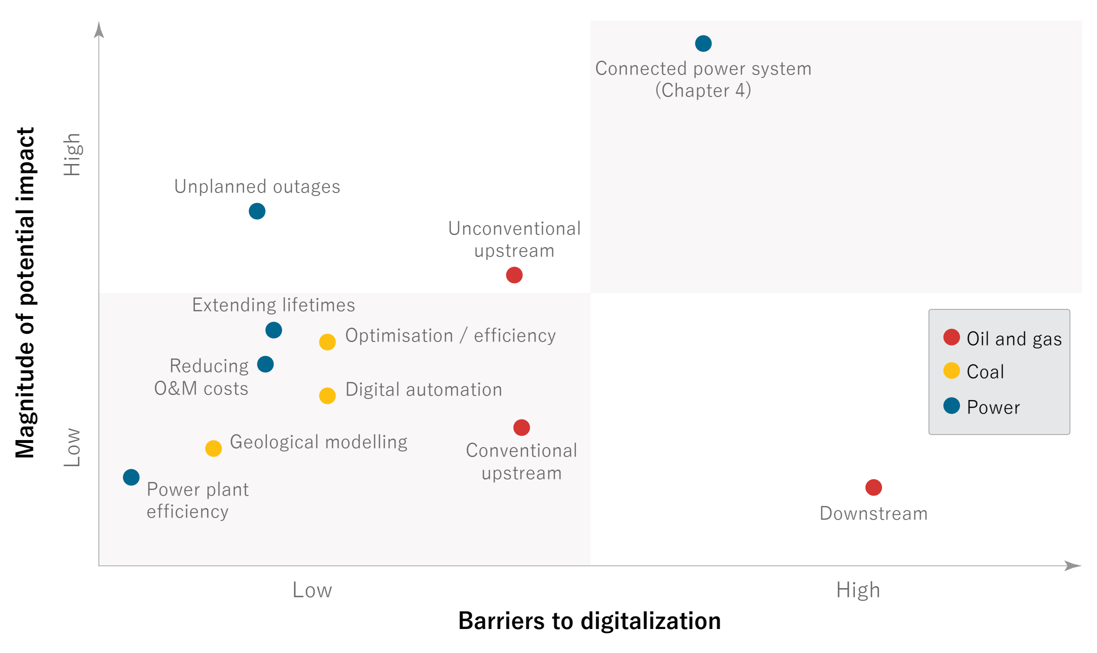
- Energy companies have been adopting digital technologies for years, helping to increase the recovery of fossil resources, improve production processes, reduce costs and improve safety.
- The **oil and gas** sector has a relatively long history with digital technologies, notably in upstream, and significant potential remains for digitalization to enhance operations further. The widespread use of existing digital technologies could decrease production costs by between 10% and 20%. With the use of both existing and emerging digital technologies, technically recoverable oil and gas resources could be boosted by around 5% globally. The potential impact of digitalization is likely to be greatest for tight oil and shale gas resources.
- In the **coal** sector, digitalization can further improve geological modelling, mining optimisation and other related processes, automation, predictive maintenance, and worker health and safety. The overall impact, however, may be more modest than in other sectors.
- Digitalization within the **power** sector has the potential to save around USD 80 billion per year, or about 5% of total annual power generation costs, based on the current system design and enhanced global deployment of available digital technologies to all power plants and network infrastructure. This can be achieved by reducing operation and maintenance costs, improving power plant and network efficiency, reducing unplanned outages and downtime, and extending the operational lifetime of assets.

Introduction

Digitalization can improve safety, increase productivity and reduce costs in oil and gas, coal and power. This chapter explores digitalization's impact within each of these supply sectors, as well as sector-specific barriers to further digitalization. The magnitude of these potential impacts – and associated barriers – varies greatly depending on the particular application (Figure 3.1).

Broad systemic implications are discussed in Chapter 4, including digitalization's ability to break down barriers between various demand and supply sectors, leading to even greater potentially transformative impacts. Cross-sectoral policy challenges such as cybersecurity, data privacy and job losses are discussed in Chapter 6.

Figure 3.1 Digitalization's potential impact in oil and gas, coal, and power



Key message: The magnitude of impacts on productivity and efficiency differ across applications in supply sectors.

Notes: The list of applications in the figure is not intended to be exhaustive; "Magnitude of potential impact" indicates the overall potential impact of digitalization on productivity and efficiency; "Barriers to digitalization" include technological, financial, regulatory and public perception components; the quadrants are illustrative only and intended to give a sense of relative magnitude; O&M = operation and maintenance.

Oil and gas

The oil and gas industry is well accustomed to pushing the boundaries of technology, especially in the upstream sector. About 40 years ago, oil and gas platforms in the Gulf of Mexico ventured into what was then considered deep water, building solid structures grounded on the sea floor about 350 metres below sea level. Today, floating dynamically positioned offshore platforms operate equipment at depths of up to 3 000 metres and drill into reservoirs several kilometres below the sea floor. Technological advances have allowed the exploitation of oil and gas fields in remote locations, whether in deep water or harsh land environments, which were once considered technically inaccessible. All of these advances would not have been possible without state-of-the-art digital technologies.

Potential for further digitalization in the upstream sector

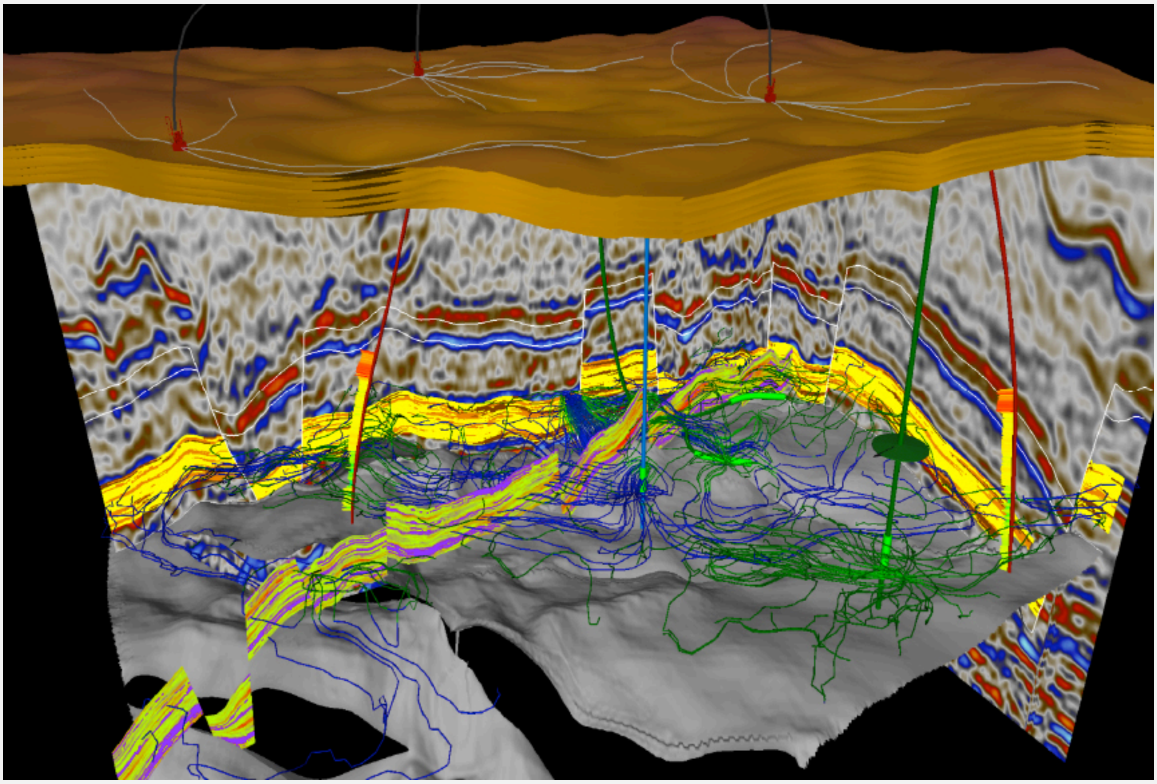
Exploration and production have traditionally been the most profitable part of the oil and gas sector, and this is the area where digital technologies have tended to have the largest impact. Technologies that can unlock more volumes of oil or natural gas or make production processes more efficient are prime candidates for research, development and deployment. The upstream industry has pioneered the complex task of processing extremely large datasets generated by seismic surveys of land and oceans, for example, in order to delineate the outline and structure of reservoirs to help optimise their development. Processing this data requires some of the world's most powerful computers. Other digital applications include the real-time, dynamic steering of drill bits from remote operations centres, or the use of highly sophisticated sensors to optimise where wellbores should be placed to maximise oil and gas recovery.

The initial focus of digitalization in the upstream oil and gas industry in the future is most likely to be on expanding and refining the range of existing digital applications already in use. For example, miniaturised sensors and fibre optic sensors in the production system could be used to boost production or increase the overall recovery of oil and gas from a reservoir. Such sensors could also be employed to measure environmental performance, such as the efficiency or emissions intensity of operations. Other examples are the use of automated drilling rigs and robots to inspect and repair subsea infrastructure and to monitor transmission pipelines and tanks. Drones could also be used to inspect pipelines (which are often spread over extended areas) and hard-to-reach equipment such as flare stacks and remote, unmanned offshore facilities. As with all new technologies, as their use becomes more frequent and widespread, the associated costs will fall, creating a snowball effect. This should lead to increased safety, lower labour costs and increased equipment reliability (due to more frequent inspections and more effective preventative maintenance).

In the longer term, the potential exists to improve the analysis and processing of data, such as the large, unstructured datasets generated by seismic studies. Rapid analysis of data can lead to faster decisions and increase the operating time of drilling rigs, wells and facilities, thereby reducing delays when executing new projects. As a result, this should also lead to lower costs and the more efficient use of capital. The use of more sophisticated processing algorithms could also assist with the finding of new oil and gas fields, the generation of development plans, and the ranking of exploration portfolio options for upstream operators.

A further option is the use of artificial intelligence (AI), which is still in its infancy but offers a great deal of promise for upstream operations. AI could be used to analyse well performance, troubleshoot underperforming fields, suggest corrective actions and even deploy robots to carry out tasks. It could also enhance reservoir modelling, and thus aid operations by rapidly detecting and correcting suboptimal production behaviour (Figure 3.2).

Figure 3.2 Example of digital visualisation of an oil well and reservoir



Key message: Enhanced modelling of the subsurface through the use of digital technologies that accurately delineate the reservoir, internal geological features, fluid distribution and flow, helps optimise production.

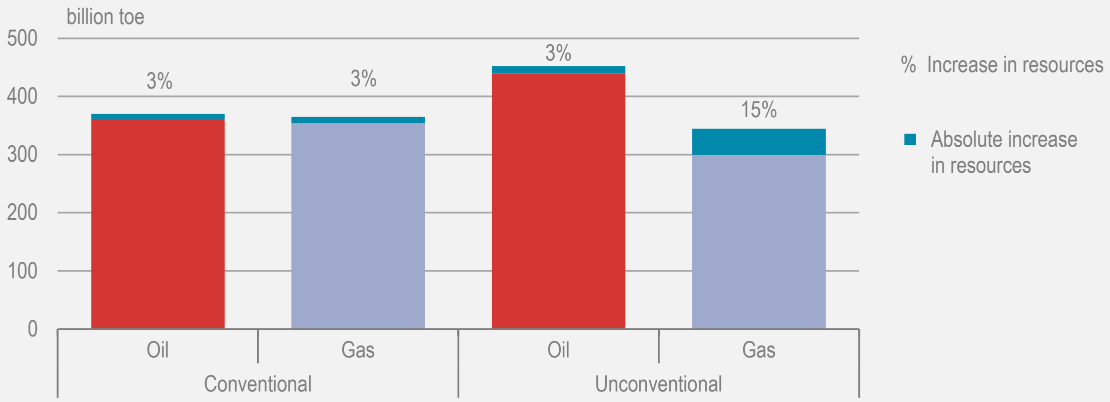
Source: © Schlumberger, 2017.

One particular area of interest for the use of digitalization is tight oil and shale gas production. Coupling AI with sensors and sophisticated data management tools could allow companies to operate and maximise production from thousands of unconventional tight oil and shale gas wells with only a handful of engineers and technicians. Tight oil and shale gas production is likely to be especially suitable for the application of new digital technologies given the shorter-term nature of investment cycles (compared with conventional fields), which should favour the introduction and implementation of new technologies in a more continuous manner. Widely shared inventories of equipment suppliers could also shorten procurement times and reduce costs, creating a more efficient "just-in-time" supply chain across the unconventional oil and gas industry.

Enhanced recovery of oil and gas resources

The volume of oil and gas resources that can be produced is a critical factor in understanding the future trajectory of oil and gas prices. Remaining technically recoverable oil and gas resources around the world are currently estimated to be around 1.4 trillion tonnes of oil equivalent (toe) (IEA, 2016). Through the widespread use of existing and emerging digital technologies across the global resource base, the IEA estimates that this could be increased by up to 75 billion toe, or around 5%, equal to over 10 years of current world oil and gas consumption (Figure 3.3).

Figure 3.3 Impact of digitalization on global technically recoverable oil and gas resources



Key message: Widespread digitalization could boost global technically recoverable oil and gas resources by around 5%.

Note: It is assumed that both existing and emerging digital technologies are deployed across the entire world oil and gas resource base.

The impact of digitalization on the volumes of oil and gas that can be recovered varies according to the resource in question, and its potential to boost recoverable resources is likely to be largest for tight oil and shale gas resources. For both of them the widespread use of digital technologies could increase recovery by around 15%.[1] This is because current recovery factors for unconventional reservoirs are much lower than those for conventional reservoirs. For example, while up to 90% of the gas trapped in a conventional reservoir can usually be recovered with existing technologies, the recovery factor for an unconventional shale gas reservoir is often only between 15% and 35%.

The digital technologies that could achieve an increase in recovery factors are wide-ranging and include advanced processing for seismic data to yield much more reliable and high-resolution digital images of the reservoir, enhanced modelling and tracking of fluids within the reservoir, and automated production control of wells. By improving reservoir simulations, digital technology can help operators optimise the spacing between wells, the lateral length of horizontal wells, and the amount of proppant used during hydraulic fracturing. All of these efforts are aimed at maintaining maximum output while minimising the required capital investment in wells and facilities.

Optimised production processes

In addition to expanding the recoverable resource base, production processes could be optimised through enhanced connectivity and monitoring to help reduce both capital and operating costs (Figure 3.4). There are few detailed estimates of the potential magnitude of these cost reductions, however, as many of the most promising digital technologies are tailored to specific subsectors and niche applications, and are still in the early stages of development. Based on discussions with operators and service providers, the IEA estimates that the widespread use of existing digital technologies could help reduce costs by around 10-20%. Even greater cost reductions could be possible if emerging technologies prove to be successful and are adopted widely.

Monitoring of methane emissions

Another important area where digitalization could improve oil and gas operations is in detecting, measuring and avoiding methane emissions. The oil and gas sector is a major source of anthropogenic methane emissions, with continuous or sporadic

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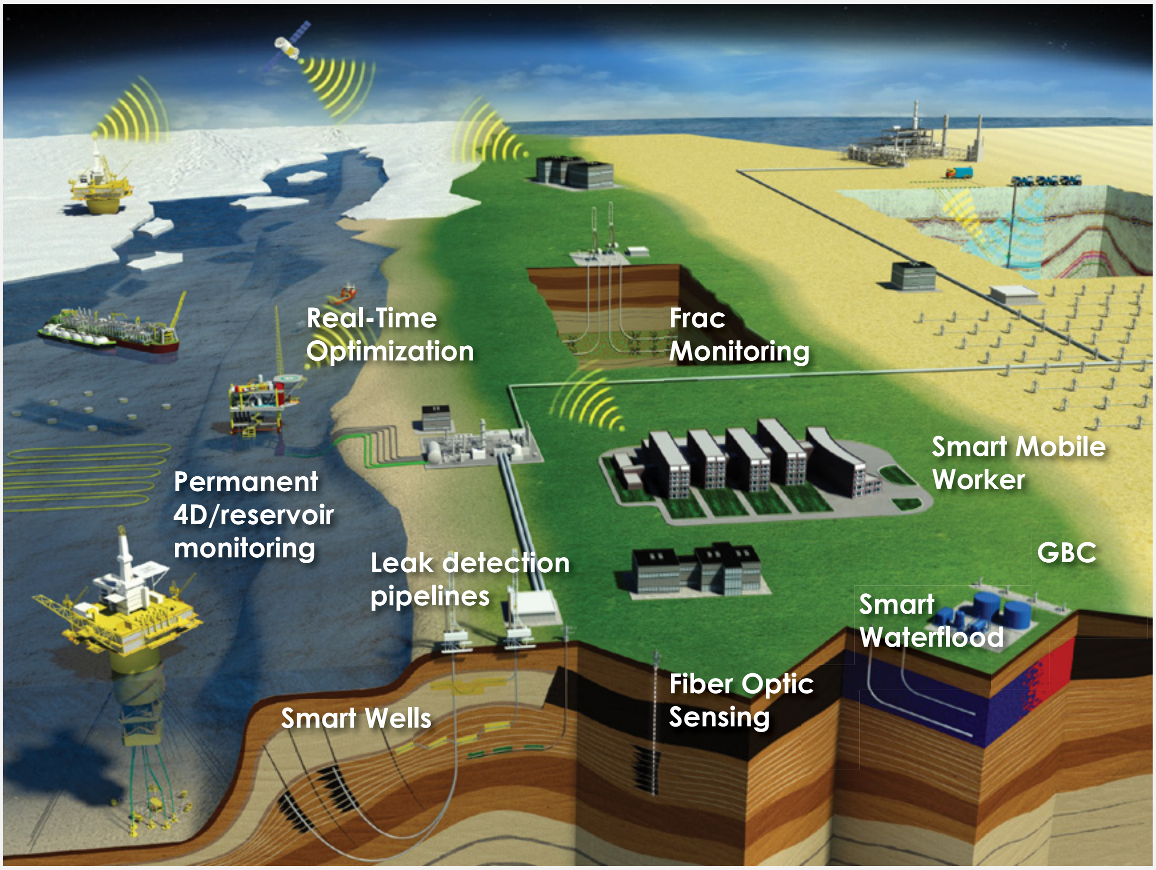
[1] The resulting increase for all unconventional oil is only 3%, as indicated in Figure 3.3. This is a result of the fact that tight oil represents the smallest share of unconventional oil resource; extra-heavy, bitumen and kerogen oil that compose the largest share do not benefit much from digitalization. Shale gas has the largest share in unconventional gas resources and a 15% increase in its recovery determines a corresponding increase for all unconventional gas.

emissions potentially occurring at any stage during production, processing and transport of oil and gas.[2]

The urgent need is for systems that can provide effective monitoring and quantification of emission levels at low cost. Digitalization could help here, either by lowering the direct cost of detection (for example, using drones in localised facilities) or by helping to understand better the data that are collected to develop parametric and predictive monitoring systems. Once a source of emissions is identified, stopping or reducing them is relatively simple.

Figure 3.4 Digitally-connected remote operations in oil and gas fields



Key message: Many oil and gas operations are digitally connected and can be monitored and operated remotely to help optimise production.

Source: Courtesy of Shell Global Solutions International B.V.

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[2] See the forthcoming IEA *World Energy Outlook 2017* for a detailed discussion on oil and gas methane emissions.

Improved downstream operations

Downstream oil and gas operations could also benefit from more widespread use of digital technologies. Profit margins in this sector are often low and therefore any small improvements would be greatly beneficial to operators.

One current example is companies that are exploring ways to customise their retail services by offering to refuel cars at home or work by bringing fuel to customers rather than customers needing to go to a refuelling station. This could be made possible by the automatic communication of data on the amount of fuel left in the vehicle's tank to a local fuel station. Another example is the use of smart gas meters (similar to smart electricity meters) that can help match gas demand and supply.

Barriers to further digitalization

Looking at the oil and gas sector, the adoption of digital technologies to date has been uneven. Overall, it trails other sectors, such as finance, retail, medicine and automobiles. Several factors explain this lag:

- **Timing**: The oil and gas industry is very capital intensive and large projects typically take many years to develop. Digital technologies, in contrast, evolve quickly. Once a large, multi-billion-dollar project has been designed and sanctioned, the industry's focus is generally on effective execution of the project; design changes are kept to a minimum, impeding the incorporation of emerging innovations.
- **Age of infrastructure**: Many oil and gas facilities around the world were installed some time ago, and do not necessarily have the appropriate infrastructure to accommodate new digital technologies. Retrofitting these facilities would carry additional costs, making the application of digital technologies less attractive.
- **Internal focus**: Since oil and gas are commodities, it is hard for companies to differentiate between products and services to consumers. As a result, digital technologies have tended to be used more to enhance safety, operational reliability and reduce costs.
- **Small mistakes have big consequences**: The oil and gas industry has developed a relatively risk-averse management perspective that can slow down the adoption rate of new technologies, regardless of their potential. The deployment of new equipment, including new digital options, often requires high-level management approval, which can lead to delays and add to costs.
- **Fragmentation**: The oil and gas industry is highly fragmented along the supply chain. The international oil companies apart, few companies are vertically integrated with interests in upstream, refining, transport and retailing.

Digitalization remains largely tailored to the needs of individual subsectors, such that companies may not be able to take full advantage of potential cross-cutting benefits (see Chapter 4). Nonetheless, large oilfield service providers, a key source of technological innovation in the industry, will undoubtedly continue to expand their digital services on offer.

- **Long-term demand trends**: Oil and gas resources may be larger than the total amount that will be consumed given current trends in the deployment of low-carbon technologies and energy efficiency. While most reservoirs could technically benefit from the use of sophisticated digital applications, it may not always make sense economically to do so.
- **Information technology (IT) support infrastructure**: While many digital technologies are already available, many operators are not well placed to exploit them, as their use requires well-developed IT infrastructure as well as a well-trained workforce.
- **Conservative management culture**: The oil and gas industry's capital-intensive nature and operational hazards have historically forged a relatively conservative management culture. Oil and gas companies may look to service companies and third-party vendors to develop digital technologies rather than bear the risks and cost of large-scale in-house research and development programmes.

Coal

Historically, the main technological advances in underground coal mining were achieved through mechanisation. This significantly reduced the number of coal miners required, while increasing productivity. In surface mining, the most significant development was the use of large-scale equipment, allowing the more efficient and rapid movement of large volumes of coal and overburden[3] involving fewer miners. The application of digital technologies, including data sensors and advanced computers, has already started and is set to grow, which will lead to significant changes in some operations in the coal sector.

Deployment of digital technologies

Digital technologies are being used throughout the coal supply chain to reduce production and maintenance costs, and enhance workers' safety. Examples include semi- or fully-automated systems, robotic mining, remote mining, operation

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[3] Overburden is the material that lies above a coal seam and needs to be removed to allow access to the coal seam.

automations, mine modelling and simulations, and the use of global positioning system (GPS) and geographic information system (GIS) tools.

The increased availability of low-cost sensors and computer-aided simulations will bring new opportunities for coal operations. For example, sensors can provide the exact status of various components of the essential equipment in real time and analytics can compare the actual configuration with the "optimal" situation as designed so that the process can be optimised. This could also improve management of constraints, such as water availability, and minimise the amount of surface land affected by mining. Digital technologies, data analytics and automation will be increasingly adopted to improve productivity while enhancing safety and environmental performance through multiple applications.

Specific applications include:

- **Geological modelling**: Modern data management techniques, new tools to simulate and define coal deposits and clearer result visualisation may help better assess reserves and their qualities, as well as enhance understanding of geological conditions. Drones are already being used to define ground profile and survey operations. The capacity to obtain and process a growing volume of data could mean that updates to the geological model can be produced continuously.
- **Process optimisation**: The combination of low-cost sensors and computer-aided simulations can help to optimise processes in the coal supply chain. For example, sensors can detect deviations from optimal operational conditions, which can be assessed and corrected. Digital optimisation of open-pit mines, especially with overburden removal, transportation and disposal, could help reduce the use of materials such as explosives, leading to significant reductions in operating costs. Materials currently represent the largest operating cost component in open-pit mining.
- **Process automation:** In some parts of the coal supply chain, automation is already common practice, notably coal transportation and washing, but there is potential for further use. Tele-remote equipment as well as driverless trucks and shovels are two possibilities. Tele-remote equipment allows mining equipment to be operated from a control room, helped by computerised tools that can simulate geological and environmental conditions. This can raise productivity as well as improve safety by removing workers from risky or hazardous working environments. While the death toll in coal mining has been reduced dramatically in recent years, it is still higher than in other industries. All major mining regions in the People's Republic of China (hereafter, "China") have targets for workerless underground mines by 2030 (NDRC/NEA, 2016). In open-pit mining, driverless trucks and shovels are already operating and full

automation of the whole chain (drilling, blasting, shovelling, dumping, washing and transportation) appears to be feasible in the medium term.

- **Predictive maintenance**: Despite the fact that mining equipment operates in a challenging environment, digitally enabled predictive maintenance[4] in coal mining is not significantly different from that in other sectors and industries. With abundant availability of low-cost sensors and analytics, maintenance practices can be based on the actual state of components, which can lead to lower equipment unavailability, higher performance and reduced costs.

Potential impacts of digitalization

Digitalization will continue to boost the productivity, improve the safety and reduce the environmental impact of coal mining. According to IEA communication with experts in the field, in some cases the application of data analysis and monitoring has already improved electric shovel performance by over 10% at zero cost by minimising wait time and truck queuing. In others, increasing fill factors, and hence reduced cycle times, have increased shovel productivity (i.e. the volume that a shovel loads per day) by over 10%. Data analysis, monitoring and computer-aided modelling have increased continuous miner productivity by over 20% in some mines,[5] while data analysis and modelling have reduced offline maintenance time by over 35% in certain underground operations.

Among the benefits of better monitoring and data processing is a better work environment. For example, noise and dust can be monitored in real time and computers can help to understand where and why high levels of emissions occur. This information can help in the timely implementation of prevention and mitigation of these issues.

Barriers to further digitalization

Digitalization of coal will undoubtedly progress in the coming years, but may not revolutionise the way the industry operates. This is due, at least in part, to the expectation that, absent deployment of carbon capture and storage (CCS, see Box 7.1), coal demand may fall in the long term as a result of concerns about air quality and climate change. The current debate about coal in certain regions is more about stranded and risky assets rather than about increasing the recoverable resource base. Without CCS, the existing recoverable resource base for coal is greater than the

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[4] Targeted maintenance to address a potential issue before it worsens, causes collateral damage or leads to downtime. Predictive maintenance is done based on the actual condition of the equipment rather than based on working hours, time lapsed, etc.

[5] A continuous miner is a common piece of equipment used in underground mining.

"carbon budget" compatible with the current internationally agreed climate targets under the Paris Agreement.

The other main barriers to digitalization of the coal industry relate to the availability of financial resources and public opinion. Perceptions of coal as a risky asset make it very difficult to channel money to the sector in certain regions, which can hamper wide-scale deployment of new technologies, including digitalization. In addition, in many countries the public is highly sensitive to threats to employment in the sector. As coal mining and, in particular, underground coal mining, is a labour-intensive business, digital technologies can be perceived as a threat to jobs.

Nonetheless, a number of factors may help overcome these barriers. Cost inflation, worsening geological conditions and increasing competition from other energy sources will most likely push coal producers into seeking ways of lowering costs, including through the application of digital technologies. In any case, their deployment is anticipated in indirect ways in the sector, as the use of digital technologies spreads throughout the broader economy. In several countries, especially China and India, coal is likely to remain an important resource, and will lead the wide-scale application of the most advanced digital technologies in the industry. Furthermore, mining of other resources besides coal will be needed for the foreseeable future, so it is likely that any general progress achieved in mining will also be applied to coal.

Power sector

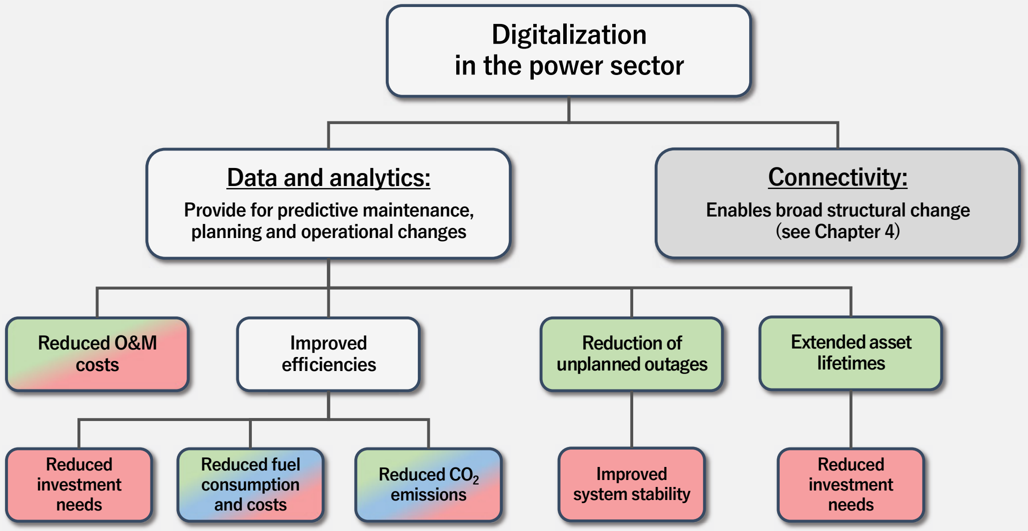
Technological innovation has always been at the core of power sector development, starting with early competition between alternating current and direct current. Over time, the range of available power generation technologies has expanded from a small set of designs, most of which burn fossil fuels, to nuclear, hydropower, bioenergy, solar, wind and geothermal.

Digitalization of power sector assets represents another step in the process of technological innovation. Digital technologies are widely available and their costs have fallen dramatically in recent years, particularly for sensors and supporting software. Applied to the current structure and operation of power systems, the data and analytics components of digitalization can provide a series of improvements, helping to reduce costs for existing and new projects across all types of power generation, improving their technical performance and competitiveness.

The role of renewable energy is expanding in many power systems around the world. A key opportunity related to the deployment of digital technologies is the enhanced ability of power systems to integrate increasing shares of variable renewables (see Chapter 4).

For all types of power plants, as well as for transmission and distribution networks, digital technologies offer an array of opportunities to improve performance for the benefit of individual companies, the system as a whole, energy consumers and the environment (Figure 3.5). The connectivity component of digitalization has the potential to reshape the power sector by connecting power supply with key demand sectors such as transport, buildings and industry (see Chapter 4).

Figure 3.5 Impact of digitalization on electricity sector assets



Key message: Digitalization in the power sector has the potential to bring benefits to the owners of power sector assets, the wider electricity system, consumers and the environment.

Notes: green: financial benefits for asset owner; red: system benefits, consumer benefits; blue: global environmental benefits; CO_2 = carbon dioxide.

Data and analytics in power plants and electricity networks

Digitalization in the power sector is wide-ranging, including the gathering of digital data about the state and performance of power sector assets, processing the information through software platforms and, ultimately, altering activities. It provides data and analytics that influence real-time actions by the owners and operators of the assets, including minor operational changes, allowing them to alter activities to avoid excessive stress on the asset. This, in turn, leads to improved system efficiency and lower costs.

In power generation, digital sensors – which can number several thousand for a single power plant – can be added to an existing plant or incorporated into the design of new ones. Sensors provide real-time information concerning the state of various components of power plants (e.g. temperature readings), as well as input flows (e.g. fuel, air or cooling water) and output flows of electricity or emissions.

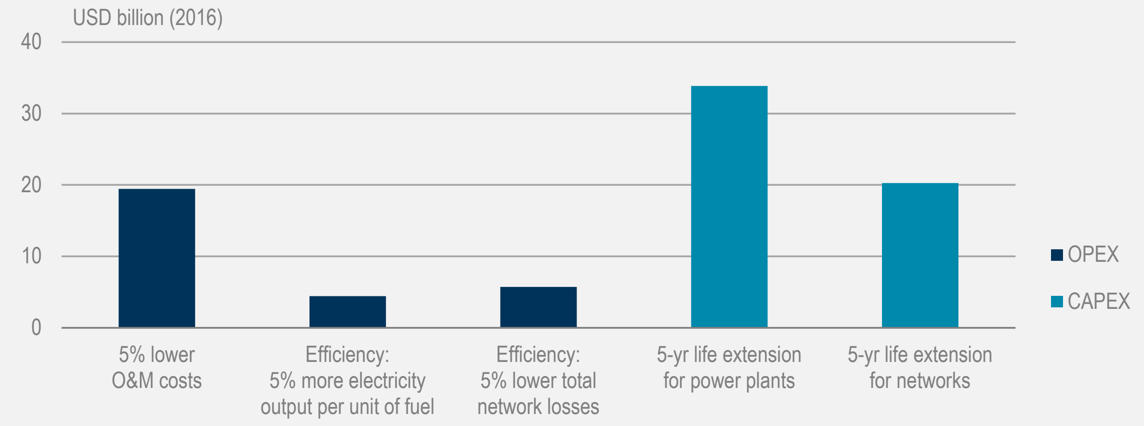
In electricity networks, sensors provide information on the state of transmission and distribution lines at various points (e.g. temperature, voltage or current). This information can be stored or transmitted to relevant parties for use in managing the grid and operating generating plant. While collecting information on the state of the power system is not new, digital sensors can provide more information on a continuous and real-time basis, something that would have been too costly or difficult to collect previously.

Sensors can also collect complementary information, such as ambient temperature, which, combined with the electrical information, can enable better management of the system. For example, high ambient temperatures may increase the physical strain on power plants, a factor that needs to be taken into consideration in operational decisions about ramping up or down the output of the power plant.

Potential benefits of digital data and analytics

Digital data and analytics can reduce power system costs in at least four ways: by reducing O&M costs; improving power plant and network efficiency; reducing unplanned outages and downtime; and extending the operational lifetime of assets. The IEA estimates that the overall savings from these digitally enabled measures could be in the order of USD 80 billion per year over 2016-40, or about 5% of total annual power generation costs based on the enhanced global deployment of available digital technologies to all power plants and network infrastructure (Figure 3.6).

Figure 3.6 Illustrative potential worldwide cost savings from enhanced digitalization in power plants and electricity networks over 2016-40



Key message: Cumulative savings from the widespread use of digital data and analytics in power plants and electricity networks could average around USD 80 billion per year.

Notes: Assumes the enhanced global deployment of existing digital technologies to all power plants and network infrastructure; CAPEX = capital expenditure; OPEX = operational expenditure; yr = year.

Reduced O&M costs

Digital data and analytics can reduce O&M costs, enabling predictive maintenance,[6] which can lower costs for the owner of plants and networks and ultimately the price of electricity for end users. This type of maintenance is only possible with detailed component-level information delivered in real time, a prohibitively difficult and expensive task without digital sensors.

Globally, the IEA estimates that O&M costs in power generation and electricity networks were just over USD 300 billion in 2016. Over the period to 2040, a 5% reduction in O&M costs achieved through digitalization could save companies, and ultimately consumers, an average of close to USD 20 billion per year. For renewable energy technologies, improved maintenance also supports better performance throughout the life of the project.

Improved efficiencies

Digital data and analytics can help achieve greater efficiencies through improved planning, improved efficiency of combustion in power plants and lower loss rates in networks, as well as better project design throughout the overall power system. In conventional power plants, efficiency gains reduce the amount of fuel consumed and CO_2 emitted per unit of output. This can be made possible through better maintenance and other improvements, such as optimising the mix of fuel and air in the combustion process. Consider the example of a 5% increase in the electricity output per unit of fuel input (equal to a 2 percentage point gain in power plant efficiency) for all subcritical and supercritical coal-fired power plants built over the past 20 years (over 900 gigawatts worldwide). In such a case, these power plants – which generated 4 500 terawatt hours in 2015 – would have consumed 70 million tonnes less coal, emitted 200 million tonnes less CO_2 less (0.6% of global energy-related CO_2 emissions) and saved more than USD 4 billion in fuel costs. Industry estimates suggest that higher efficiency gains are possible for individual power plants using digital technologies (Annunziata et al., 2016).

In electricity networks, efficiency gains can be achieved by lowering the rate of losses in the delivery of power to consumers, for example through remote monitoring that allows equipment to be operated more efficiently and closer to its optimal conditions, and flows and bottlenecks to be better managed by grid operators. Additional gains are possible through enhanced connectivity (see Chapter 4). In addition, losses from theft can be identified more accurately through monitoring enabled by smart metering.

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[6] Predictive maintenance in the power sector refers to the ability to perform targeted maintenance of power plants and electricity networks in order to address a potential issue before it worsens, causes collateral damage or leads to downtime for the asset.

Reduced losses mean less electricity needs to be generated to meet demand. As a result, fuel consumption and associated costs are reduced, along with CO_2 and other emissions and, ultimately, electricity prices to end users. Globally, losses in the transmission and distribution of electricity account for 8% of total electricity generation, equivalent to the amount of electricity consumed in global iron and steel production, lighting and cooking combined today. Losses in transmission and distribution are very large in many developing countries, exceeding 15% of total generation in Africa, Latin America and India.

Data and analytics can improve planning, as well as project design throughout the overall power system, making them more efficient and less costly. Investment in new power plants and electricity networks can be better co-ordinated, strategically located to supplement existing infrastructure and meet the dynamic needs of consumers at minimum cost. In addition, data and analytics can also be applied to the design of individual projects in order to maximise the value of the project to the system. For example, sophisticated designs for new wind power projects are now possible based on digital data, enabling the optimal choice of turbine technology and distribution of turbines to maximise the potential of resources while minimising integration challenges.

Reduced frequency of unplanned outages

Digital data and analytics can also reduce the frequency of unplanned outages through better monitoring and predictive maintenance, as well as limit the duration of downtime by rapidly identifying the point of failure. This reduces costs and increases the resilience and reliability of supply. Network failures are expensive, both for the utility and for the economy. For example, power supply interruptions in the United States alone have been estimated to cost around USD 100 billion per year (LaCommare and Eto, 2006). Emerging economies generally suffer most from frequent power cuts.

Extension of operational lifetimes

In the long term, one of the most important potential benefits of digitalization in the power sector is likely to be the possibility of extending the operational lifetime of power plants and network components, through improved maintenance and reduced physical stresses on the equipment. Longer lifetimes would increase revenues to the owners of the assets while reducing the investment requirements of the power system as a whole. This would lower prices to end users. A potential downside of extending the lifetime of fossil-fuelled power plants is that it could slow a transition to cleaner sources of electricity, raising an additional challenge to curbing CO_2 and local pollutant emissions.

While the full extent of the lifetime extensions that could be achieved through digitalization is not yet known, especially as many technologies are just emerging, the potential cost savings are substantial. Electricity supply infrastructure is generally long-lived, with expected lifetimes ranging from 20 or 25 years for wind turbines and solar photovoltaics, to 40 to 50 years for fossil-fuelled power plants and network infrastructure, and up to 70 years for hydropower assets. Were the lifetime of all the power assets in the world to be extended by five years,[7] the IEA estimates that close to USD 1.3 trillion of cumulative investment could be deferred over 2016-40, or about 7% of total power sector investment in the Central Scenario.[8] On average, investment in power plants would be reduced by USD 34 billion per year and that in networks by USD 20 billion per year.

Barriers to further digitalization

There are few barriers to the deployment of digital technologies in the electricity sector compared with most other energy sectors. Companies that own and operate power plants have direct financial incentives to invest, as they benefit directly from fuel cost savings, reduced O&M spending and the competitive advantage of lower overall operating costs in the wholesale market.

Nonetheless, misaligned financial incentives can present a significant barrier for fully exploiting the potential of data and analytics in electricity networks. This is especially so in regulated markets where total investment in physical assets is the basis of revenues, while investments in digital technologies are not incentivised.

Difficulties in obtaining data may also present a significant barrier to using digital technologies to improve the planning of power systems. Information concerning individual power plants and network infrastructure is essential, but asset owners and operators may not be willing to share it for reasons of commercial confidentiality. One way to solve this problem would be for regulators to introduce disclosure requirements that protect confidentiality.

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[7] In this estimate, assets must operate for at least 25 years in order to gain the full benefit of digitalization. For those with fewer than 25 operational years remaining, their operational lives are extended in proportion, e.g. where a plant has ten more years of expected lifetime, its operations are extended by two years.

[8] As defined in Chapter 1, the IEA Central Scenario describes the pathway for energy markets and technological progress based on the continuation of existing energy and climate policies and measures, and to a certain extent announced commitments and plans. It is broadly in line with the New Policies Scenario of the IEA *World Energy Outlook* and with the Reference Technology Scenario in *Energy Technology Perspectives 2017*. This should not be interpreted as a forecast.

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Chapter 4

System-wide impacts: From energy silos to digitally interconnected systems

Highlights

- The greatest transformational potential for digitalization in energy is its ability to break down boundaries between energy sectors, increasing flexibility and enabling integration across entire systems.
- The electricity sector is at the heart of this transformation. Together with the progressive electrification of the energy system and the growth of decentralised sources of power, digitalization is blurring the distinction between supply and demand, and creating opportunities for consumers to interact directly in balancing demand with supply in real time. Throughout this process, centralised transmission networks will continue to be the backbone supporting the transition, balancing the overall system.
- Digitalization can enable the active participation of consumers from all demand sectors in energy system operations. By 2040, 1 billion households and 11 billion smart appliances could actively participate in interconnected electricity systems, allowing them to alter when they draw electricity from the grid. This smart demand response could provide 185 GW of system flexibility – comparable to the currently installed electricity supply capacity of Italy and Australia combined. This could save USD 270 billion of investment in new electricity infrastructure that would otherwise have been needed to ensure security of supply.
- Digitalization can help integrate variable renewables by enabling grids to better match energy demand to when the sun is shining and the wind is blowing. In the European Union alone, increased storage and demand response could reduce the curtailment of solar photovoltaic (PV) and wind power from 7% to 1.6% in 2040, and avoid about 30 million tonnes (Mt) of carbon dioxide (CO_2) emissions in 2040.
- The roll-out of "smart charging" of electric vehicles (EVs), which shifts demand to off-peak times, could save between USD 100 billion and

USD 280 billion (depending on the number of EVs deployed) in avoided investment in new electricity infrastructure over 2016-40.

- Digitalization can facilitate larger shares of distributed energy resources, turning consumers into "prosumers"; new tools such as blockchain may facilitate such local energy trading systems.
- Fundamental changes to policy and regulation will be required to ensure that the benefits of the digital transformation of electricity are fully realised and the risks minimised.

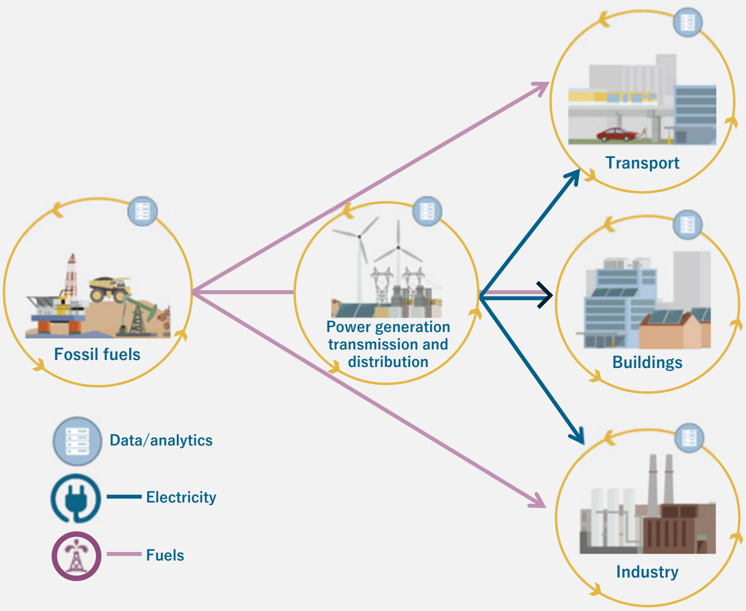
Digitalization is transforming the way the electricity system functions

Beyond the direct efficiency gains and cost savings described in the previous two chapters, digitalization holds the potential to catalyse more fundamental, system-wide changes. Electricity is likely to be the first energy sector to see the impact of this deeper transformation and the one that will ultimately be most affected. Traditionally, electricity is generated in large power plants, transferred through transmission and distribution networks and delivered to end users in the residential, commercial, industrial and transport sectors (Figure 4.1). This model is set to change dramatically.

By matching demand to the needs of the overall system in real time, digitalization opens up the opportunity for millions of consumers as well as producers to sell electricity or provide valuable services to the grid. Connectivity is the key factor. It permits the linking, monitoring, aggregation and control of large numbers of individual energy-producing units and pieces of consuming equipment. These assets can be big or small, e.g. a rooftop solar PV system in a home, a boiler on an industrial site or an EV.

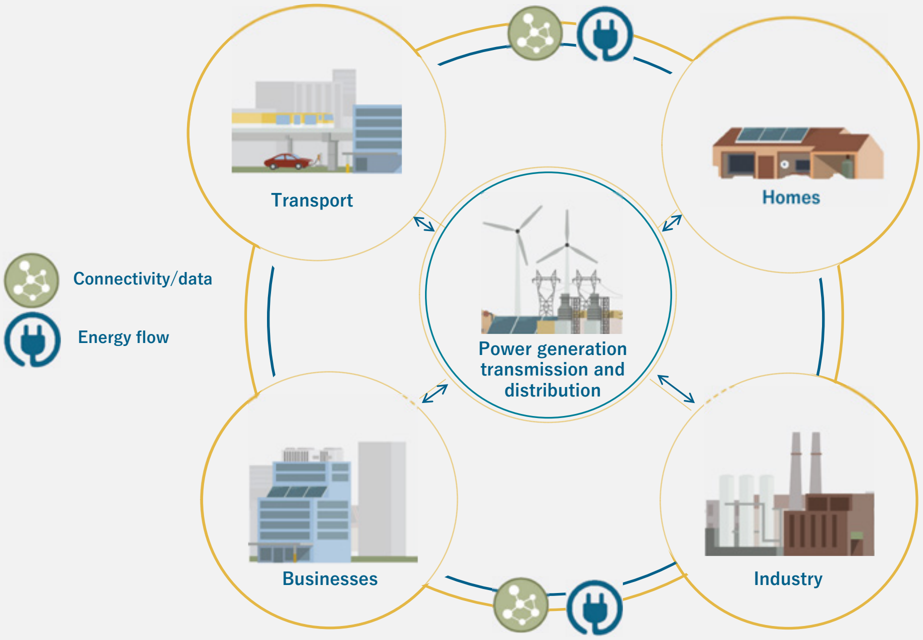
As digitalization advances, a highly interconnected system can emerge, blurring the distinction between traditional suppliers and consumers, with increasing opportunities for more local trade of energy and grid services (Figure 4.2). As this physical infrastructure evolves and stakeholders' roles change, centralised grids and the owners and operators of transmission networks will continue to provide the backbone that balances the overall electricity system.

Figure 4.1 Traditional structure of electricity sector



Key message: Data and analytics can improve performance and enable cost savings, but, without connectivity, do not fundamentally change the way the electricity sector functions.

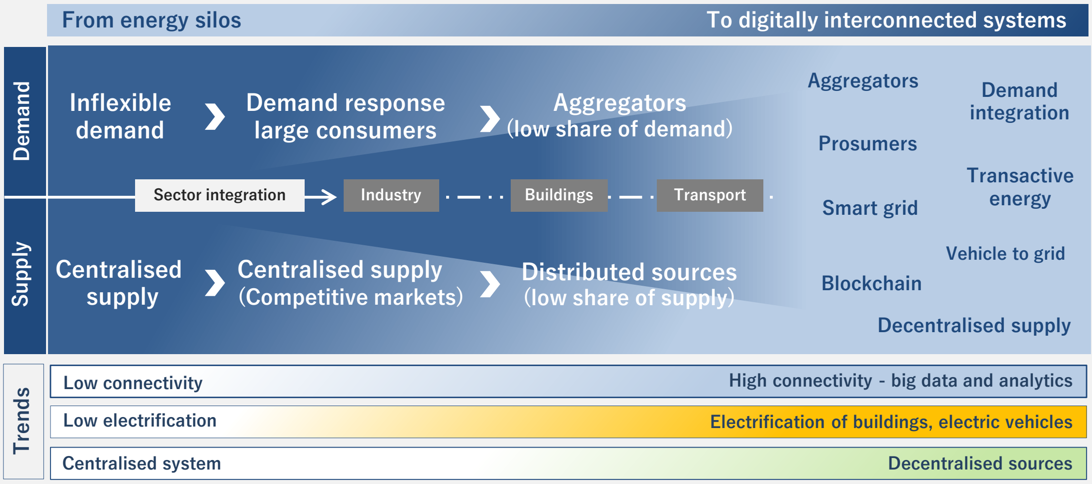
Figure 4.2 The role of digitalization in reshaping the electricity sector



Key message: Connectivity, combined with electrification and decentralisation, holds the potential to create a highly interconnected system, transforming the way electricity is supplied and consumed.

Digitalization is one part of this process. The continuing electrification of energy services across all end-use sectors, notably transport, and the growth of decentralised sources of power – which would happen even without digital technologies – are the other drivers. But digitalization – particularly the growth in connectivity among producers, grid operators and end users – is supporting these trends and helping to accelerate the transformation of the electricity system and the establishment of new business models. By allowing for the exchange of operational information in real time between equipment anywhere in the energy system, inefficiencies within each sector are removed, improving reliability and lowering costs, as consumers and producers respond instantaneously to changing market conditions (Figure 4.3).

Figure 4.3 Possible steps in the digital transformation of the electricity system



Key message: The deployment of digital technologies is creating a more interconnected and responsive electricity system, with the potential to help increase flexibility, efficiency and reliability.

The low-voltage electricity distribution network – the section of the grid closest to consumers – will be central to realising the potential of digital technologies to transform the electricity system. Distribution grids will increasingly have to take on the role of balancing supply and demand, including hosting more heterogeneous, distributed energy resources, including EVs, solar PV and battery storage. Distribution grids, however, are nested within broader networks and the overall transmission grid, which will continue to provide overall balancing of the system, and form the backbone for the transformations described in this chapter. Transmission networks themselves will benefit from the increased capability to manage operations brought about by digitalization, and will have to monitor and interact more strongly with distribution grids. The interface between operators of transmission and distribution grids will thus have to be strengthened. This will require technical, market and institutional changes (Box 4.1). The process is at an early stage in most countries, but is set to accelerate in the years to come as digital technology improves, costs fall and opportunities for cost-effective deployment expand.

Box 4.1 From one-way electricity grids to smart energy systems

The regulatory, financial and institutional structures in place around the world today allow grid owners and operators to plan investments and operate in a way that meets demand and service quality requirements while recovering costs. Traditional grids are based on a technical paradigm where the low- and medium-voltage parts – the distribution grids – traditionally pass on power generated elsewhere in one direction to consumers, who are passive recipients.

Impending transformation in the way the electricity system functions will call for fundamental changes at technical, economic and institutional levels. All of the deeper cross-sectoral changes shaped by digitalization will be hosted and supported by the physical grid. On the demand side, digitalization enables consumers to become direct participants in energy markets through demand response, helping to balance supply and demand locally. On the supply side, consumers can become local producers and periodic exporters of energy to the grid.

With more distributed production (electricity generated by small-scale plant and injected into the local distribution grid) and local trade, distribution networks will have to take on responsibility for balancing supply and demand locally, as well as providing security and reliability to the overall system. This role is currently performed by large-scale transmission network operators. The latter will continue to have a fundamental role in providing the physical backbone of the overall system and participating actively in efficient data exchange and market design. For instance, data exchange platforms – hubs where information can be made available to interested parties – will be necessary to maximise the use of distributed or centralised energy where it is most valuable and to devise new business models to make the new arrangements work.

Both transmission and distribution network operators will have to strengthen co-operation and information exchange. Ultimately, the role of networks, and particularly local distribution grids, will have to evolve from the traditional one of delivering energy one-way into providing, on the one hand, local and regional hubs for active trade in electricity produced in centralised and distributed locations, and on the other, services such as reliability, security and flexibility.

The continuing electrification of the global economy makes the transformation of the electricity system all the more important and opens up greater opportunities for exploiting new digital technologies. As economies mature, the share of electricity in the overall energy mix typically increases across all end-use sectors. Electrification of end uses, such as EVs, heat pumps and electricity-based production of metals, can also be a means of decarbonising (to the extent that power is generated with clean energy sources) and curbing local air pollution. In fact, low-carbon technologies represent almost two-thirds of electricity generation in advanced economies in 2040 under the Central Scenario (IEA, 2016).[1]

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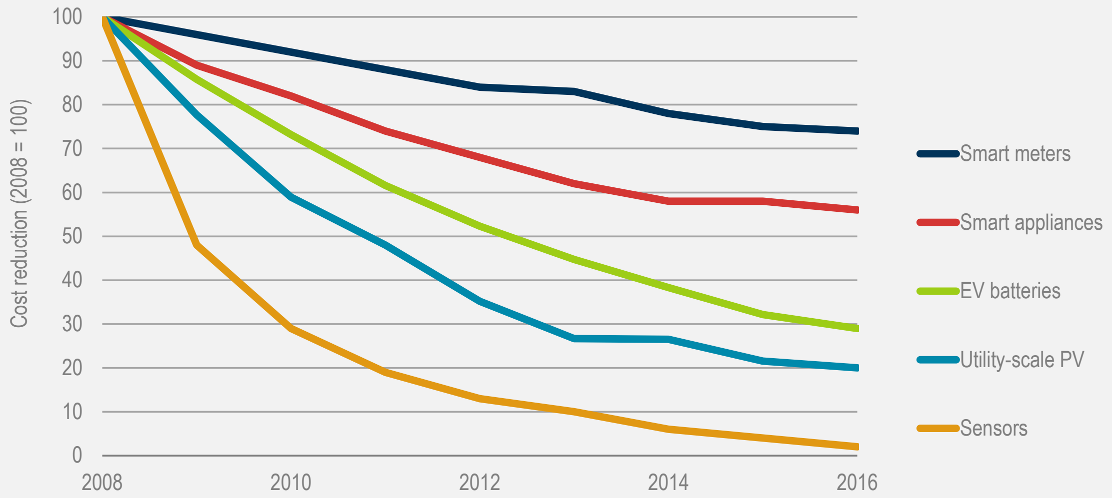
[1] As defined in Chapter 1, the IEA Central Scenario describes the pathway for energy markets and technological progress based on the continuation of existing energy and climate policies and measures, and to a certain extent announced commitments and plans.

Digitalization of electricity is part of a broader process of technological change, which – along with changes in regulatory and market design – is both driving and responding to the underlying trends in electricity demand and supply. This is reflected in the cost reductions that have been achieved across a range of electricity-related technologies over the last decade. For example, the unit cost of small-scale PV has dropped by a factor of five since 2008, sensors by more than 95% and battery storage by more than two-thirds (mostly thanks to the deployment of EVs) (Figure 4.4). The average cost of a smart meter has dropped by about one-quarter, with nearly 600 million smart meters being deployed globally.

Figure 4.4 Unit costs of key emerging electricity technologies



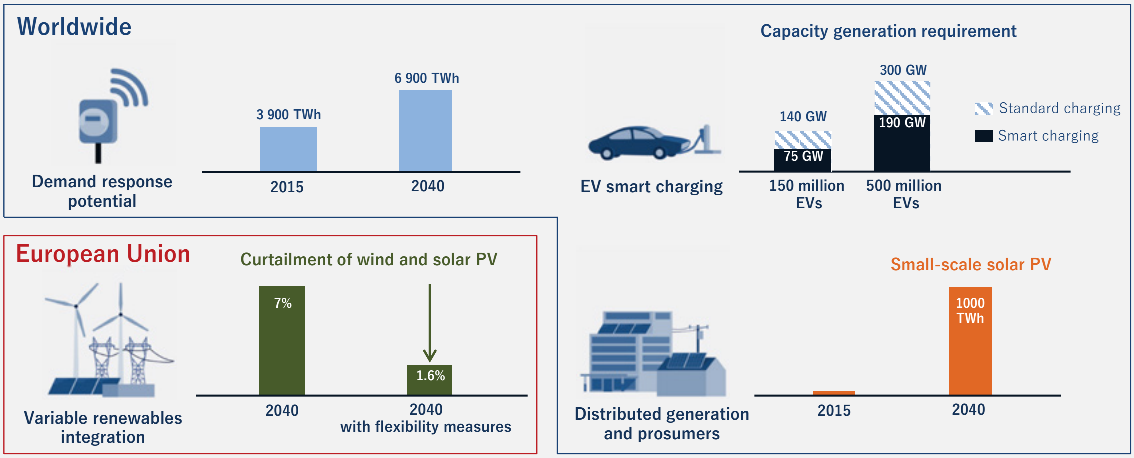
Key message: Technology cost reduction is a key driver enhancing connectivity throughout the electricity sector.

Sources: IEA analysis based on Bloomberg New Energy Finance (2017); Holdowsky et al. (2015); IEA (2017a; 2017b; 2017c); Navigant Research (2017).

The four main elements of the transformation of the electricity system that digital technologies can make possible or support are: 1) smart demand response; 2) the integration of variable renewable energy sources; 3) the implementation of smart charging for EVs; and 4) the emergence of small-scale distributed electricity resources such as household solar PV. They are interlinked as, for example, demand response will be critical to providing the flexibility needed to integrate more generation from variable renewables. All four of these elements are expected to contribute significantly to the emergence of digitally interconnected electricity systems (Figure 4.5).

It is broadly in line with the New Policies Scenario of the IEA *World Energy Outlook* and with the Reference Technology Scenario in *Energy Technology Perspectives 2017*. This should not be interpreted as a forecast.

Figure 4.5 Four key elements in the creation of a digitally interconnected electricity system



Key message: Digitalization is set to greatly enhance demand flexibility, the integration of variable renewables, smart changing for EVs and distributed generation.

Sources: Analysis based IEA (2016; 2017d).

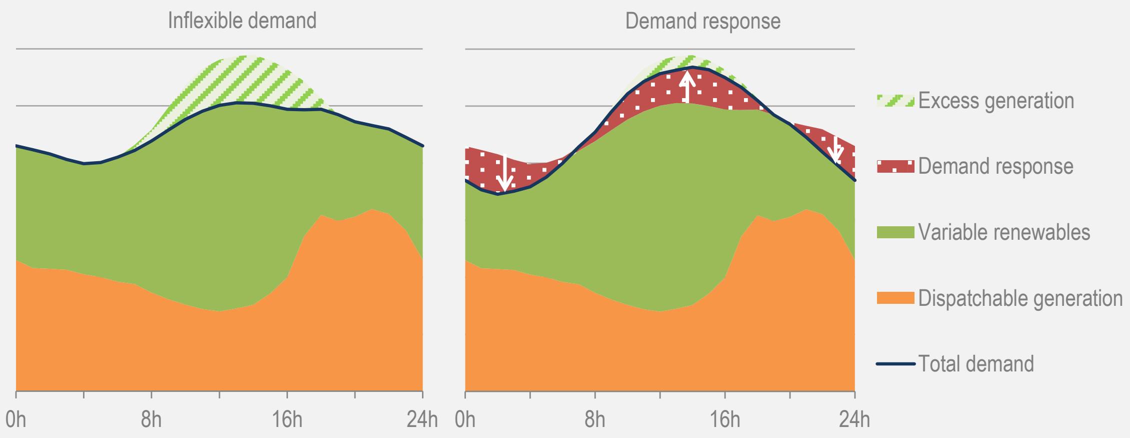
Smart demand response

Digitalization allows for a greater number of electricity consumers to respond flexibly to signals from the system – a mechanism known as demand response. The aim of demand response is to maintain security of supply at least cost. Digital connectivity allows appliances and equipment to be monitored continuously and connected to the grid. The information is collected and then used to shape demand to optimally match it with available supply.

During the hours when supply is scarce or electricity networks are congested, connected devices such as smart electric heaters and air conditioners, industrial boilers and smart home appliances can be switched off or run at lower load automatically. These connected devices can reduce or shift consumption to other periods when supply is abundant, for example, when the sun shines, the wind blows or when there are no technical problems with the electricity grid (Figure 4.6). Sophisticated new digital technologies allow this to be done in a way that does not affect the comfort of the consumer. The end user is typically compensated for the break in service through a price incentive.

Demand response has been in operation in some regions for many years, but has remained very limited in scale and largely restricted to large industrial consumers. Today, only 1% of demand globally, or about 40 GW of capacity, is able to directly respond to shortages or excess supply (Navigant Research, 2017). Generally, a small group of large consumers, typically energy-intensive industries, are offered financial incentives in return for accepting the possibility of their supply being interrupted at short notice when the grid operator deems it necessary to ensure the security of the electricity system (Box 4.2).

Figure 4.6 Impact of demand response on the daily load curve



Key message: Demand response, facilitated by digital technology, shifts consumption to those hours with a surplus of electricity supply.

Box 4.2 Interruption of large electricity consumers as the first form of demand response

The most basic form of demand response is through programmes focused on interrupting demand from large consumers, directed mainly at large industries. This type of demand response – also called interruptible service – is a demand-side management tool aimed at providing flexible and rapid response to the needs of the grid operator in situations of imbalance between generation and demand. For example, an exceptional peak in consumption due to extreme weather conditions, unplanned outages in supply, or a combination of the two could compromise the security and regular operation of the grid and may even result in an electricity blackout.

As a preventive measure, large electricity consumers, such as energy-intensive industries, in response to an order issued by the system operator, reduce their consumption to help maintain the balance between generation and demand, so that other consumers are not affected. These large energy consumers receive financial rewards in return for providing this service. In most mature electricity markets, the grid operator allocates the interruptibility services through competitive auction mechanisms.

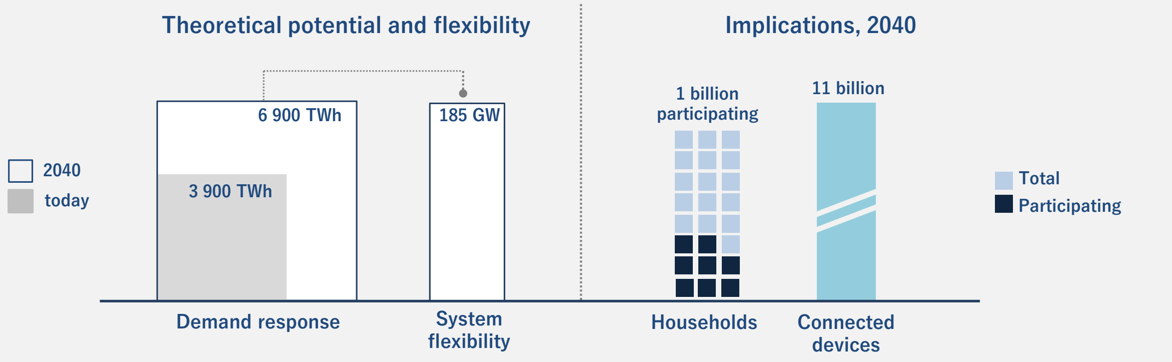
A combination of technologies at the intersection between digitalization and energy can help demand response penetrate to a larger share of consumption. Greater automation, the diffusion of Internet of things (IoT) devices in the residential and commercial sector (e.g. smart thermostats directly connected to the power market and to weather forecast providers) and higher deployment of EVs and smart charging systems will all allow further integration across demand and supply, and unlock greater cost savings for individual consumers and the system overall (Gils, 2014;

O'Connell et al., 2015. Artificial intelligence (AI) could potentially greatly enhance the efficiency and effectiveness of demand response in the longer term.

Globally, the IEA estimates that about 3 900 TWh of current electricity consumption is technically available today for demand response, and it is expected to almost double by 2040 to about 6 900 TWh, or nearly 20% of electricity consumption worldwide. The potential for demand response varies by region and sector, but in all regions, most of the current and future technical potential at lower cost lies in the buildings sector, especially in space and water heating and cooling. Electricity demand for space heating and cooling can be shifted over a certain number of hours, the extent depending on the thermal inertia. Most of the remaining potential in buildings is related to electricity used for large appliances, such as washing machines, refrigerators, dishwashers and clothes dryers. EVs are expected to become participants in demand response programmes over time (IEA, 2016).

The benefits of increased demand response are enormous. In the IEA Central Scenario, the implementation of the full technical potential of demand response (6 900 TWh) results in about 185 GW of additional flexibility for the electricity system globally in 2040 – roughly equivalent to the currently installed electricity supply capacity of Italy and Australia combined. This amount of flexibility would avoid a cumulative USD 270 billion (in 2016 dollars) of investment in new electricity infrastructure (new power-generation capacity and transmission and distribution). As the bulk of demand response potential is in the buildings sector, almost 1 billion households and 11 billion connected appliances participate in demand response programmes by 2040 under the Central Scenario (Figure 4.7). Large commercial buildings, such as supermarkets, hotels and offices, industry and EVs can also play a significant role.

Figure 4.7 Global potential of demand response and its implications



Key message: The largest potential for demand response lies in the buildings sector, with 1 billion households and 11 billion smart appliances expected to be contributing by 2040.

Sources: Analysis based IEA (2016; 2017d).

While the potential benefits to the entire system are enormous, the financial savings to individuals may not be sufficient to persuade a large proportion of consumers to participate in demand response on their own, as they typically account for a small percentage of the average electricity bill in developed countries. This highlights the need for regulatory and policy frameworks that distribute the costs and benefits adequately through incentives for both the system operator and consumers, while ensuring the cybersecurity of the grid.[2]

The role of aggregators may also prove to be key. Aggregators – also known as demand response providers – gather consumer demand of any type, as well as the supply of distributed producers such as renewables-based power plants, to provide balancing services to the grid by adjusting power demand and/or shifting loads at short notice. The "pool" of aggregated load is managed as a single flexible consumption unit – equivalent to a virtual power plant – and sold to the markets or to the grid operator. In this way, the aggregator provides an interface between large numbers of individual consumers/producers and power markets/grid operators (Box 4.3).

Box 4.3 Demand response market and aggregators

The demand response market has witnessed steady growth in recent years and is expected to further increase into the future. Globally, the market is worth more than USD 5 billion in 2014 and is expected to grow fivefold by 2022 (Grand View Research, 2016). As of today, North America remains the dominant market – mainly concentrated in California. The Asia-Pacific region currently accounts for more than 10%, with increasing penetration of smart meters being an important driver for further growth.

In 2014, over 50% of total revenues from demand response came from industrial applications. The residential segment is poised to grow at double-digit percentages, with an increasing number of consumers involved. Despite the growing interest from traditional utilities and investors, the demand response market is still highly fragmented and particularly region-oriented, with some aggregators having a strong position over a particular region but little influence globally. That said, key participants have started expanding globally through mergers and acquisitions[3] and upcoming smart grid projects in countries such as Australia, India, the People's Republic of China (hereafter, "China") and Japan could attract more global players. The aggregator business model depends on a regulatory framework that allows the grid operator to buy demand flexibility from a third party. The relatively underdeveloped state of the market and its geographic distribution fully reflect this circumstance. The further development and stability of such regulatory frameworks will thus be key for the future growth of the aggregator model.

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[2] The risk of intentional and unintentional threats to system infrastructure has to be assessed and managed in order to maintain the stability and the reliability of the electricity system (see Chapter 6).

[3] For example, in June 2017 EnerNOC, one of the main demand response providers, was acquired by Enel Group.

Integration of variable renewables

Variable renewables, such as solar PV and wind power, are inherently intermittent, with output that can be predicted accurately only a few hours to days in advance. These technical properties make variable renewables less predictable than traditional power plants. Under the IEA 450 Scenario,[4] more than one-quarter of global electricity is generated by wind and solar PV by 2040 (IEA, 2016). In many regions such as the European Union, this share is much higher in 2040 under this scenario (Box 4.4).

Beyond a certain threshold of market penetration by variable renewables, having enough flexibility in the power system becomes crucial for maintaining reliability and cost-effectiveness, affecting how infrastructure is planned and operated. While other sources of flexibility are available (e.g. ramping up and down production from conventional energy sources), there is a vast untapped potential for digitally enabled demand response that, together with storage, can cost-effectively help to accommodate a higher share of variable renewables and accelerate the decarbonisation of the electricity sector.

Box 4.4 Digitalization can help to decarbonise the EU electricity sector

In the European Union, variable renewables are playing a pivotal role in decarbonising the power sector. Under the 450 Scenario, over 570 GW of wind and solar PV installations will need to come online by 2040 (IEA, 2016). In this scenario, renewables make up more than 60% of total electricity generation, reaching almost 2 100 TWh in 2040, more than twice today's level. Wind and solar PV account for almost 60% (1 250 TWh) of the overall renewable generation, making the European Union one of the regions with the largest combined share of wind and solar PV in total power generation.

Improving cross-border interconnections within and between countries is one of the main actions undertaken by the European Union to give flexibility to the power system and accommodate a greater share of variable renewables.[5] Nevertheless, additional flexibility measures are needed as soon as the share of variable renewables in the generation mix increases beyond 27%, on average, across the continent. These are required to avoid periodic curtailment of solar PV and wind power generation at times when total supply from those sources exceeds demand. In the absence of additional flexibility measures, total curtailment would exceed 85 TWh in 2040, which is equivalent to nearly 7% of the combined generation from wind and solar PV.

The introduction of measures to prevent curtailment will be critical to increased deployment of wind and solar PV. The IEA projects that in 2040 digitally enabled demand response measures can reduce

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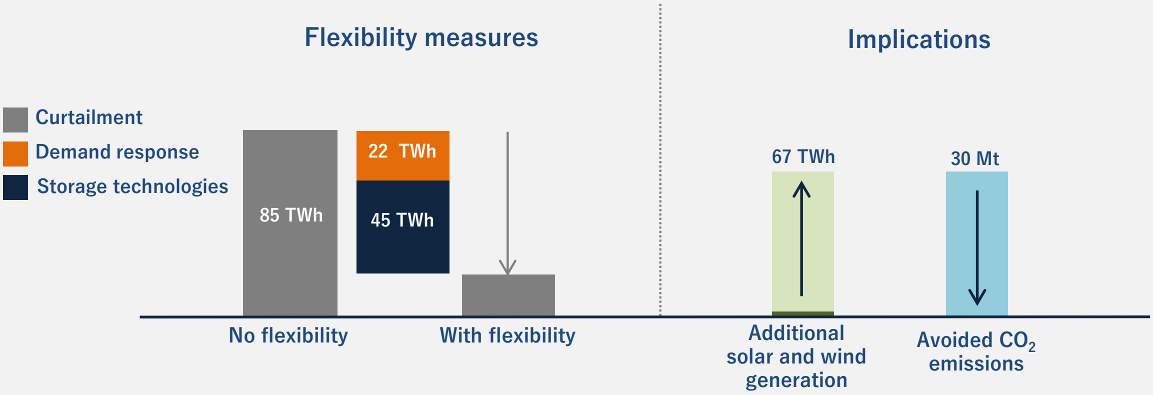
[4] The 450 Scenario sets out an energy pathway consistent with the goal of limiting the global increase in temperature to 2°C by limiting concentration of greenhouse gases in the atmosphere to around 450 parts per million of CO_2.

[5] Cross-border power interconnections between countries are equivalent to 11% of the installed generation capacity across the European Union.

curtailment by some 22 TWh, and a further 45 TWh can be saved through additional energy storage, a substantial share of which would be digitally enabled battery storage, limiting curtailment to 1.6% of total wind and solar PV generation. This allows the system to accommodate 67 TWh of additional generation from variable renewables and to avoid about 30 Mt of CO_2 emissions (Figure 4.8).

Figure 4.8 Flexibility measures and their implications in the European Union in 2040



Key message: Digitally enabled demand response and storage technologies are expected to drastically reduce curtailments of solar and wind, boosting their share of power generation and reducing CO_2 emissions.

Source: Analysis based on IEA (2016).

The growing role of EVs

EVs have the potential to revolutionise passenger car transport, with far-reaching implications. EVs start from a very low base, however: in 2016, the global fleet of EVs – including plug-in hybrids and battery EVs – doubled to two million, or around a tenth of 1% of the total vehicle fleet (IEA, 2017d). The way in which EV charging infrastructure is deployed and the technologies that are used could have significant impacts on energy systems.

Providing enough power to fully top up the battery of a typical EV in four hours would require nearly 9 kilowatts (kW) of capacity today[6] – equivalent to the current peak demand of an average Californian household. Shifting the charging of EVs to when demand is low and there is abundant low-cost generation (such as wind and solar power) could reduce the need for additional generation capacity to meet EV demand, delivering significant savings for the system.

The deployment of EVs requires new investment to build charging infrastructure. EVs represent mobile demand for electricity, and as such can theoretically be charged at

[6] Assuming a 35 kilowatt hour EV battery.

any point in the day, at low recharging rates either at home or the office, or via faster charging using public charging infrastructure (Eurelectric, 2015; Fitzgerald and Nelder, 2017). When, where and how much power EVs draw from the grid will vary significantly and will depend not only on drivers' behaviours, but also on incentives and signals that could be provided to consumers in the form of monetary savings and to the entire system in the form of greater flexibility and reduced investment needs.

Co-ordination of charging strategies through digital technologies (so-called "smart charging") will be required to take full advantage of this opportunity. With smart charging, price and control signals provide incentives for connected EVs to charge when there is abundant production of low-cost, low-carbon electricity or to stand by when the network is congested. Smart charging requires digital infrastructure to permit communication between charging points and back-end systems, so as to allow grid operators to send requests to increase or reduce demand at certain times.

In the IEA Central Scenario, global electricity capacity reaches 12 000 GW. The increase in capacity needs due to EV penetration depends heavily on the penetration of EVs themselves. Due to the uncertainties surrounding EV deployment, assessment is made of a range of impacts at different levels of EV penetration.

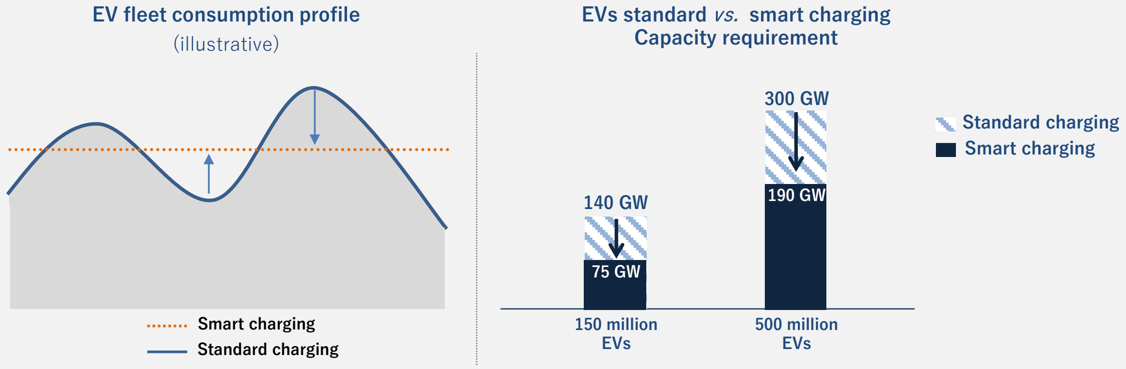
In a scenario where 150 million EVs are deployed by 2040, capacity needs for standard EV charging reaches 140 GW in 2040. This compares with a 75 GW charging capacity requirement were smart charging to be implemented, resulting in a reduction of 65 GW by 2040. In a more ambitious scenario where the global EV fleet reaches 500 million by 2040, capacity savings increase to 110 GW.

This flexibility provided by smart charging avoids, respectively, USD 100 billion and USD 280 billion of investment in electricity infrastructure (new power generation capacity and transmission and distribution), otherwise required to cover the peak in electricity demand from EVs (Figure 4.9). The higher the penetration of EVs, the more significant the savings from deploying them together with digitalized infrastructure. In the case of 500 million EVs, the savings are equivalent to about two-thirds of the projected investment in all EV charging infrastructure out to 2040.

Smart charging can also provide services to the grid to enhance power quality and reliability, which could increase its value further. Beyond smart charging, deeper flexibility can also be unlocked through vehicle-to-grid (V2G) technologies that allow for bidirectional charging (Box 4.5).

Where and when the charging of EVs will occur is also critical, especially from the perspective of utilities and distributors. EVs can be charged "behind the meter", whereby the additional load is met by rooftop PV systems and/or batteries, and the charging is optimised to occur either at home or at work during the day. Leading manufacturers of EVs, batteries and PV systems are already aiming to exploit this potential through mergers and acquisitions. EVs can also be charged on the distribution network at public charging stations. In this case, the revenues of traditional utilities/grid operators would be higher and flexibility services from delayed charging would be more readily available.

Figure 4.9 Impact of smart versus standard charging of EVs



Key message: Smart charging infrastructure can reduce peak demand from EV charging by at least 65 GW and result in system savings of USD 100 billion in 2040.

Sources: Analysis based IEA (2016; 2017d).

Box 4.5 Vehicle-to-grid: EVs as mobile batteries

As a roaming battery on wheels, an EV can both withdraw electricity from and inject electricity into the grid, thus being able to sell balancing services to the grid operator, or to meet demand within the home when necessary. While the benefits from flexibility provided to the grid could be enormous, technological issues remain, mainly linked to a faster reduction of EV battery lifetimes as a consequence of the number of charging-discharging cycles that would result from increased use by V2G.

Currently, V2G technology is being experimented through pilot projects and small-scale commercial initiatives. Recent studies have shown that using V2G only to provide valuable grid services such as frequency regulation does not affect EV battery lifetimes. Using V2G, however, to balance residential energy consumption (also called V2Home) may not be economically attractive compared to other residential storage solutions.

The economic use cases for V2G remain uncertain. However, unlocking V2G as an option requires specific investments and measures, from charging infrastructure to interoperability requirements, that need to be built into EV deployment from the outset. Early assessment and eventual action will be required to avoid having to retrofit future systems to enable V2G at a cost premium.

Distributed generation, mini-grids and “prosumers”

The electricity sector is becoming more decentralised with the proliferation of distributed energy resources connected directly to local distribution grids. Digitalization is allowing customers (in most cases through aggregation) to become more active in adapting their own electricity production (largely from solar PV), use and storage.

The rise of small-scale, distributed generation allows consumers to increasingly have the choice to buy electricity from a retailer or to produce at least part of it themselves, becoming “prosumers”. As the costs of solar PV and batteries continue to decline and the share of consumers participating in demand response programmes grows, the volumes of energy produced and stored “behind” the electricity meter could substantially increase. Withdrawals and injections of electricity from and into the grid can be actively managed using new digital technology.

These developments could transform the way the electricity supply functions. With the growth in small-scale distributed generation, the electricity generated and distributed through the grid is set to fall as a result of lower net consumption, potentially driving down the revenues obtained by traditional utilities and grid operators unless well-designed regulated use-of-system charges are raised. This, in turn, may constrain the ability to invest in maintaining or upgrading infrastructure, or generate distortions whereby consumers fully reliant on the grid could end up subsidising prosumers, who take less energy from the power network but still need the grid infrastructure to be maintained. To some extent, electrification – particularly from new loads such as EVs – could help compensate for the reduction in grid-based electricity consumption, but sweeping regulatory changes will be required to maximise these opportunities at minimum cost (MIT, 2016). Local communities and cities may gradually begin to leverage some of the opportunities from transactive and community energy (Box 4.6).

Box 4.6 Blockchain, transactive energy and peer-to-peer trading

Blockchain – also called distributed ledger technology – first drew attention ten years ago as the basis for the cryptocurrency Bitcoin. Blockchain is a decentralised data structure in which a digital record of events (such as a transaction, or the generation of a unit of solar power) is collected and linked by cryptography into a time-stamped “block” together with other events. This block is then stored collectively as a “chain” on distributed computers. Any participant to a blockchain can read it or add new data.

As no single computer system that could fail or be compromised is relied upon, data written to the blockchain is very secure against hacking (see Chapter 6). Because blockchains are transparent and trustworthy, they facilitate direct exchanges of value between parties, peer to peer, without the need for a third-party intermediary institution or service provider. In principle, these peer-to-peer transactions can be faster and cheaper than transfers sent through an intermediary (such as an energy exchange). Blockchain transactions can also be automated using “smart contracts” that instruct machines to sell or buy among themselves: self-initiating and self-verifying according to pre-determined conditions and preferences, and transferring funds.

Both start-up companies and utilities see potential for blockchain to help solve key energy sector challenges, including co-ordination between increasing numbers of heterogeneous devices, owners and operators in smart grids, and the need for low-friction, automated trading to enable flexibility. Projects testing uses for blockchain in the energy sector increased rapidly in 2015-16. Many focus on customer markets and enabling micro-trading among solar power prosumers.*

LO3 Energy in New York is using blockchain and a microgrid to enable a Brooklyn community to buy and sell locally generated renewable electricity peer to peer within a small neighbourhood. German start-up StromDAO uses blockchain to create a "virtual power plant" where participants can self-supply by investing in off-site renewable capacity and reselling this production in a spot market. Grid tariffs and taxes are built in. Utility company Innogy (formerly RWE) is creating a blockchain electronic wallet to manage billing for EV charging, also in Germany. Car owners will be able to pay using smart contracts for electric charging at different points, for parking fees and highway tolls. They would also benefit from receiving car-sharing fees.

Although still early-stage and small-scale, projects of this kind suggest that decentralised energy, flexibility from transactive energy and blockchain could develop together to positive effect. Several factors, however, might limit uptake of energy blockchains. Fully independent peer-to-peer systems such as Brooklyn may not be scalable, not least because larger and more complex blockchains require increasing investments in computing power. Geographically more extensive projects such as StromDAO rely on utility networks, which constrains the negotiability of the prices implemented within their additional layer of transaction. While the range of applications is huge, the realisable potential of blockchain in energy sector applications is highly uncertain, and solutions can often be delivered equally effectively using conventional information and communications technology, e.g. transactive energy and associated services such as those proposed by the Innogy project.

Note: * This is not all that blockchain could be applied to. Other uses are being tested throughout the energy chain. Peer-to-peer trading and settlement in wholesale power and natural gas markets is being trialled in Europe by Enerchain, backed by companies Enel, Iberdrola, RWE, Total, and Vattenfall (https://enerchain.ponton.de). Start-up Grid Singularity is using blockchain to collect energy generation and grid equipment performance data (http://gridsingularity.com). Volt Markets in the United States uses blockchain to track Renewable Energy Certificates (RECs) (https://voltmarkets.com/blockchain). Millions of solar facilities have joined a project to post live solar data to blockchain for use by scientists and researchers at www.electricchain.org/. In 2014, BAS Nederland was the first energy company in the world to accept Bitcoin for bill payment, since followed by companies in Germany (Enercity), Belgium (Elegant) and Japan (Marubeni).

In more mature markets, the implementation of such microgrids could lead to benefits for the local community: increasing the amount of renewable energy generated, traded and distributed within their members; developing a connected network of distributed energy resources that will improve the overall resiliency and efficiency of the grid; and creating financial incentives and business models that encourage community investment in renewable sources and energy efficiency.

Despite the expected growth in decentralised generation and storage in more developed energy markets, the majority of electricity systems are likely to remain largely based on centralised generation and a robust transmission and distribution network for the foreseeable future. Moreover, many of the technologies highlighted in this chapter can be deployed in a more centralised fashion as well. Indeed, tracking solutions such as blockchain applied to transactive energy in distribution grids will need supportive centralised infrastructure.

Decentralised generation and storage may also be a highly attractive method for bringing energy access to those areas of the world currently without sufficient energy services (see Chapter 7). In fact, it may be that digitally enabled decentralised solutions are able to provide energy access first, with the grid connection only coming later in time, if ever.

The prospects for centralised versus decentralised solutions will differ significantly from country to country. How much infrastructure is already in place in a given country, how much new investment is required to meet demand, the existing energy mix and resource endowments, as well as the current policy framework, all enhance or curb the potential for digitally enabled decentralisation. In many systems, the role of centralised infrastructure is likely to evolve into a complementary but essential function of delivering services that decentralised infrastructure cannot provide – reliability and other services beyond energy-only delivery. In China, for example, large-scale investments in the transmission network have become necessary to connect remote centralised generation to main demand centres.

Towards ever-smarter energy systems

The electricity sector in each country has a unique set of characteristics. How much infrastructure has already been deployed (and how), the fuel mix in power generation, the abundance of renewable and conventional energy resources, patterns of demand and the structure of the broader economy all vary across and within countries. Consequently, there is no unique end point to the digital transformation of the sector. In fact, no jurisdiction will ever reach an optimal end point, as technologies will continue to develop and policy understanding will continue to evolve.

The cornerstone of the transformation of the electricity sector will be the emergence of new business models that monetise the cross-sectoral linkages explored in this chapter. These are set to reshape the experience of energy consumers, as digitalization redefines their interaction with energy suppliers. The fundamental shift may be away from energy-only, asset-intensive business models to platforms that enable the exchange of services (WEF, 2017b). For instance, the sale of electricity, energy management technologies that allow consumers to optimise their in-house consumption, EV charging and other services can be packaged together.

Traditional utilities, network operators and third parties are already developing joint platforms for decentralised energy that include installing rooftop solar PV and batteries behind the meter, and operating them as “virtual power plants”. Community energy, peer-to-peer trading or virtual marketplaces are already being tested in a number of pilot projects at varying scales in France, Denmark, the United States, Korea and Japan.

Policy will be key to the pace and success of this transformation. Deployment of digital technologies and decentralised resources, as well as the electrification of transport and other end uses, is already being supported by governments in many countries. This is helping to drive down technology costs and encourage faster diffusion.

Besides physical assets, many countries are also redesigning their electricity market to create a coherent and well-structured regulatory framework that can unlock the full potential of digitalization while ensuring energy security and a proper functioning of the market. For example, the European Commission has proposed a series of measures – from a Digital Single Market to “Clean Energy for All Europeans” – to allow consumers, utilities and other stakeholders to fully benefit from digitalization. Policy co-ordination across sectors and ministries will be fundamental to achieve the full potential of digitalization and to effectively manage the challenges it engenders.

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Chapter 5

Energy use by information and communications technologies

Highlights

- Information and communications technologies (ICT) – including data centres, data networks and connected devices – have emerged as an important source of energy demand.
- As billions more devices and machines are connected over the coming years, they will draw electricity at the plug while driving growth in demand for – and energy use by – data centres and network services. However, sustained gains in energy efficiency could keep overall energy demand growth largely in check for data centres and networks over the next five years.
- **Data centres** worldwide consumed around 194 terawatt hours (TWh) of electricity in 2014, or about 1% of total demand. Despite a forecasted tripling in data centre workloads by 2020, their electricity use is projected to grow by only 3% thanks to continued efficiency improvements.
- **Data networks** consumed around 185 TWh globally in 2015, or around 1% of global electricity use. Mobile networks accounted for around two-thirds of the total. Depending on future efficiency trends, electricity consumption of networks could increase by 70% or fall by 15% by 2021.
- The rapid proliferation of **connected devices**, giving rise to the "Internet of Things" (IoT), is creating opportunities for more efficient energy use. But these devices also use electricity. By 2020, more than 20 billion connected IoT devices and nearly 6 billion smartphones are expected to be online. Policies to improve device efficiency and to reduce standby power consumption will be critical to limit energy demand growth.
- Providing credible forecasts of ICT energy use beyond the next five years is extremely challenging. Alongside the expected huge data demand growth, the key uncertainty over the longer term is whether efficiency gains will continue, or whether they will slow or stall.

Introduction

As the world becomes increasingly digitalized, information and communications technologies (ICT) are emerging as an important source of energy demand in their own right. This chapter looks at the direct[1] energy use of three key ICT segments:

- **Data centres**, which are facilities used to house networked computer servers that store, process and distribute large amounts of data. Data centres use energy to power both the information technology (IT) hardware (e.g. servers, drives and network devices) as well as the supporting infrastructure (e.g. cooling equipment).
- **Data transmission networks**, which transmit data between two or more connected devices. Data networks use energy to transmit data through fixed and mobile networks.
- **Connected devices**,[2] which are consumer electronics, appliances and other devices that can be connected to networks and interact with the network or other devices.

As billions more devices and machines are connected over the coming years, they will draw electricity at the plug while also driving growth in demand for data centres and network services. Between 2007 and 2012, worldwide electricity use by ICT grew at an estimated 7% per year, compared with 3% per year for electricity use overall (Van Heddeghem et al., 2014).[3]

Improvements in energy efficiency could help to limit the growth in energy demand in all three segments. Major improvements in the efficiency of computing (described by Koomey's Law[4]) coupled with the short lifespans of devices and equipment, which hastens turnover, is improving the efficiency of the overall stock of devices, data

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[1] This chapter focuses primarily on the direct operational (use-phase) energy use of ICT. From a life cycle perspective, operational energy use dominates for data centres and networks, while for connected devices, energy used to manufacture and dispose of devices is generally more important. This is particularly true for mobile, battery-powered devices that are already very efficient, tend to have shorter lifetimes and are used less intensively than, for instance, data centres, which are used continuously and have longer lifetimes (Hischier et al., 2014).

[2] Connected devices are also often referred to as "networked", "end", or "edge" devices (i.e. at the edge of the network).

[3] ICT included data centres, data networks and personal computers in this study.

[4] Koomey's Law describes the doubling of peak-output efficiency every 1.57 years for computing hardware (Koomey et al., 2011). Peak-output efficiency is the number of computations that can be performed per kilowatt hour of electricity consumed during peak output. More recent analysis shows a slowing of this trend to every 2.7 years since 2000 (Koomey and Naffziger, 2015, 2016) due to the end of Dennard Scaling (described in Bohr [2007]). That said, most computers only run a small fraction of the time at peak output (e.g. about 1% for mobile devices and laptops; 10% for enterprise data servers). Encouragingly, "typical-use efficiency", a metric that considers average efficiency across a year and is perhaps more appropriate for devices, is expected to continue to double every 1.5 years to 2020 (Koomey and Naffziger, 2015).

centres and networks. Devices are becoming smaller and more efficient, as evident, for example, in shifts from CRT to LCD screens, and from personal computers to tablets and smartphones (Malmodin and Lundén, 2016; Stobbe et al., 2015; Urban et al., 2014). In the United States, data centre energy use has already levelled off since 2010 (Shehabi et al., 2016), despite strong growth in demand for data centre services. The future direction of ICT energy use will depend on how these trends play out over time.

Current energy use and near-term outlook

Data centres

Most of the world's Internet Protocol (IP)[5] traffic goes through data centres. Increasing connectivity is driving demand for data centre services and energy use (mostly electricity), with multiplying effects. For every bit of data that travels the network from data centre to end users, another 5 bits of data are transmitted within and among data centres (Cisco, 2016a).

The IEA estimates that global data centre electricity demand in 2014 amounted to around 194 TWh, or about 1% of global final demand for electricity. Despite large increases in demand for data centre services, concerted efforts to improve energy efficiency have limited electricity demand growth in recent years. Koomey (2011) estimated that data centres consumed 203-272 TWh in 2010, or 1.1-1.5% of total global electricity use for that year.[6]

The United States remains the world's largest data centre market measured by workload[7] (Cisco, 2016a) and by number of data centre servers (Shehabi et al., 2016). The electricity consumption of US data centres remained essentially flat over 2010-14, accounting for around 1.8% of overall US electricity use in 2014 (Shehabi et al., 2016). Without efficiency improvements, energy use would have nearly doubled over the same period. The Asia-Pacific region, the second-largest market, is expected to account for more than one-third of global data centre workloads in 2020 (Cisco, 2016a).

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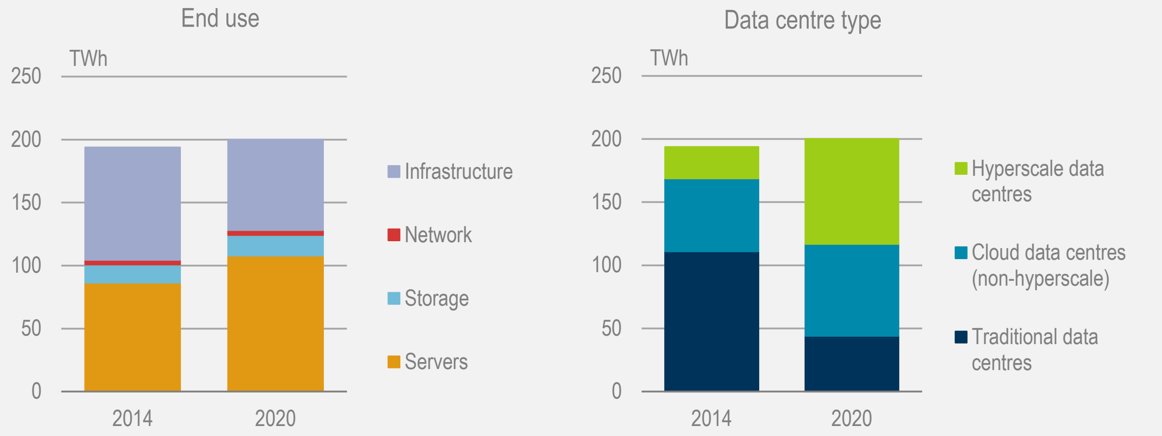
[5] IP traffic includes fixed and mobile internet traffic (IP traffic that crosses an internet backbone), corporate IP wide area network (WAN) traffic, and IP transport of TV and video on demand (VoD).

[6] There have been few estimates of global data centre energy use since Koomey (2011). One example is Van Heddeghem et al. (2014), who estimated worldwide consumption of 268 TWh in 2012. Studies estimating energy use of data centres vary widely in their methodology and scope, making comparisons across studies difficult. The IEA global estimates are derived using the Lawrence Berkeley National Laboratory (LBNL) data centre model and technology assumptions (Shehabi et al., 2016), and global server and storage stock assumptions derived from Cisco's Global Cloud Index (GCI) series (Cisco, 2016a), and is compatible with the approach in Koomey (2011). IEA believes this approach to be sound, as the LBNL methodology and data were thoroughly vetted by the IT industry, and data from Cisco's GCI on global server and storage stocks allow for generalisation globally.

[7] A workload is a unit of measurement quantifying the amount of processing that a computer can do in a given amount of time.

Based on current trends in the efficiency of hardware and data centre infrastructure, the IEA expects global data centre energy demand to grow by about 3% to 200 TWh in 2020 (Figure 5.1).[8] This is despite a projected tripling of data centre workloads, a 22% increase in the number of servers and a 46% increase in storage drives (Cisco, 2016a; Shehabi et al., 2016).[9] The strong growth in demand for data centre services is offset by continued improvements in the efficiency of servers, storage devices, network switches and data centre infrastructure,[10] as well as a shift to much greater shares of cloud and hyperscale data centres. Hyperscale data centres are very efficient, large-scale public cloud data centres operated by companies such as Alibaba, Amazon, and Google (Cisco, 2016a).

Figure 5.1 Global data centre energy demand by end use and data centre type



Key message: Despite an expected tripling of data centre workloads, global data centre electricity demand is expected to grow by only 3% to 2020 thanks to efficiency improvements in IT hardware and data centre infrastructure, and a shift to hyperscale data centres.

Note: Data centre infrastructure refers to energy consumed by non-IT equipment such as cooling.

Sources: IEA analysis based on Cisco (2011a, 2012a, 2013a, 2014a, 2015a, 2016a, 2016b, 2016c); Cook et al. (2017); Shehabi et al. (2016).

The shift away from small inefficient data centres towards much larger cloud and hyperscale data centres, often through outsourcing data centre services, is a major and growing source of energy efficiency gains. This trend is evident in the shrinking share of data centre infrastructure in total energy demand (Figure 5.1, left) given the

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[8] This analysis uses data centre workload projections from the Cisco GCI; at the time of analysis, the latest available projections run to 2020.

[9] Cisco (2016a) projects that the global data centre installed server base will rise from around 39 million in 2014 to around 48 million in 2020, and that global data centre installed storage capacity will rise from around 380 exabytes in 2015 to over 1 800 exabytes in 2020.

[10] Data centre infrastructure includes cooling, uninterruptible power supply, lighting, etc. (Shehabi et al., 2016).

very low power usage effectiveness (PUE)[11] of large data centres. Hyperscale data centres have highly efficient IT equipment and run at high capacity, thanks in part to virtualisation software which enables data centre operators to deliver higher work outputs with fewer servers (Cisco, 2016a). However, hyperscale data centres are only viable for operations where latency – the time delay in data transmission – is not critical, given that hyperscale data centres are typically located further away from the end user. Hyperscale data centres could represent 47% of all installed data centre servers by 2020, up from 21% in 2015 (Cisco, 2016a).[12]

Near-term trends in global energy consumption by data centres will largely be determined by the efforts of the ICT industry to continue to improve energy efficiency, as well as government policies and programmes to promote efficient data centre operations. An analysis of the prospects for energy use in data centres in India illustrates the technical potential for saving energy, and the risk of significant increased energy use if that potential is not realised (Box 5.1).

Box 5.1 Two futures of data centre energy use in India

Despite its large population and role as a hub for the technology industry, India is still a relatively small player in the global data centre industry. As of 2016, India accounted for only around 1.5% of global server sales, or around 150 000 server units (IDC, 2016, 2017). This compares with estimated sales of around 3 million servers in the United States alone (Shehabi et al., 2016). However, the Indian data centre market is expected to grow by more than 20% per year over the next several years, with much of this growth coming from large cloud data centres (Alchemy Research and Analytics, 2015). This growth is consistent with Cisco's GCI forecast of workload growth in the overall Asia-Pacific region (Cisco, 2016a). IEA analysis of data from the Manufacturers' Association for Information Technology (MAIT, an ICT industry association in India) and Cisco GCI workload growth suggests that the installed base of servers in India will grow from around 460 000 in 2014 to around 820 000 in 2020 (MAIT, 2016).

The IEA estimates that 2014 data centre energy demand in India amounted to around 2.2 TWh, or about 0.2% of India's total electricity consumption (Figure 5.2). Under current trends, data centre energy demand could grow by more than 50% by 2020, driven mostly by servers and growth in the largest data centre types (cloud and hyperscale). This growth rate is higher than that expected at the global level or in the United States, due to more rapid growth in workload demand occurring in the Asia-Pacific region. Under an improved management scenario (modelled after US improved management practices in Shehabi et al. [2016]), energy demand could be reduced by around 15% compared with the current trends scenario in 2020. This represents a significant slowing of energy demand growth, despite strong growth in the numbers of IT devices and data centres in the Indian market.

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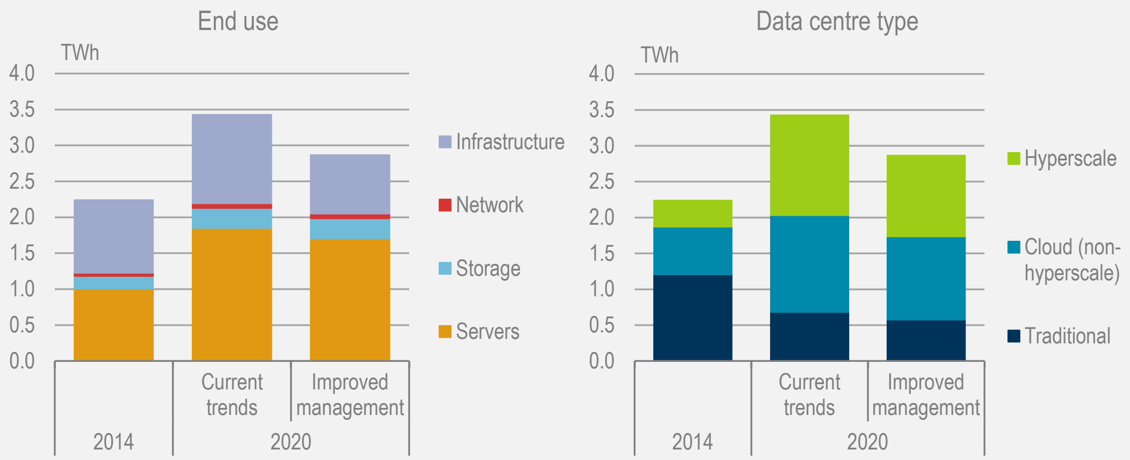
[11] PUE is a measure of how efficiently a data centre uses energy; the very best hyperscale data centres can have PUE values of around 1.1 (meaning 0.1 kilowatt hours [kWh] used for cooling/power provision for every 1 kWh used for IT equipment).

[12] Over the same time period, Cisco (2016a) projects that the percentage of global servers located in traditional (i.e. non-cloud) data centres will decrease from 52% to 23%.

Figure 5.2 Data centre energy demand in India by end use and data centre type



Key message: Improved management practices could help slow energy demand growth from data centres in India, reducing energy demand by around 15% compared to current trends in 2020.

Note: The improved management scenario (Shehabi et al., 2016) includes reductions in the number of installed servers due to removal of inactive servers and improvements in PUE to reflect global best practice values by data centre class.

Sources: IEA analysis based on Cisco (2011a, 2012a, 2013a, 2014a, 2015a, 2015b, 2016a, 2016d); Confederation of Indian Industry (2013); Confederation of Indian Industry and LBNL (2016a, 2016b); Cook et al. (2017); MAIT (2016); Shehabi et al. (2016).

Data transmission networks

The IEA estimates that global electricity use by internet data transmission networks[13] in 2015 amounted to around 185 TWh, or around 1% of total worldwide electricity demand (Figure 5.3).[14] Mobile data networks accounted for around two-thirds of this total. As with data centres, future energy demand depends on the growth of demand for data and the pace of further efficiency improvements.

The range of possible outcomes is wide. The IEA projects electricity demand in 2021[15] under two energy efficiency improvement scenarios: one assuming a moderate rate of improvement of 10% per year, which is close to conservative estimates of historical

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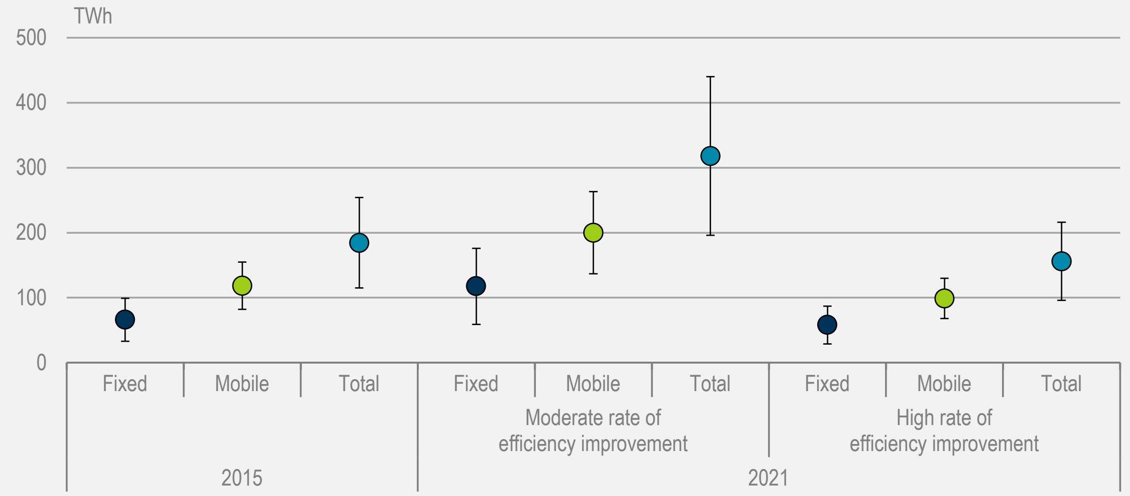
[13] Internet data transmission networks include core, metro, edge and access (wired, WiFi and mobile). Traditional fixed telephony systems and equipment on customer premises are excluded from the energy totals.

[14] Other recent estimates of global electricity use attributable to transmission networks typically amount to around 1-1.5% of total worldwide electricity demand, with about half from mobile networks (Andrae and Edler, 2015; Corcoran and Andrae, 2013; Ericsson, 2015; Malmodin, Bergmark, and Lundén, 2013). However, comparing global energy estimates is difficult due to differences in data sources, system boundaries and assumptions for data traffic. Therefore, there are large uncertainty ranges around the data network energy use estimates in this report (see Figure 5.3).

[15] IEA analysis uses IP traffic projections from the Cisco Visual Networking Index; at the time of this analysis, the latest available projections run to 2021.

improvements; and one assuming a more rapid rate of improvement of 20% per year, based on the historic rates achieved in well-managed networks in developed countries with high capacity utilisation. In the moderate efficiency-improvement scenario, the midpoint of the electricity demand range in 2021 rises by over 70% to about 320 TWh. Under the high efficiency-improvement scenario, the midpoint drops by 15% to about 160 TWh (Figure 5.3).

Figure 5.3 Electricity use by internet data transmission networks



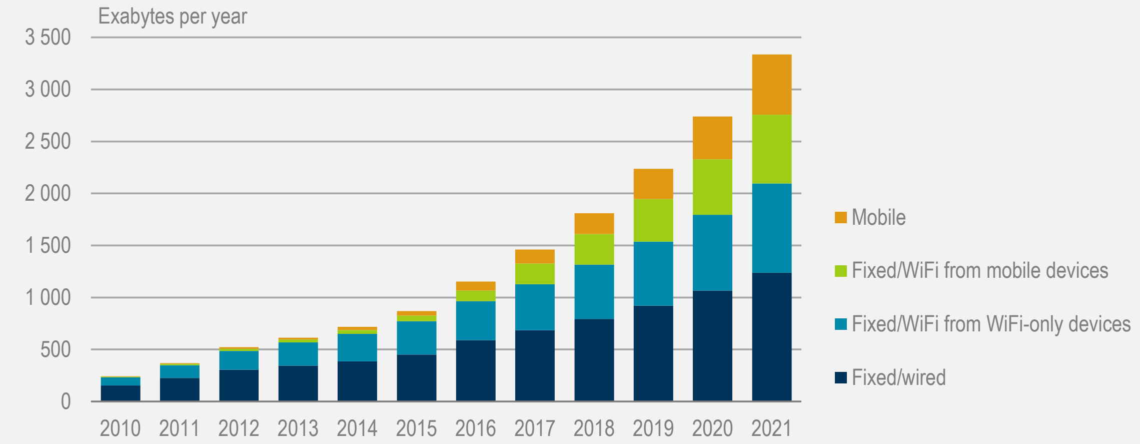
Key message: The prospects for future electricity demand from data transmission networks hinge critically on the pace of efficiency improvements.

Note: Points are the midpoint of the estimated range, which is denoted by vertical bars.

Sources: IEA analysis based on Cisco projections for global IP traffic (Cisco, 2016e, 2017a) and network energy intensity estimates from Andrae and Edler (2015); Aslan et al. (2017); Fehske et al. (2011); GSMA (2012); Malmodin (2017); Malmodin et al. (2014); Schien and Preist (2014); Schien et al. (2015).

Several relevant trends are shaping the future of data network electricity use. Global IP traffic increased more than threefold over 2011-16 and is projected to grow by a similar rate between 2016 and 2021 (Cisco, 2017a). Global average fixed broadband speeds are projected to nearly double from 2016 levels to 53 megabits per second (Mbps) by 2021 – a thousand times faster than 56k modems that were widely used 15-20 years ago (Cisco, 2017a). Data demand growth over the next five years will be driven strongly by consumer markets, which currently account for 80% of all data demand – mostly for video (Cisco, 2017a). The nature of data transmission is changing rapidly, with traffic from wireless and mobile devices expected to account for more than 63% of total IP traffic by 2021, up from 49% in 2016 (Figure 5.4).

Figure 5.4 Global IP traffic by access mode



Key message: The nature of data access is changing rapidly from wired to wireless devices.

Sources: IEA calculations based on Cisco (2011b, 2012b, 2013b, 2014b, 2014c, 2014d, 2015b, 2015c, 2016e, 2016f, 2017a, 2017b, 2017c).

This shift toward greater use of mobile networks may have significant implications for the energy use of data transmission networks, given the considerably higher electricity intensities (kWh per gigabyte [GB]) of mobile networks compared with fixed-line networks at current traffic rates. 2G networks can be roughly two orders of magnitude (i.e. over 100 times) more energy intensive than fixed-line networks, 3G roughly one order of magnitude (i.e. over 10 times) and 4G roughly four times (Figure 5.5).[16] While the latest mobile telecommunications technologies are much less energy intensive than older technologies (e.g. 4G can be more than 50 times more energy efficient than 2G), their higher speeds may also allow for greater usage and traffic volumes.

One of the fastest-growing areas of mobile connections and traffic is machine-to-machine (M2M). This includes GPS for logistics and vehicles, smart metering and other IoT technologies, which enable the many energy efficiency and demand response opportunities discussed in Chapters 2 and 4. It is projected that there will be over 13 billion M2M connections by 2021, up from around 6 billion in 2016 (Cisco, 2017c). A shift in some M2M connections to a technology called low power wide area (LPWA), which has very low energy use, may mitigate some of the energy demand effects of the huge projected growth in M2M connections. At the same time, associated security and privacy risks of LPWA also need to be considered (GSMA, 2017a).

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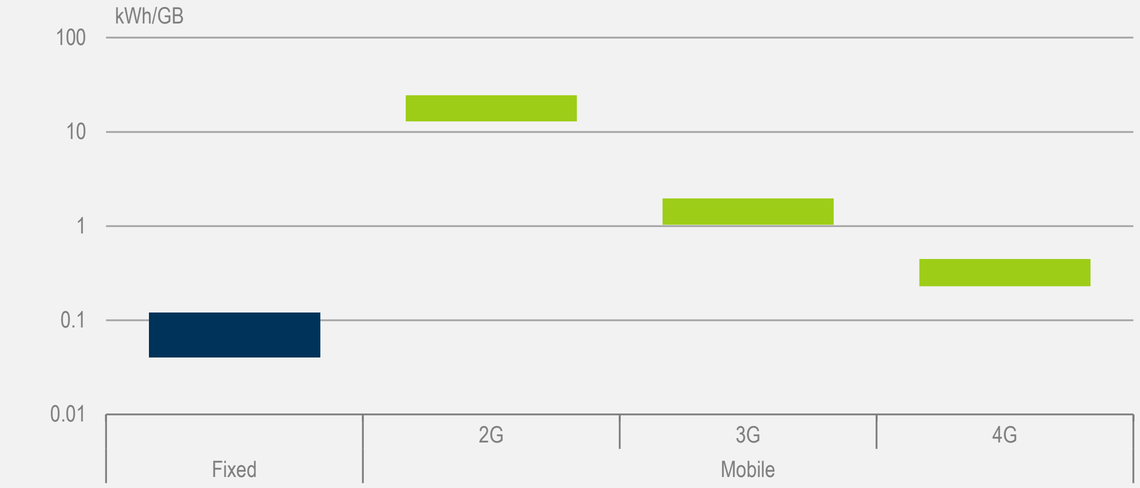
[16] The average energy intensity of mobile networks can also vary greatly depending on their capacity utilisation. As traffic within a given access mode (e.g. 2G, 3G or 4G) increases, its overall average energy intensity can decrease, which means precise comparisons with fixed-line energy intensities are highly case-specific. Still, the overall rank order of energy intensities implied here can be generalised globally.

Figure 5.5 Electricity intensity of network transmission by access type in 2015



Key message: Mobile networks typically have higher electricity intensities (kWh/GB) than fixed-line networks, but newer generation mobile networks and increased mobile network capacity utilisation are closing the gap.

Notes: Fixed and mobile network energy intensities are inclusive of core, metro, edge and access networks; due to large differences in electricity intensities, a log scale is used to illustrate orders of magnitude differences; the energy intensities of fixed and mobile networks are highly dependent upon assumed traffic rates.

Sources: IEA analysis based on Andrae and Edler (2015); Aslan et al. (2017); Fehske et al. (2011); GSMA (2012); Malmodin (2017); Malmodin et al. (2014); Schien and Preist (2014); Schien et al. (2015).

Despite strong growth in data demand and shifts to mobile transmission, three important trends can help counteract these growth trends and limit overall growth in energy demand:

- Data transmission network technologies are rapidly becoming more efficient, meaning more data can be sent using less energy. Fixed-line network energy intensity has halved every two years since 2000 in developed countries (Aslan et al., 2017). Mobile access network energy efficiency has in recent years improved at annual rates of around of 10-20% (Fehske et al., 2011; GSMA, 2012; Verizon, 2012).
- Capacity utilisation of networks is increasing, driving down energy use per byte sent, even with existing equipment.
- Mobile networks are shifting rapidly away from older networks towards more efficient 4G. By 2021, 4G is expected to cover around 80% of mobile traffic, while 2G is expected to cover less than 1% (Cisco, 2017b).

Connected devices

Connected devices – also referred to as networked, edge or end devices – are consumer electronics, appliances and other devices that can be connected to networks and interact with the network or other devices. Until recently, only a few devices were typically connected to communications networks, primarily computers, televisions, routers and modems. With the widespread diffusion of broadband internet, as well as wireless and mobile access, an increasing variety of consumer devices, appliances and infrastructure across all sectors are being connecting to the internet and to each other.

Billions of new connected devices are expected to be connected over the next few years. The number of smartphones is expected to increase from 3.8 billion in 2016 to almost 6 billion by 2020 (GSMA, 2017b),[17] while the number of connected IoT devices is expected to triple from about 6 billion in 2016 to over 20 billion by 2020 (Gartner, 2017). Over the longer term, it is conceivable that most electrical devices – and even some consumer items such as clothing – could become connected IoT devices, using energy to collect, process, store, transmit and receive data.

In discussing the energy use of connected devices (as a segment of ICT), it is helpful to distinguish between two types of connected devices: "electronic edge devices", whose primary function is data storage/use, such as laptops and smartphones, and "other edge devices", whose primary functions are not data-related, such as networked kitchen appliances and cars. Only data-related energy use is considered in this section, specifically energy use by "electronic edge devices" as well as any networked standby energy use of "other edge devices".[18]

Several studies have estimated the energy use of connected devices (e.g. Andrae and Edler, 2015; Corcoran and Andrae, 2013; IEA, 2014; Malmodin et al., 2010; Malmodin et al., 2013; Van Heddeghem et al., 2014). However, differences in time, scope/boundaries, assumptions and data sources make any direct comparisons across studies difficult.[19]

It is important to note that the direct energy use of devices at the plug is just one part of the energy story for connected devices. Energy is also used to manufacture and

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[17] Smartphones are already playing an important role in driving efficiency and new business models across all sectors, including energy. In transport, for instance, smartphones are the key enabler of app-based ride-hailing services (see Chapter 2).

[18] While "other edge devices" do consume energy to provide their primary service, these energy demands should be considered a part of their respective end-use sectors (e.g. a connected fridge is a home appliance, which is part of the buildings sector).

[19] For example, Van Heddeghem et al. (2014) estimated total consumption of 307 TWh in 2012 from personal computers (including desktops, laptops and monitors), while Malmodin, Bergmark, and Lundén (2013) estimated that user, home and office ICT equipment would consume around 380 TWh in 2015.

dispose of these devices, which is more important in smaller, highly efficient and shorter-lived devices such as tablet computers and smartphones.[20] More than three-quarters of lifecycle[21] energy use for a tablet is associated with production, while for desktops, use-phase energy accounts for more than half (Hischier et al., 2014).

The growth in the number of connected devices will continue to drive up the volume of data being generated and transmitted, along with the energy used in data centres and data networks. Again, these indirect impacts are proportionally more significant for smaller devices given their high operational efficiency. For tablets, the energy used to provide its internet services is estimated to be over 10 times greater than the energy needed for the production, use and disposal of the device (Hischier et al., 2014).

Long-term energy demand outlook

Given the rapid pace of technological progress and change, providing credible forecasts of ICT energy use beyond the next five years is extremely challenging. This section briefly explores the key drivers of future ICT energy demand.

Demand for **data centre** services is expected to continue to grow strongly after 2020. How this affects energy use will continue to be largely determined by the pace of energy efficiency gains. The continued shift to efficient cloud and hyperscale data centres will reduce the energy intensity of data centre services. The use of artificial intelligence (AI) and machine learning may also help. In one recent case, machine learning was applied to Google data centres, which reduced their energy use for cooling by 40% (DeepMind, 2016). If demand for data centre services outpaces efficiency gains, powering data centres with renewable energy will become increasingly important to curbing greenhouse gas emissions (Box 5.2).

For **connected devices,** standby power consumption is a particular concern, with devices such as smart TVs and connected appliances using energy continuously to maintain connectivity. Inefficient networked standby could waste around 740 TWh per year by 2025, equivalent to the current annual electricity consumption of France and the United Kingdom combined (IEA, 2014). The standby power consumption of IoT devices that are plugged in[22] (excluding televisions and computers) is projected to grow to 46 TWh by 2025, with 36 TWh coming from home automation (4E TCP, 2017).

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[20] From a life-cycle perspective, operational energy use dominates for data centres and networks, while for connected devices, energy used to manufacture and dispose of devices is generally more important (Hischier et al., 2014).

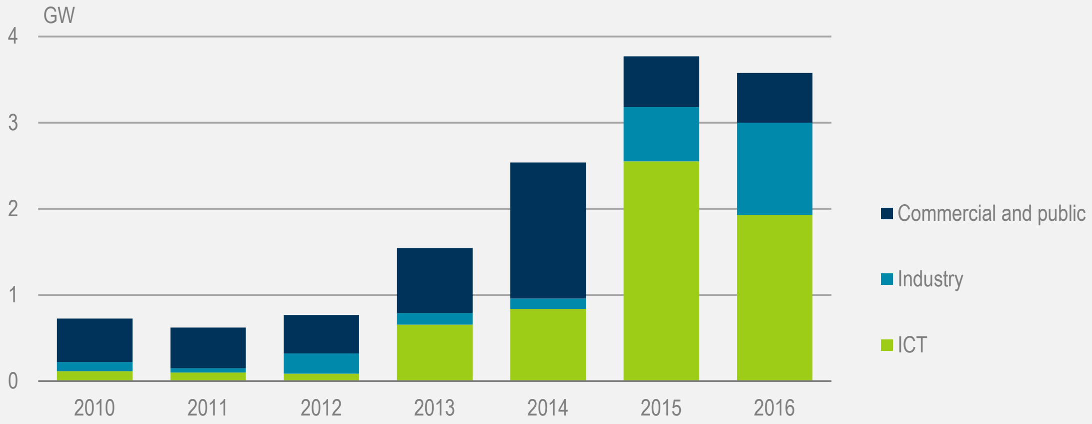
[21] Includes energy used for production, use, and end of life (i.e. disposal). Refer to the Hischier et al. (2014) for a full discussion of assumptions.

[22] Also known as "mains-connected" IoT devices, i.e. not battery- or self-powered and need to be plugged in to operate.

Box 5.2 Data centres, renewable energy and demand response potential

ICT companies, particularly hyperscale data centre operators, are already investing heavily in renewable energy to protect themselves from the volatility of power prices, reduce their environmental impact and improve brand reputation (Cook et al., 2017; World Resources Institute, 2017). Over 20 of the top 50 ICT companies by revenue have quantified renewable energy procurement goals, including some committing to 100%, primarily through power purchase agreements (PPAs) with electricity producers. Overall, ICT companies have been responsible for more than half of total corporate renewable energy PPAs over the past three years (Figure 5.6). While ICT PPAs remain small as a proportion of overall new renewables capacity, accounting for just 1.9 GW out of over 160 GW brought online in 2016, procurement by ICT companies could still be a significant driver of renewables investment in various regions due to the size and influence of these companies (Miller et al., 2015).

Figure 5.6 Corporate renewable power purchase agreements by type of buyer



Key message: Corporate buying via PPAs has accounted for about 10 GW of new utility-scale renewables-based generating capacity over the past three years, led by ICT companies looking to hedge price volatility, diversify supply and meet sustainability goals.

Notes: Includes projects based on utility green tariffs in the United States; shares by buyer type are calculated based on contracted capacity.

Sources: Calculations based on BNEF (2017); Platts (2017); Rocky Mountain Institute (2017).

Digitally enabled demand response could yield considerable cost savings for the grid as a whole while also facilitating greater integration of variable renewable energy (see Chapter 4). As large and growing electricity users with a high degree of flexibility, data centres could play an increasingly important role in demand response (Wierman et al., 2014). Data centres are highly automated and monitored, making them significantly more flexible and responsive compared to conventional industrial facilities. For instance, 5% of load can typically be shed in five minutes without changes to how the IT workload is handled (Ghatikar et al., 2012).

Battery-powered connected devices are already highly energy efficient, and emerging "energy harvesting" technologies could eventually help to further reduce energy use or even make some low-power electronics battery-free.[23] Energy harvesting describes the process by which energy is harvested or scavenged from sources in the environment, such as solar, wind, movement and sound, to power a device.

The nascent IT infrastructure for blockchain and cryptocurrencies is evolving rapidly, and its implications for global electricity use are not yet well understood. Early estimates suggest that the electricity use of Bitcoin data miners – one prominent example of the emerging blockchain IT infrastructure – may currently be on the order of less than 1/40th of 1% of global electricity use (Bevand, 2017; Deetman, 2016). However, as blockchain applications grow, understanding and managing its energy use implications may become increasingly important for the energy analysis and policy communities.

Efforts by the ICT industry to improve energy efficiency and government policies to promote best practices could help to continue to hold down ICT energy demand growth over an extended period. For instance, in data networks, policies to accelerate the early phase-out of energy-intensive legacy networks could be particularly important. With data demand growth expected to be strongest in Asia-Pacific and North America (Cisco, 2017a), continued efforts toward more efficient networks and data centres in these regions will be critical.

Nonetheless, there is considerable uncertainty about how long current ICT efficiency trends can continue. As an upper bound, Koomey, Matthews and Williams (2013) estimated that, should current trends continue, processor efficiency limits may be reached by around 2040 based on the physical efficiency limits of transistors.[24] Other experts estimate that theoretical limits to Koomey's Law may be reached by around 2060 as a result of Landauer's Principle (Demaine et al., 2016; Lääkkölä, 2015).[25] It is also possible that the rate of energy efficiency improvements will diminish well before these theoretical limits are reached.[26] Complicating matters further, emerging

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[23] Researchers at the University of Washington recently demonstrated a battery-free cellphone (Talla et al., 2017).

[24] In 1985, physicist Richard Feynman estimated that improvement by a factor of 10^{11} would be possible compared to computer technology at the time. Efficiency improved by $4x10^4$ from 1985 to 2009, meaning that if long-term trends of Koomey's Law continue, Feynman's limit would be reached in 2041 (Koomey, Matthews and Williams, 2013). Feynman assumed a three-atom transistor to calculate his limit, but smaller transistors (such as the one-atom transistor demonstrated in 2012 [Fuechsle et al., 2012]) could push these limits out even further.

[25] Laundauer's Principle is the minimal amount of energy that must be consumed by erasing one bit of information.

[26] Although gains in peak-output efficiency have already slowed as processors face the physical limitations of shrinking transistors, ongoing improvements in chip design and power management have continued to deliver overall computing efficiency gains (Koomey, 2015; Koomey and Naffziger, 2015, 2016).

computing technologies such as quantum computing[27] may change the nature of energy use for computing, although their application may not become widespread.

Policy considerations

Actions and commitments by device manufacturers as well as network and data centre operators will be central to driving further efficiencies and moderating overall ICT energy use. Government policies can also continue to play a key role, including through:

- Regulations, policies and programmes for more efficient devices, such as minimum energy performance standards, information campaigns, and energy labelling.[28] Such efforts should include a strong focus on reducing standby losses of networked devices (e.g. European Commission Regulation EU 801/2013), improvements to power management and the use of energy-harvesting technologies.
- Policies and programmes to encourage more efficient and sustainable device manufacturing practices, such as product eco-labels (e.g. Electronic Product Environmental Assessment Tool [EPEAT]) and incentives for energy-efficient industrial processes and renewable energy.
- Incentives and guidance for efficient data centre operations (e.g. see Huang and Masanet [2015] for a summary of best practices and how to calculate savings for incentives programmes).
- Policies and programmes for more efficient data transmission networks, including network device energy efficiency standards, improved metrics and incentives for efficient network operations, and support of international technology protocols (e.g. Institute of Electrical and Electronics Engineers [IEEE]) and standards development for low-energy networks.
- Better national data systems to collect data on ICT devices and their energy use characteristics[29] to inform energy analysis and policy making – e.g. the US Energy Information Administration has collected data on connected devices in homes and commercial buildings (Residential Energy Consumption Survey

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[27] While conventional computers use bits represented by 0s or 1s, quantum computers use quantum bits (qubits) to encode information as 0s, 1s, or both at the same time, allowing them to solve problems faster, while potentially using less power to perform calculations.

[28] For example, EU regulations covering a wide range of connected devices; ENERGY STAR labelling in the United States to encourage low-energy connectivity.

[29] The lack of data for this important end use severely limits analysts' ability to conduct robust analysis of ICT energy use and provide sound policy advice.

[RECS], Commercial Buildings Energy Consumption Survey [CBECS]), and has started to collect data on servers in data centres (CBECS).

- Governments leading by example through purchasing only efficient ICT and running their own data centres in the most efficient ways.
- Voluntary agreements with companies and industries on efficiency and CO_2 emissions targets – e.g. the European Union and the United States have adopted voluntary agreements to improve the efficiency of connected set-top boxes; Verizon has stated public efficiency goals for their network operations, for which they publish indicators (kWh/GB) and progress annually.
- Uptake of other voluntary initiatives, such as the Connected Devices Alliance (CDA) Voluntary Principles for Energy Efficient Connected Devices.[30]

The policy challenges in addressing energy use from connected devices are inherently different from those related to other historically important plug-loads such as refrigerators, freezers, air conditioners and televisions, which have been on the market for decades. With these traditional products, policy makers were able to study a relatively stable market and implement informed energy performance standards. In contrast, the market and scope of connected devices are evolving at an unprecedented pace, with new types of devices with complex operating modes coming into use almost daily. In this new reality, policy makers will need to make creative use of available policy tools and levers.

Policy approaches to address the direct energy impacts of greater digitalization also need to be developed as part of an overall strategy that addresses wider aspects associated with the role of connectivity in the energy system and beyond.[31] For digital technologies to play their role in delivering energy and environmental benefits, favourable market conditions will be needed to stimulate the take up of smart appliances and equipment, as well as the associated infrastructure.

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[30] The CDA Voluntary Principles for Energy Efficient Connected Devices have two focuses: 1) Design Principles provide guidance on the key features of energy-efficient connected devices, networks and communications protocols – for use by designers, manufacturers and protocol authors; and 2) Policy Principles encourage a common global framework for the development of government policies and measures (CDA, 2016). See: https://cda.iea-4e.org/cda-principles.

[31] See recent reports from the Global e-Sustainability Initiative (GeSI), e.g. #SMARTer2030 (Global e-Sustainability Initiative, 2015).

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Chapter 6

Cross-cutting risks: Cybersecurity, privacy and economic disruption

Highlights

- Digitalization carries three main cross-cutting risks which, while not unique to the energy sector, need to be assessed and managed: cybersecurity, privacy and economic disruption.
- Digitalization can make energy systems more vulnerable to digital risks, such as geomagnetic storms and cyber-attacks. Governments and companies need to work together to manage the increased complexity of threats to cybersecurity. Full prevention of cyber-attacks is impossible, but their impact can be limited if countries and companies are well prepared. Digital resilience needs to be integrated into technology research and development, and policy and market frameworks.
- Privacy and data ownership are becoming a major concern as more and more detailed data are collected, in particular information from smart meters about household energy use. Policy makers need to balance privacy concerns with other objectives, which include promoting innovation in markets, operational needs of utilities and the wide-ranging potential of the digital transformation of electricity.
- Digitalization is leading to major disruptions in the energy sector and the broader economy, affecting jobs and skill requirements. It is changing work patterns and tasks, causing job losses in some areas and creating new jobs in others. The impact varies across the different parts of the energy sector. Policy makers in the energy field should participate fully in relevant government-wide decision-making on digital matters.

Digitalization entails a number of wider challenges which, while not unique to the energy sector, need to be assessed and managed. This chapter will explore the three most important: cybersecurity, privacy and economic disruption. Energy policy makers will need to work with colleagues across their governments to track the implications for energy operations and business, and to contribute to well-considered policies.

Digital security

Cyber threats to energy security

Digitalization brings many benefits, but it also opens the door to increasing risks for energy security, both from natural hazards such as geomagnetic storms and from unintended cyber incidents and intentional cyber-attacks (Box 6.1). For example, in 1989, a severe geomagnetic storm caused a nine-hour outage in transmission grids in Quebec. In December 2015, hackers illegally breached the computer and control systems of a Ukrainian regional electricity distribution company and managed to disconnect substations, resulting in the loss of power for 225 000 customers. This was followed by a second attack in December 2016 that appears to have used malware specifically designed to take over control of electric grid circuit breakers (ESET, 2017). Generic cyber-attacks, such as the worldwide "WannaCry" and "NotPetya" ransomware incidents in May and June 2017 respectively, have also impacted the energy sector by damaging information technology (IT) business systems.

Box 6.1 Malware, ransomware, phishing and bots

- **Malware** is software (e.g. a virus, worm, rootkit, or botnet) specifically designed to disrupt, damage, or gain unauthorised access to an information and communications technology (ICT) system.
- **Ransomware** is a type of malware that encrypts user data, asking victims to pay a ransom in order to obtain a decryption key.
- **Phishing/whaling** is trying to obtain sensitive information, such as usernames and passwords, by means of an email (or other electronic communication) that is disguised as a trustworthy communication, but which, when opened or when a link is clicked on, allows the sender a point of access.
- **Botnets** (short for robot networks) are automated programs that run over the internet. Some botnets run automatically, while others only execute commands when they receive specific input. Not all botnets are malicious.

The disruption caused to energy supply by reported cyber-attacks to date (Table 6.1) has been small compared to major power outages from storms and mechanical equipment failures, or from geopolitical disruptions to oil and natural gas supply. However, cyber-attacks – whether aimed at sabotage, taking control of energy systems, industrial espionage, or ransom – are becoming easier and cheaper for hostile actors to organise. These range from amateurs to professional hackers-for-hire, to other states and state use of proxies (HMG, 2016a).

Table 6.1 Open source information regarding cyber-attacks affecting energy infrastructure

Incident	Description (from open-source information)
Shamoon 1 and 2 (Saudi Arabia, 2012 and 2016)	"Shamoon 1" virus carried out cyber-sabotage and destroyed over 30 000 computers at Saudi Aramco. There was no direct impact on oil production, but the company was forced to revert to traditional paper and telephone trading for several weeks. Qatari natural gas company, RasGas, was also impacted. The virus was set to execute after working hours in order to minimise detection. "Shamoon 2" virus targeted similar vulnerabilities and was used to overwrite parts of computer hard discs.
Western Ukraine power grid (2015)	The first confirmed cyber-attack specifically against an electricity network. Attackers accessed substations' supervisory control and data acquisition (SCADA) and firmware with a combination of malware, personnel credentials obtained by means of email phishing, and Denial of Service (DoS) to prevent customers from obtaining call centre information about the blackout. Investigators concluded that a large well-co-ordinated team had prepared the attack over several months.
The Mirai Botnet (2016)	"Mirai" malware exploited low security in connected smart devices, such as cameras, to use a botnet (a network of devices under simultaneous command by the attacker to overload the victim by continuously sending data) to deliver the largest DoS attack to date. This attack did not target or impact energy infrastructure, but illustrates the vulnerability of the Internet of Things (IoT).
Industroyer/ Crash Override (Ukraine, December 2016 – reported May 2017)	A second brief but significant attack on the Ukrainian electricity system, thought to have been a test run for malware "Industroyer" (also known as "Crash Override"). This versatile malware enables attackers to view, block, control or destroy grid control equipment such as circuit breakers. Its design suggests expert knowledge of several standardised industrial communication protocols widely used to control infrastructure – not only electricity grids – throughout Europe, Asia and the Middle East. This was an example of a cyber intrusion into the control systems of critical infrastructure.
Nuclear plant spear phishing attack (2017)	This incident occurred in the United States. It used targeted email messages containing fake Microsoft Word résumés for engineering jobs, potentially exposing recipients' credentials for the control engineering network. The hackers also compromised legitimate external websites that they knew their victims frequented (known as a watering hole attack).
WannaCry (2017)	"WannaCry" ransomware hit hundreds of thousands of computers in thousands of organisations in some 150 countries, taking advantage of an access point in Microsoft operating systems for which some users had failed to install the secure update (or "patch"). These attacks did not target energy infrastructure, but several energy companies reported problems. In the People's Republic of China (hereafter, "China"), over 20 000 China National Petroleum Corporation (CNPC) petrol stations went offline.

Some cyber-attacks target operational technology (OT): the computers, software and networks used to control, monitor, manage and protect energy delivery systems. Other attacks might target only the IT business systems of energy companies that do not control the physical process of energy delivery, but result in administrative interruptions (as in the case of Shamoon). Unintentional cyber incidents linked to the increasing complexity of "systems of systems" that combine many layers of ICT and OT are also becoming more frequent, for example when an update in one type of equipment causes malfunctions in other equipment.

The growth of the IoT and changes in digital technologies are increasing the potential "cyber-attack surface" in energy systems. The expansion of the IoT, combined with the diversification and decentralisation of energy technologies, will link millions of new small-scale prosumers and billions of devices into the electricity system. Industry forecasts estimate that total numbers of connected IoT devices could more than double to over 20 billion by 2020 (Gartner, 2017).[1] If there is one suspect device at the edge of a network, this can be a weak point for the whole system. A recent study by the European Parliament concluded: "The development of smart energy has also led to exponential growth of networked intelligence throughout the energy grids and also consumer premises. The result is that a massively expanding 'attack surface' now forms the operational foundation of the energy ecosystem. As the energy system is also fundamentally interconnected with every other critical infrastructure network, the cybersecurity threat to the energy sector impacts every aspect of our modern society" (European Parliament 2016; see also Global Smart Grid Federation, 2016).

Digital technologies used in centralised energy systems are also changing. Early digitalization often relied on IT and OT that were proprietary or vendor-specific. Electricity substations typically might use several generations of equipment, assembled piecemeal over time. This older infrastructure often pre-dates embedded security standards, but can benefit from an element of "security by obscurity", so that hacking it requires specialised knowledge. Today, with more connectivity between system components, more automation, a shift to cloud computing, and the replacement of energy-specific IT by sophisticated open-protocol industry standards, newer systems have higher security, but lose the protection of obscurity and the level of specialised energy system knowledge needed for attack diminishes.[2]

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[1] Machine-to-machine (M2M) connections, which include energy sector applications such as smart meters and process sensors in power plants, will be the fastest-growing category, growing at around 20% a year (Cisco, 2017). See also Chapter 5.

[2] There can be advantages to maintaining "old-school" (manual) control-of-key infrastructure as a backup to remote digital management. In the case of the December 2015 incident in Ukraine, operators were quickly able manually to switch circuit breakers back on and override the cyber-attack. Many power grids in other countries are now fully automated, where a similar attack could be more difficult to counteract.

Cyber-attack techniques can target personnel, products (both data and physical infrastructure) and processes (system data flow). This means that there is greater need to protect the integrity and confidentiality of information, and to identify trustable sources and authorised recipients, also in supply chains and procurement. Meanwhile, the global scope of the internet and the geographical reach of multinational energy companies mean that an attack at one location can instantly spread worldwide. Risk analysis, therefore, needs to span products, people and processes.

Taking all of this into account, some experts in strategic risk assessment see credible scenarios for "low-probability, high-risk" attacks that could shut down the electricity grids of a major economic region for a period of days or – on a rolling basis – weeks (Lloyd's, 2015; Cambridge Centre for Risk Studies, 2016; National Academies of Sciences, Engineering, and Medicine, 2017; Madnick, 2017). Energy professionals and oversight authorities also foresee a future of many small-scale nuisance attacks from bots (numbering thousands per day).

While cyber-attacks can affect a variety of parts of the global economy, attacks on energy systems are likely to be particularly disruptive. Unlike most IT systems, electricity OT systems must operate in real-time and cannot simply install patches or updates, or shut down and reboot as in the typical response to digital failures or breaches. Special security considerations and precautions are therefore needed.

Building resilience

Full prevention of cyber-attacks is impossible, but their impact can be limited if countries and companies are well prepared and have built-in resilience. This is particularly important for critical infrastructure: the physical and institutional assets that are essential for an economy to function, such as large-scale energy systems. For example, Mexico has around 3 000 "strategic installations", half of them owned by the national oil company PEMEX and another 13% by the Federal Electricity Commission (Government of Mexico, 2014). Any infrastructure in Germany on which more than 500 000 people depend is considered critical. This includes all gas power plants and electricity transmission grids.

Building system-wide resilience depends on all actors and stakeholders first being aware of the risks. The success of any one attack will depend not only on the capability of the attacker, but also on the vulnerability of the target and its preparedness to respond. For example, a recent study finds that few oil and gas companies today acknowledge cyber breach as a major risk. Some categorise cyber risk together with other risks such as labour disputes; others do not mention cyber risk in their company strategies. The same report finds that three-quarters of oil and gas companies were victims of some kind of cyber-attack at least once in the last year. Furthermore, older upstream equipment was not built with security in mind and lacks monitoring tools, while only 14% of companies have fully operational security monitoring centres on their networks (Mittal, Slaughter and Zonneveld, 2017).

Digital energy security should be built around three key concepts:

- **Resilience**, i.e. the ability of a nation, system or institution to adapt to changing contexts, to withstand shocks, and to quickly recover or adapt to a desired level of stability, while preserving the continuity of critical infrastructure operations (Larkin et al., 2015).
- **Cyber hygiene**, i.e. the basic set of precautions and monitoring that all ICT users should undertake. This includes first and foremost building awareness. Other key elements are secure configuration of equipment and networks, keeping software up to date, avoiding giving staff and users unnecessary system privileges or data access rights, and training to establish a security-conscious culture throughout an organisation. For example, staff may need to be trained on the secure use of their personal computers at home and mobile devices.
- **Security by design**, i.e. the incorporation of security objectives and standards as a core part of the research and design process; security should not be a later add-on after a product has been built or supplied to users. Security by design can be an efficient way to reduce overall risk.

The choice of technology and system architecture is an important factor for resilience. Cybersecurity and resilience need to be made a central part of energy research, development and deployment. For example, the National Renewable Energy Laboratory in the United States has developed a cybersecurity testbed that imitates the power and communication network of a typical distribution utility. It incorporates a nine-layer security architecture that has real-time transactions between different actors (end users and/or systems).

Microgrid electricity networks may have an advantage in that they can be islanded (temporarily segregated from the rest of the grid). Blockchain technology is part of the cyber problem as cryptocurrencies can be used to collect ransomware payments. But blockchain can also be a potential cybersecurity solution at the grid edge, for example if used to validate whether a device is running up-to-date firmware and has not been tampered with (see Chapter 4). The Pacific Northwest National Laboratory in the United States is developing blockchain solutions to strengthen the cybersecurity of transactive energy systems, including within microgrids and building-to-grid connections, as well as validate that a device is running up-to-date firmware, and confirm that it has not been tampered with.[3] Countries that are still building their energy systems have the advantage of being able to design into new infrastructure both high security and networks that can be rapidly isolated.

Establishing clear and accepted definitions is also crucial, both for analytic concepts such as "threat" and "risk" (Marchese and Linkov, 2017), and for more technical specifications, such as varying definitions of "air-gapping" (the physical separation of ICT devices from other devices/networks). For example, cybersecurity specialists highlight that IT and OT personnel often have different security priorities. In IT, these are the confidentiality, integrity and availability of a system. In OT, safety is first, followed by availability. Confusion can result.

In relation to technical specifications, the International Electrotechnical Commission (IEC) has an important role. IEC develops worldwide standards and conformity assessments for equipment and business processes, and is currently incorporating cybersecurity. To date, it has identified around 650 electrotechnical standards from 40 different standard-setting organisations that have applicability to cybersecurity. A categorisation of cybersecurity standards is being prepared for 2018.

Another critical need is clarity about the division of responsibilities for security, preparedness and response among market players, including for-profit energy system operators, and governing bodies, including government agencies and regulators. A company or local operator is likely to be able to handle attacks by botnets or amateurs (the "script kiddie" teenage hacker), but will not be able to manage the impacts of a major systemic attack (Figure 6.1).

Uncertainty about risks makes it difficult to justify large expenditure on staff or on cyber-insurance policies. Setting regulatory requirements can help ensure necessary investments are made, for example, adding cybersecurity criteria to the rate base for electricity grids.

At the same time, companies acknowledge that compliance with regulatory standards does not, on its own, guarantee infrastructure will be secure. In general, regulatory standards will struggle to keep up with rapid technological changes and new vulnerabilities.

Governments and energy companies, therefore, need to be both proactive and adaptive. In some cases, innovative solutions might be found when energy companies work together. In an interesting experiment, Austrian energy market actors have

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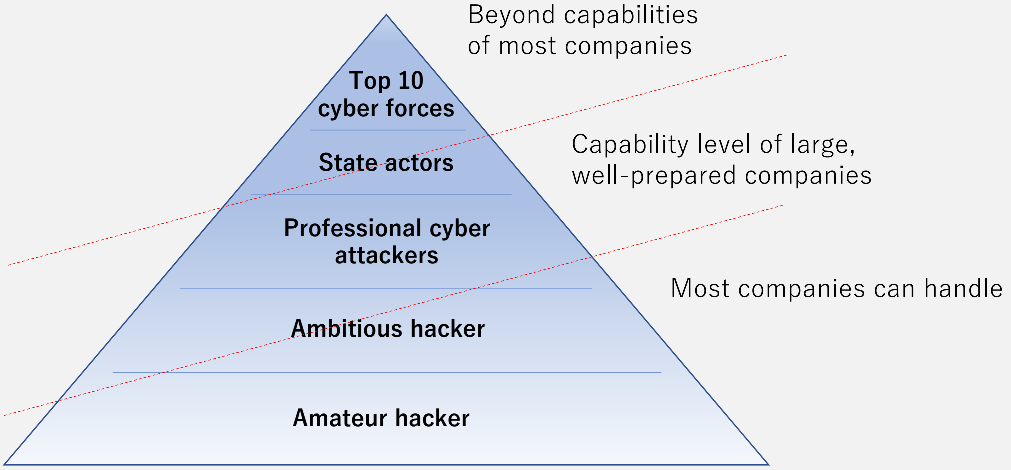
[3] Several other US national laboratories are also doing research into cybersecurity for energy delivery systems: www.energy.gov/oe/activities/cybersecurity-critical-energy-infrastructure.

decided to set up a joint team on cybersecurity, with the aim of saving costs, pooling expertise and improving early visibility of attacks and risks (see also Carr, 2016).[4] A wider group of European companies have formed a European Network for Cyber Security to collaborate on training.[5] Examples like this suggest that companies may find benefits in enhancing information sharing among themselves, beyond any requirements to report to regulators. Wider consultation with experts in the university sector[6] and with other industry sectors can also be valuable.

Figure 6.1 Capabilities of companies to handle cyber-attacks



Key message: The handling of some attacks falls within the capability of companies themselves, while larger-scale attacks by sophisticated actors may require more active government responses.

Source: Presentation by Swissgrid at Florence School of Regulation workshop on Cybersecurity in the Energy Sector, 24 March 2017 (adapted by IEA).

Best practices and policy

Much can be learned by examining how a variety of governments are currently structured and organised to deal with cyber threats. In many countries, cybersecurity is part of governance frameworks that are broader than energy, but which include measures specific to energy.

In the United States, the federal Department of Energy (DOE) is the lead for cybersecurity in the energy sector. DOE has facilitated the development of a series of industry-led roadmaps to provide a strategic framework to co-ordinate public and

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[4] https://cert.at/reports/report_2016_chap05/content.html.

[5] www.encs.eu.

[6] For example, the CERT Division of the Software Engineering Institute at Carnegie Mellon University (www.cert.org/about/) and the Cyber Security Centre at Warwick University (https://www2.warwick.ac.uk/fac/sci/wmg/research/csc/).

private initiatives for resilient energy delivery systems, most recently the 2011 *Roadmap to Achieve Energy Delivery Systems Cybersecurity* (DOE, 2011). In 2013, DOE launched a public-private partnership *Cybersecurity Risk Information Sharing Program* (CRISP) to provide electricity sector organisations with near-real-time cyber threat information and analysis.[7]

In addition, the US Federal Energy Regulatory Commission works jointly with Canada within the North American Electric Reliability Corporation (NERC) to set and maintain critical infrastructure protection standards.[8] NERC also operates the Electricity Information Sharing and Analysis Center – a secure forum for the sharing of cybersecurity threat information within the electricity sector. For example, NERC issued an alert and recommendations in February 2016 upon findings from the December 2015 cyber-attack in Ukraine.

In Europe, the 2016 Network Information Security Directive (NIS)[9] requires EU member states to adopt a national cybersecurity strategy.[10] NIS created a co-operation group and a computer emergency response team, and establishes security and notification requirements for operators of essential services and digital service providers. At EU level, proposals for a strengthened cyber resilience strategy were published by the European Commission in September 2017,[11] while detailed work on electric grid security codes is under way in the Smart Grids Task Force.[12]

The EU cybersecurity strategy is also closely linked to a wider critical infrastructure protection programme.[13] Under this framework, the German federal network regulator, Bundesnetzagentur, published a catalogue of minimum IT security standards in August 2015.[14] The Cyber Essentials Scheme in the United Kingdom plays a similar role, although its mandate is broader than the energy sector (HMG, 2016b). In France, the National Agency for the Security of Information Systems (Agence nationale de la securité des systèmes d'information, ANSSI) formulates and supervises cybersecurity

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[7] https://energy.gov/oe/energy-sector-cybersecurity-preparedness-0.

[8] www.nerc.com/pa/CI/Comp/Pages/default.aspx.

[9] Directive (EU) 2016/1148 of the European Parliament and of the Council of 6 July 2016 concerning measures for a high common level of security of network and information systems across the Union, http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016L1148&from=EN.

[10] At the time of writing, all EU countries except two have finished drafting their cybersecurity strategies. Fifteen out of the 26 strategies do not specifically mention the energy sector.

[11] https://ec.europa.eu/digital-single-market/en/policies/cybersecurity.

[12] https://ec.europa.eu/energy/en/topics/markets-and-consumers/smart-grids-and-meters/smart-grids-task-force.

[13] https://ec.europa.eu/home-affairs/sites/homeaffairs/files/what-we-do/policies/crisis-and-terrorism/critical-infrastructure/docs/swd_2013_318_on_epcip_en.pdf.

[14] Energy suppliers must appoint an IT security officer registered with the regulator, and they are obliged to introduce and certify an information security management system (ISMS), www.ids.de/en/news/article/newsletter-dezember-2015.html.

standards and regulations for "operators of vital importance." ANSSI also collects and provides information about incidents and cyber-attacks.

Japan adopted a cybersecurity framework law in 2014. This requires the government to establish clear responsibilities for operators of critical infrastructure and strengthens the role of the National Center of Incident Readiness and Strategy for Cybersecurity.[15] An updated cybersecurity strategy adopted in 2015 highlights the need for "a policy platform to build a common understanding on security measures required for the entire IoT system as well as for the individual components of IoT systems" (Government of Japan, 2015).

In March 2017, the Japan Electricity Information Sharing and Analysis Center (ISAC) was set up to share and analyse cyber-risk information and build capability in the electricity industry. Japan also specifically calls for strengthening international co-operation among ISAC groups and developing international rules and norms regarding cyberspace, as well as capacity building in other countries.[16]

Many countries also organise large-scale exercises to test emergency preparedness, providing an important opportunity to identify vulnerabilities and to strengthen public-private co-operation. Leading examples of country and regional cyber-attack preparedness include the following:

- NERC organises a biennial electricity grid exercise, GridEx, simulating both cyber and physical attacks. GridEx 2015 involved more than 300 organisations across North America, including industry, law enforcement, and government agencies (NERC, 2016a).
- The EU Agency for Network and Information Security has co-ordinated major cybersecurity exercises since 2010. The 2014 exercise included an energy infrastructure scenario in which several operators were severely impacted by a cyber-attack in the middle of a harsh winter. The exercise involved over 200 organisations (27 from the energy sector) from the 28 EU member countries. Among its objectives was to provide an opportunity to individual member states to evaluate their internal contingency plans and to explore the public affairs handling of large-scale cyber incidents. The 2016 exercise introduced a focus on the IoT, drones, cloud computing and ransomware (ENISA, 2017).

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[15] State of Japan, Cybersecurity Basic Act, No. 104 of 2014, www.shugiin.go.jp/internet/itdb_gian.nsf/html/gian/honbun/houan/g18601035.htm.

[16] The Initiative for Cyber Security Information-Sharing Partnership of Japan (J-CSIP) promotes information sharing in seven priority Special Interest Groups, including electricity, oil and gas industries.

- Various exercises are also held at national or regional level; in 2015, for example, Nordic countries organised an exercise on co-ordinated handling of a potential disruption in the regional power system.[17]

International efforts can also play a critical role in helping governments, companies and others to build up digital resilience. A variety of organisations are involved in this effort in one form or another, including the Group of Seven (G7), the IEA (see Box 6.2), the Organisation for Economic Co-operation and Development (OECD), and national security organisations such as the North Atlantic Treaty Organization (NATO). For example, work by the OECD Committee on Digital Economy, Policy Working Party on Security and Privacy in the Digital Economy includes a Recommendation on the Protection of Critical Information Infrastructures (OECD, 2008; currently being updated).

Ensuring that each international organisation focuses on its own comparative strengths, complements others' efforts, and establishes open lines of communication (as appropriate) will be critical. For example, the NATO Warsaw Summit in July 2016 highlighted a "need to enhance strategic awareness on energy security, including through sharing intelligence and through expanding our links with other international organisations such as the IEA" (NATO, 2016).

Box 6.2 IEA digital resilience efforts

Digital resilience is a growing challenge for the IEA family of countries and corporate partners. Identification of digital risks and appropriate resilience measures needs to be core to technology policy development and the design of various regulatory frameworks for energy markets. Governments and energy system operators need to work together proactively to manage the increasing complexity of risks and threats.

As the world's premier energy security organisation, the IEA stands ready to help its members by supporting efforts to strengthen digital resilience. Certain aspects of digital resilience are appropriate for IEA analysis and multi-party collaboration. These include: raising awareness; helping to establish the business case for utilities to become cyber-prepared; helping to mainstream digital resilience into a variety of government and company plans and strategies; and developing and sharing best practices and policies. Operational aspects of digital security, such as threat assessment and monitoring, and incident management and response, are sensitive matters of national security and outside of the scope of IEA analysis.

The IEA work on energy security raises awareness among countries on new digital risks within a wider context of planning for resilience over the short, medium and long term. The IEA conducts emergency response reviews of its members; these reviews investigate, among other topics,

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[17] NordBER meeting 9-10 September 2015 in Reykjavik, "Energy shortage: Coordinated handling of a potential disturbance in the Nordic power system".

whether members have robust national governance arrangements for internal co-ordination and information sharing on resilience to a wide variety of risks. In the future, these reviews will also include governance of digital resilience.

The IEA also organises emergency response exercises on a regular basis to test the preparedness of the IEA and its member countries to respond to oil, natural gas and electricity disruptions. These exercises expose participants to analysis conducted by the IEA Secretariat in assessing various disruption scenarios, which may include potential high-level impacts on energy markets resulting from a cyber-attack.

In a follow-up to this report, the IEA will undertake a more thorough overview of policies and practices on digital resilience among its members. This will then be used to develop best policy recommendations that can be applied in reviews and exercises.

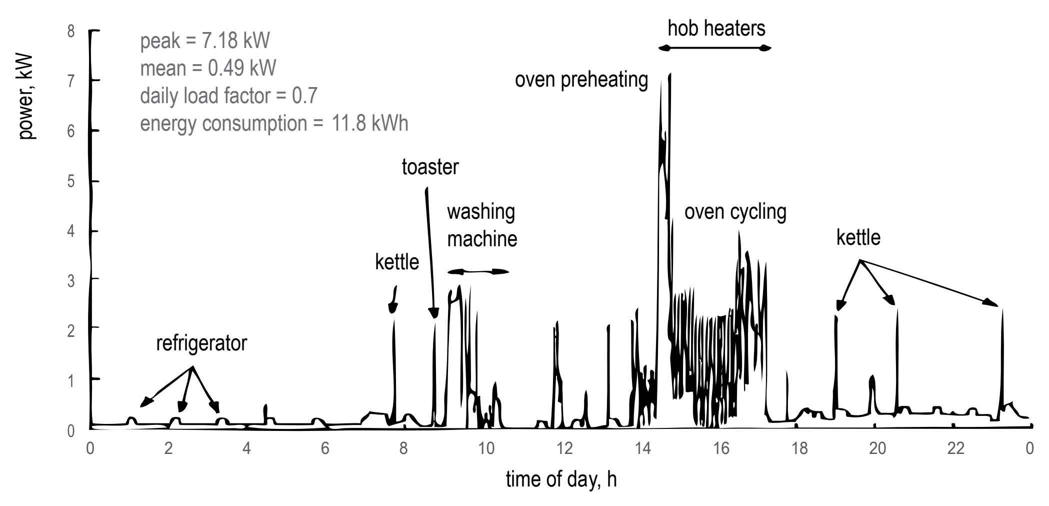
Data privacy and ownership

As in other sectors of the economy, the growing use of digital technologies in the energy sector raises questions about data privacy and ownership. Smart grids and demand response technologies rely on vast quantities of consumer-specific, real-time electricity usage data. In the case of active management by utilities or aggregators of behind-the-meter smart home appliances, this will include records of personal energy use events, such as heating water for a shower or opening a refrigerator, giving anyone who has access to those data a snapshot of householders' personal daily routines and activities (Figure 6.2).

How much information people are comfortable sharing with service providers, how confidentiality can best be protected, who owns this type of consumer-specific data (the customer/prosumer who generates it or the service provider who collects it), and who can use or share data and for what purposes, are becoming critical questions. Many household consumers want to protect their anonymity; they may worry that energy data could be linked to other personal information, such as health records, to create a profile or score. Such data could be used for commercial data mining that might expose them to intrusive targeted marketing techniques. This kind of detailed behind-the-meter energy data could also be used to find out when buildings are empty, and could be used for criminal activity (National Geographic News, 2012).

For industrial and commercial consumers, demand response infrastructure that tracks energy use might reveal information about business practices and operations that that might be considered as proprietary. Data breaches might impact the willingness of customers to use new services, something that operators that collect energy data – for example, utilities and energy management service providers – must protect against.

Figure 6.2 Behind-the-meter energy use data



Key message: Some energy consumers are concerned that detailed behind-the-meter data could reveal personal daily routines.

Notes: Data from the customer's side of the utility meter; h = hour; kW = kilowatt; kWh = kilowatt hour.

Source: Newborough and Augood (1999), "Demand-side management opportunities for the UK domestic sector" (reproduced courtesy of the Institution of Engineering and Technology).

At the same time, consumers and companies will sometimes want to share their energy data with third parties, for example to a marketplace for energy efficiency services. Utilities see opportunities to monetise energy use datasets, establishing a new source of revenues. Utilities in New York have proposed that regulators could allow a fee to be charged for making granular "value-added" data (such as aggregated customer usage information) available to local distributed energy resource (DER) providers.[18]

A key step to enabling equipment and devices to communicate and make decisions in digitalized energy and transport systems is to establish their interoperability (Box 6.3).

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[18] Joint Utilities, Supplemental Distributed System Implementation Plan, Case 16-M-0411, November 2016. "Data access is also important in the context of developing new market-based revenue streams that are tied to providing value-added services. One example of a potential value-added service is a data analysis service that makes available more granular and customized information to developers and other market participants. The Joint Utilities distinguish between basic data that is available at no incremental cost and value-added data that will be available for a fee. Examples of value-added system data may include forecasted load data, circuit voltage profiles, and power quality data. An example of value-added customer data is aggregated data."

Box 6.3 Interoperability and standardisation

Interoperability of different data formats, technologies and applications allows systems to function and interact with one another in a reliable, safe, secure and user-friendly manner. This smooth interface may require the alignment of physical, semantic and organisational elements. Routing protocols for distributed energy resources in smart grids are an example of the role of standard setting, and can help to enable the digitalization and automation of demand response.

The lack of interoperability of technology standards can be a barrier to the effective use of new technologies; overly narrow one-size-fits-all standards or standards that might prove burdensome or conflicting, conversely, could slow down innovation and technology deployment. Optimally, standardisation should build on synergies between the various players rather than lead to fragmentation of the market and duplication of efforts (OECD, 2017).*

The digital sector in particular is characterised by rapid development of technologies, and often technical solutions to interoperability are developed within fora and consortia (e.g. the Industrial Internet Consortium) rather than in formal standard-making bodies. But policy makers also have a role to play in encouraging or guiding sufficient standardisation so that consumers retain a wide market choice, and are not locked into using products that are only interoperable with other products from the same manufacturer or that are based on the same protocols (European Smart Grids Task Force, 2016).

The European Union is particularly active in standard setting, especially because of the impact that standards can have on the EU single market. A key participant in European work on standards for digital interoperability in energy is the European Committee for Standardization-European Committee for Electrotechnical Standardization (CEN-CENELEC), which brings together the national standardisation bodies of 34 European countries and includes as stakeholders industry, consumer rights representatives, trade unions and environmental groups. Recent areas of work by CEN-CENELEC include the development of standards for electricity and telecommunications networks, energy management systems, data formats for electronic invoicing, and for the proficiency levels to be reached in order to obtain professional qualifications in digital skills. Some of this work builds on legislation, while some anticipates future policy decisions by European governments. The European Union also participates in international standard setting, so that around 80% of CENELEC standards in electrotechnology are adoptions of international standards developed under parallel procedures in the International Electrotechnical Commission (CEN-CENELEC, 2017).

Regarding future challenges for interoperability in smart grids, an interesting resource is the roadmaps and frameworks issued by the National Institute of Standards and Technology (NIST) in the United States.

* Standard setting can also help to establish design priorities, as in the case of "(cyber)security by design".

Balancing privacy and other policy objectives

Policy makers are often caught in the middle of these privacy debates. Viewed from an overall systems perspective, policy makers might consider that there is a wide public interest in making aggregate data available publicly. For instance, such data could provide insights for urban planners or allow researchers to investigate aggregate efficiency opportunities that cannot be realised by individual consumers on their own. At the same time, policy makers must also take into account the privacy concerns of their constituents.

Some governments may seek arrangements to access data from private firms in exchange for access to markets, as was the case in a deal struck between the city of Boston and the ride-sharing company Uber. At the same time, policy makers are also increasingly concerned that the concentration of data collection and processing in the hands of a few large companies could have possible competition and anti-trust impacts. In this regard, the OECD is undertaking work on how data-driven network effects, reinforced by user feedback loops, and the great economies of scale associated with IT infrastructure may lead to situations of dominant market power (OECD, 2016a; The Economist, 2017).

Some possible solutions are technical. Data can be made anonymous by means of aggregation so that private information could not be attributed to a specific household. Another solution is to limit data granularity by adding a time lag. In Germany, the law on smart meter data allows transmission of household data only every 15 minutes; in France, 10 minutes is considered sufficient for the purpose of smart grid operations.[19]

Other solutions involve policy choices about how to balance different societal objectives. Policy makers wanting to encourage the development of demand response markets will need to strike an appropriate balance between consumers' privacy concerns, fostering innovation in demand response markets, and the operational needs of utilities.

A key question for policy makers is whether regulation should take an opt-in or an opt-out approach to customer authorisation. Opt-in programmes give maximum protection and require affirmative customer authorisation for certain data to be shared. Opt-out programmes, however, are more likely to favour mass participation in demand response markets.

Alternatively, customers could be given a range of confidentiality options. "Minimum" customers might choose only to participate in sufficient data collection to enable "core" smart grid operations, such as load balancing and price formation. "Maximum" customers might agree to detailed data being made available for marketing purposes to commercial energy efficiency providers, with the aim of learning about possible

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[19] Federal Republic of Germany, Messstellenbetriebsgesetz vom 29 August 2016; for France, see www.cnil.fr/fr. But such is the potential power of these data that time lags of three to six months for detailed data could still transform understanding of energy demand (see Chapter 7).

savings. One example of this approach is a voluntary code of conduct developed by the US DOE and the Federal Smart Grid Task Force in 2015, which distinguishes between primary-purpose use of data that can be "reasonably expected," and more extensive secondary-purpose data sharing that requires an opt-in consent (DOE, 2015).

While each jurisdiction is different and faces different opportunities, cultural context and circumstances, there are several real-world examples that may be useful to policy makers (Box 6.4).

Box 6.4 Examples of specific approaches to privacy regulation

- **California:** Since 2011, California has adopted some of the world's first rules specifically addressing smart meter data protection. State laws prohibit utilities from sharing or otherwise disclosing a customer's consumption data and patterns to a third party without the customer's prior consent. The law also requires utilities to provide security, including encryption for usage data gathered through smart meters or otherwise. In 2014 these provisions were extended to internet service providers, financial institutions and other businesses that might handle or receive smart meter data.*
- **South Korea:** From 2011 to 2015, South Korea adopted a set of strong general-purpose protections for personal information, specifying limits on data collection, use, outsourcing, disclosure, editing, searching, storage and destruction. The 2011 Smart Grid Construction and Utilization Promotion Act also emphasises data protection, requiring operators to obtain individual consent for the collection of personal data.**
- **European Union:** The General Data Protection Regulation (GDPR) was adopted in 2016 and came into full force in May 2018. It establishes an updated framework for personal data protection in the European Union. The GDPR requires data privacy and customer consent for any data collection or use to be designed into all business processes for products and services, including where foreign-based companies collect or process the data of EU residents. All data breaches must be reported to the relevant national authorities. A principle of "data portability" establishes a right to transfer personal data from one service provider to another. The GDPR means significant changes to business practices for many companies. Some of the implications for implementation in the energy sector have been analysed by the European electricity sector association Eurelectric (Eurelectric, 2016).
- **France:** In 2016, French legislation established the concept of "public interest data", enabling the government to request commercial entities to give access to data that they hold for the purpose of establishing public statistics.***

* California Civil Code, Division 3: Part 4: Obligations arising from particular transactions, and draft bill SB-356 on energy data transparency, currently in process of adoption by the legislature, http://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB356; see also, for example, California utility PG&E's smart meter data collection opt-out program, www.pge.com/en_US/residential/save-energy-money/analyze-your-usage/your-usage/view-and-share-your-data-with-smartmeter/smartmeter-updates/smart-meter-opt-out-program.page;
** Smart Grid Act 2011, 지능형전력망의 구축 및 이용촉진에 관한 법률/知能型電力網法;
*** Article 19 of Loi N° 2016-1321 du 7 octobre 2016 pour une République numérique.

In many cases, the legal frameworks in force today regarding privacy, consumer protection and electronic communications are not specifically designed for energy. Moreover, many of these general frameworks do not adequately establish up-to-date technical definitions. For example, is transmission of consumer energy usage data over the smart grid an "electronic communication", or should a smart meter network be classified as a remote computing device? Lack of clarity or robust protections could hinder participation in sharing digital energy information, and therefore limit overall system efficiency and possibly lead to a backlash from consumers.

As policy makers, regulators, companies and consumers grapple with these problems, they will need to consider implementing a number of actions, including:

- Physical, administrative and technical security measures to protect and, where possible, anonymise customer information.
- Procedures to maintain data quality and integrity, including means for consumers to access and correct any errors in stored personal data.
- Transparency about the purposes for which data will be collected and used, as well as clear limitations on their use.
- Provisions for consumers to give informed consent prior to any release of usage data, particularly to third parties.
- Provisions for consumers to choose to share their data with third parties when the release of such information is beneficial for them, or to freely transfer their data from one service provider to the next.

Economic disruption: Jobs and skills in an increasingly digitalized energy world

Throughout the broader global economy, digitalization is changing the nature of existing jobs, creating entirely new jobs and threatening job losses. There will no doubt be both winners and losers as a result of increasing digitalization, and policy makers must play a proactive role in preparing for an uncertain future.

Significant research is under way to explore the impact of digitalization across the broader economy, including the OECD's Going Digital project. This OECD project includes a number of cross-cutting initiatives as well as in-depth analysis of economic disruption, including further analysis of jobs and skills, and the potential societal impacts of job polarisation and income inequality. OECD reports during 2018-19 will put forward specific policy recommendations to help a range of policy makers to navigate and manage the digital transition.

Building on IEA analysis of the impact of investment on energy employment (IEA, 2017), a review of key energy sectors demonstrates the many – and varied – ways in which digital technologies can affect jobs in the energy sector.[20] Overall, digitalization is likely to lead to further efficiencies along the supply chain, but is less likely to replace still-sizeable labour needs for major engineering and construction activity related to physical infrastructure.

Workers supporting digital infrastructure will need specialised ICT skills, such as coding and cybersecurity, while across the energy sector, all workers will need generic ICT skills to operate digital technologies. Complementary "soft" skills such as leadership, communication and teamwork skills will also be required for the expanding number of opportunities for ICT-enabled collaborative work (OECD, 2016b).

While digitalization may lead to lower labour intensity across energy systems as a whole, the impacts of digitalization are highly sector-specific:

- In the life cycle of a power plant, digitalization has the greatest impact on equipment – its manufacturing, siting, and operation and maintenance – raising the productivity and reliability of the plant and therefore potentially reducing labour intensity. In thermal generation, digitalization may change the tasks of existing operation and maintenance, while creating new jobs in data science. In the renewables sector, the use of robots to clean solar panels and drones to monitor wind turbines could reduce the need for some employees.
- In upstream oil and gas, a large portion of employment is associated with initial field development. Digitalization and other innovations have helped to lower costs and raise productivity, although reductions in employment are difficult to disaggregate from the wider effects of the lower oil price environment. The widespread use of 3D seismic analysis has reduced drilling needs, but created new jobs in ICT and data science roles, which require very different skill sets and often are located in a different region than drilling operations.
- In energy efficiency of buildings, almost all jobs are upfront by nature (e.g. construction and refurbishment), that is, fewer jobs are associated with the operation of the energy-efficient equipment once it installed. That said, those working on the operations and maintenance of buildings may need additional skills to deal with new technologies through training and development, as the lack of new skills may be a barrier to energy efficiency.

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[20] Empirical studies of energy employment variously measure employment effects in up to three categories: Direct employment (construction workers and facility operators); Indirect employment (persons employed to produce inputs for the new facility, in manufacturing industry or service sectors); Induced employment (jobs generated by consumption as the wages earned in direct employment.

- In manufacturing, some jobs involve predictable, routine and repetitive physical tasks, putting them at a higher risk of automation. While the use of robotics and automation has historically yielded substantial operational benefits (including safety and productivity), the deployment of such technologies requires careful consideration of its impact on jobs, in particular job loss for low-skilled workers. At the same time, the increased use of data, sensors and 3D printing could provide new job opportunities in advanced manufacturing.
- In transport, enhanced connectivity has created new employment opportunities on ride-hailing app platforms, but fully autonomous cars could threaten to eliminate the jobs of substantial numbers of human drivers (Box 6.5).

Box 6.5 Automation and jobs: Focus on autonomous cars and trucks

The potential impact of automation on jobs has been the focus of a series of studies from academia, international organisations and consulting firms over the past five years (Arntz, Gregory and Zierahn, 2016; Bughin et al., 2017; Frey and Osborne, 2013; PWC, 2017). This work highlights that jobs composed of a high share of automatable tasks – such as those involving predictable, routine and repetitive physical activities, and the collection and processing of data – are at higher risk of automation than less routine activities. In the energy sector, significant attention has focused on the potential impact of autonomous cars on jobs.

Fully autonomous cars and trucks* could threaten the livelihood of commercial drivers around the world. The United States alone has around 3.5 million truck drivers, 665 000 bus drivers, 230 000 taxi drivers and at least 500 000 active drivers with ride-sharing companies Uber and Lyft. Digitalization could therefore have immense impacts on jobs even in this single sector, especially if technological change and adoption is rapid.

Fears of widespread job losses, however, need to be tempered with a closer look at the labour market and demographics, as well as technical feasibility, public acceptance and the regulatory environment. For example, the US trucking industry already has a shortage of around 50 000 drivers, growing to 800 000 by 2030 (ITF, 2017), and the turnover rate of drivers is very high due to the nature of the work (long working hours, extended periods of time away from home, safety and risk issues). Moderate to high levels of automation in trucks, especially over the near term, could be deployed to complement human drivers, helping bridge the gap of driver shortages and job creation. But even with fully autonomous or connected platooning trucks on highways, human drivers may be needed for last-mile, in-city driving where decision-making is more complex.

The pace and extent of automation and its impacts on jobs in the energy system remain highly uncertain, and will depend on a number factors that will vary across regional and sectoral contexts (Bughin et al., 2017). Facing an uncertain future, governments must prepare for a variety of scenarios, including a rapid transition to fully autonomous cars and trucks. Detailed analysis and key policy recommendations specific to potential labour impacts resulting from autonomous trucks are available in a recent report released by the International Transport Forum: *Managing the Transition to Driverless Road Freight Transport* (ITF, 2017).

* Autonomous driving technologies and other digitalization trends in transport are discussed in Chapter 2.

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Chapter 7

Policy

Highlights

- Technological advances and falling costs are driving the digital transformation of energy systems, but policy and market design are critical to help steer the digital transformation onto a secure and sustainable path.
- Fully harnessing digital tools can help achieve specific policy objectives. For example, enabling policy regimes and new business models could assist in providing electricity to the 1.1 billion people who still lack access to it. New digital tools can also promote sustainability, for example the use of satellites to monitor and verify greenhouse gas emissions, and cutting-edge tools to track air pollution at the neighbourhood level.
- Policy-making processes can also benefit from more timely and sophisticated collection and publication of key energy data. Emerging low-cost digital tools, such as online registries, web-crawled data and quick response codes can lead to more targeted and responsive programmes.
- While there is no simple roadmap for what an increasingly digitalized energy world will look like in the future, this chapter recommends ten no-regrets policy actions that governments can take to prepare.

Technological advances and falling costs are driving the digital transformation of energy systems, but policy and market design are critical to help steer the digital transformation onto a secure and sustainable path. This chapter considers how digitalization can help achieve specific policy objectives, for example, energy access, sustainability and energy security. It then examines how digital tools can improve the policy-making process itself, and summarises lessons learned from the entire report about implementing well-considered, integrated policy frameworks. Finally, this chapter – and this report – conclude with a series of no-regrets recommendations to help policy makers best navigate the inherently undefinable future of increasing digitalization in energy.

Promoting energy access, sustainability and security

As discussed throughout this report, while the digitalization of energy may not be a policy end in itself, it can be a means to help achieve a variety of energy policy objectives. These include increased productivity and efficiency, improved safety, enhanced revenue collection, and accelerating the pace of innovation. Three specific policy objectives are now explored in greater depth: energy access, sustainability, and security.

Energy access

In sub-Saharan Africa and other developing countries, decentralised energy sources, such as off-grid solutions, can be an effective and rapid option to bring electricity access to the population. Receptive policy environments and new business models are tapping the opportunities presented by digital connectivity, including smart payments and mobile phones.

Access to modern and reliable forms of energy is a critical enabler of human and economic development. According to the latest analysis from *Energy Access Outlook: from Poverty to Prosperity*,[1] around 1.1 billion people still lack access to electricity, although momentum is building towards the Sustainable Development Goal of ensuring access to affordable, reliable, sustainable and modern energy for all by 2030. Digitalization, especially when guided by policy, can help accelerate the pace.

In certain countries in sub-Saharan Africa, mobile phones are more prevalent in homes than electricity, and mobile phones and the associated infrastructure, such as cell towers, may be able to help facilitate access to a large array of energy services (Figure 7.1). Companies such as BBOXX, M-Kopa, Off-Grid Electric and Mobisol have developed new business models for the provision of energy access that target areas covered by mobile networks but not electricity grids. There are two main business models that utilise pay-as-you-go (PAYG) mobile financing and payment schemes to provide access to renewable off-grid systems:

- Rent-to-own, where consumers can use their phones to pay a fixed amount up-front for an off-grid device, such as a solar home system, and then pay for the rest of it in affordable instalments.
- Solar-as-a-service, where consumers pay a regular fee for the energy service, but never actually own the device.

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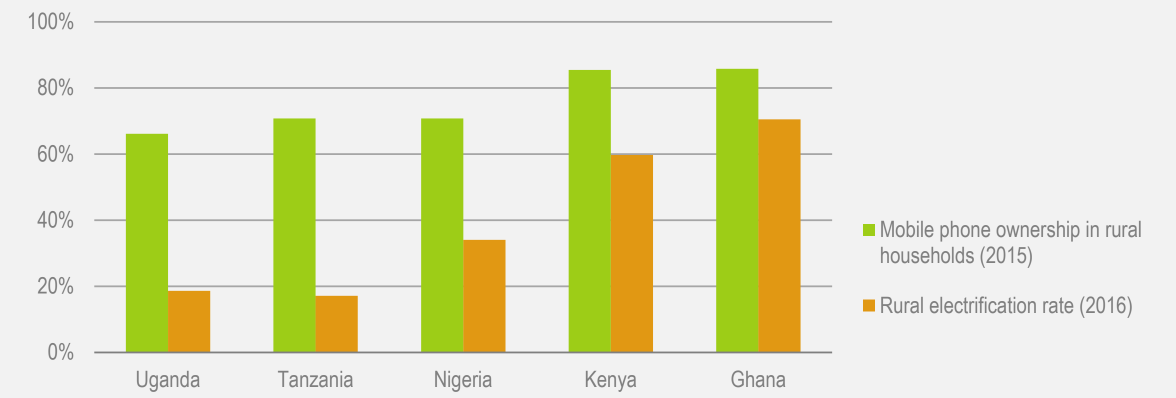
[1] For more on energy access, see *Energy Access Outlook: from Poverty to Prosperity* (IEA, 2017), part of the *World Energy Outlook* series, at www.iea.org/energyaccess.

Figure 7.1 Mobile phone ownership and electricity access in selected sub-Saharan African countries



Key message: Mobile phones provide an opportunity to accelerate electricity access.

Sources: IEA (2017), *Energy Access Outlook 2017: From Poverty to Prosperity*; USAID (2017), STATcompiler.

Crucially, mobile networks enable companies to remotely monitor products and collect usage data, disable a device when a customer misses a payment, and turn the device back on when the payment has been made. The availability of well-established telecoms, widely used mobile money systems and relatively friendly business markets has been a strong driver of the location of these businesses. At the end of 2016, East Africa accounted for 55% of the registered mobile money accounts in sub-Saharan Africa, followed by West Africa at around 30% (GSMA, 2017a). As a result, PAYG energy service business models are most active in four countries: Kenya (where the PAYG model started, see Table 7.1), Tanzania, Rwanda and Uganda. Other markets are opening up, however, especially in Ethiopia, Ghana, and Nigeria.

Table 7.1 Illustrative electricity offers from PAYG market leaders in Kenya

Company	Products offered	Cost (USD)
M-KOPA	8 W solar home system (4 x 1W LED, flashlight, radio)	Upfront deposit: USD 33.50 Per day: USD 0.48 (for 365 days) Total: USD 208
BBOXX	15 W solar home system (4 x 1W LED, radio)	Upfront deposit: USD 9 Per month: USD 9 (for 36 months) Total: USD 336
	50 W solar home system (4 x 1W LED, radio, LED TV)	Upfront deposit: USD 21 Per month: USD 21 (for 36 months) Total: USD 761

Notes: Values as of 31 January 2016 and are described here in USD, although customers pay in their local currency; LED = light-emitting diode; W = watt.

Source: Adapted from Sanyal et al. (2016)

Paired with PAYG financing, solar home systems (consisting of a solar module and a battery) are the most popular and successful off-grid solutions, often substituting for kerosene and diesel. On average, these systems provide customers with basic energy access at Tier 1 and Tier 2 (GSMA, 2016a and 2016b).[2]

Increasingly, these systems are bundled with energy-efficient appliances, which can offer higher levels of modern energy services at lower cost and are able to be supported by the off-grid system. Over the past four years, over USD 360 million has been invested in PAYG solar (GSMA, 2017a and 2017b). Despite the investment, to date it remains a relatively small market.

The emergence of this new model does not need to be in direct competition with existing access efforts, especially as it represents an inflow of additional capital from private investors. Some governments are entering into partnerships with companies to distribute solar home systems, such as the partnership recently forged between the Republic of Togo and BBOXX, where the goal is to distribute over 300 000 solar home systems in Togo over the next five years (ESI Africa, 2017). In some cases, digitally enabled access models are causing some existing players, such as utilities, to rethink their role and approaches to providing access. Some utilities are exploring how they might use the electricity provided to telecom towers, which provide the load and security of payment necessary to justify greater investment, as an anchor for the electrification of nearby households. In this way, beyond just the use of information and communications technology (ICT) for solar home systems, the potential exists for a mutually beneficial expansion of ICT-related infrastructure and electricity access.

In addition, increasing attention has focused on how mobile technology beyond just digital payment, such as cloud-based metering and software platforms, can also be paired with larger systems such as minigrids. These grids could offer customers additional services and support commercial activities and agriculture, contributing to economic growth.

There are challenges, however, especially related to financing and how to scale up the products offered by PAYG providers to offer a higher level of energy services to consumers. Policy uncertainty and a lack of transparency can create the perception of risk, discouraging investment and halting the progress of decentralised systems and non-state actors. Co-ordinated planning is important and should take account of approaches to upgrading existing systems and integrating decentralised systems into the grid when or if it arrives. Additionally, while some of these new business models are competitive without aid or subsidy, they have much greater effect if government policies set appropriate tariff structures and simplify the permitting and licensing

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[2] Tier 1 access means enough energy for a light and phone charging. Tier 2 can run general lighting, a TV and a fan.

processes. Fundamentally, for these new models to be effective, they must offer services that are affordable to consumers. Rural customers may pay more for their electricity than urban users or be unable to use higher-powered appliances, because the unit cost of electricity is typically higher for decentralised systems than a grid tariff unless the government decides in favour of cross-subsidisation to even costs out, as has been the case historically.

Environmental sustainability

This report identifies a number of ways in which digitalization can help policy makers to improve energy systems' environmental impact. These include energy use improvements in transport, buildings and industry that can help reduce air pollution and greenhouse gas emissions. For example, in industry – a sector responsible for 24% of total carbon dioxide (CO_2) emissions in 2014 – there is clear value in digitalization to improve the efficiency of energy and materials use (Chapter 2). Drones and data analysis can improve the detection and measurement of methane emissions, at low cost, in oil and gas operations (Chapter 3). Digitalization can help better integrate variable renewables such as wind and solar, highlighting the potential to avoid 240 million tonnes of CO_2 emissions cumulatively to 2040 in the European Union alone (Chapter 4). Meanwhile ICT companies are playing a strong role in renewables investment, including some companies committing to 100% renewable energy procurement goals (Chapter 5).

However, in certain circumstances digitalization could actually increase energy use and emissions. For example, self-driving vehicles might encourage increased travel. Digitally enabled efficiency gains will not only lower the cost of wind generation, but also coal. Smart controls and connected devices consume energy in order to maintain connectivity, even when on standby. Connected devices also have energy and environmental impacts from manufacture and disposal (e.g. electronic waste). It is thus important that policy makers bear in mind that digitalization's impact may not always align with environmental protection and that well-thought-through policies will need to take all of these dynamics into account.

Specific technologies that are critical for sustainability might also receive a significant boost from digitalization. Take the ability of carbon capture and storage (CCS) to reduce CO_2 emissions from power and industry. Each element in the CCS value chain could significantly benefit from advances in digital technologies (Box 7.1).

Wide scope also exists for more creative use of digital technologies, both by companies and policy makers, to help promote environmental sustainability. For example, many cities measure air pollution using static monitoring stations, but high costs can limit deployment. Pilot projects are extending this network into the Internet of Things (IoT) by means of additional sensors added to vehicles. Google even has a new initiative to track air pollution in its Streetview map.

Box 7.1 Digitalization and CCS

Digital technology applications for CO_2 capture are similar in nature and benefit to digitalization in industry and power generation. Specifically, optimisation of control processes through automation and enhanced data collection and analytics are likely to reduce overall costs. Digitalization can be increasingly important in the future when CO_2 emissions from smaller and more dilute sources will need to be captured and stored.

Digitalization of CO_2 transport and storage has been evolving along the same lines as the digitalization of upstream oil and gas (see Chapter 3). In fact, much of the digital transformation and innovation from the oil and gas industry appears to be transferable to CO_2 storage assessment and development. As in the oil and gas industry, the nascent CO_2 storage industry will be dealing with large volumes of time-series information/data captured from instruments that monitor and control plant processes. CCS will also face similar "big data" challenges as oil and gas operations, with both structured and unstructured data for assets spread over wide geographies.

Future CO_2 storage projects should be able to benefit from key technology innovations that are revolutionising the oil and gas industry (Managi et al, 2004, 2005). Such technologies include 3D seismic (Bohi, 1999) as well as smart drilling and other developments related to directional, multi-stage hydraulic fracturing and unconventional gas resources (Wood Mackenzie, 2014).

It is also necessary to integrate multi-dimensional and multi-disciplinary models and tools to understand the performance of reservoirs where CO_2 is injected and assess impacts on other resources and the environment over large areas. Real-time leakage detection and CO_2 monitoring using state-of-the-art technologies over different domains (subsurface, surface and atmospheric) and over time (prior to, during and post-injection) will be essential to assure both the public and regulators that CO_2 storage is safe, to estimate how much CO_2 is stored and to minimise risks of leakage.

Another example will be the use of drones (see Box 2.1) to monitor remotely the CO_2 storage sites, both offshore (www.stemm-ccs.eu/) and onshore. Technology could improve safety with unmanned CO_2 injection at offshore platforms, which could be operated remotely thanks to smart sensors and controls.

The world's largest supercomputer is being used by digital energy company Envision Energy in China to design and optimise sites for wind farms.[3] In the solar sector, GTM Research's Solar Data Hub tracks and forecasts solar installation markets across the United States.[4] And start-up company BioCarbon Engineering is using drones to plant

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[3] www.envision-energy.com/2016/10/18/envision-energy-launches-energy-analytics-platform-ensight/.

[4] www2.greentechmedia.com/solardatahub.

trees by firing up to 100 000 germinating seed pods per day into the ground from the air in an effort it calls “industrial-scale reforestation” (ABC News, 2017; WEF, 2017).

Another creative example of how digital technologies can advance sustainability policy objectives is work by national space agencies to improve the monitoring, reporting and verification of greenhouse gas emissions. More precise accounting is critical for verification schemes and towards ensuring integrity in carbon certification schemes such as carbon markets.

Today, such accounting is usually calculated using data on fossil fuel consumption, land-use, and/or economic trends. An alternative method is being pioneered by the Japan Aerospace Exploration Agency and NASA, using satellites that track CO_2 and methane from space by measuring concentrations of gases in a column of air, combined with results from a network of ground-based monitoring stations (Kornei, 2017).

The technology is complex and satellite launches are expensive and difficult to schedule, but by 2030 several satellites are expected to be operational, forming a co-ordinated fleet of monitoring stations shared by several space agencies. This effort builds on a joint declaration by space agencies in 2015 that “satellite observations are the key element of a global measuring system aimed at verifying the reality of commitments taken in line with the United Nations Framework Convention on Climate Change” (International Academy of Astronautics, 2015).

Both the United Nations and the World Bank have supported programmes exploring the potential of big data to provide new insights in monitoring, analysing and adapting to climate change. The UN initiative “Data for Climate Action,” launched in March 2017, challenges data-rich organisations, both public and private, to make large amounts of data available for free. Scientists, researchers and entrepreneurs, in turn, could then use these data flows to identify novel insights and means to influence human behaviour and its effect on climate change.

Policy makers should be aware of these types of new digitally enabled opportunities to promote sustainability, including more cutting-edge options.[5] This, in turn, will help policy makers to be able to implement more cost-effective policies, including additional public-private partnerships.

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[5] See also recent reports from the Global e-Sustainability Initiative (GeSI), which highlight opportunities from the energy sector and beyond, e.g. SMARTer2030: http://smarter2030.gesi.org/.

Energy security

While digitalization can increase cybersecurity risks (see Chapter 6), it can also bring positive security benefits. For example, among the supply-side effects of digitalization (Chapter 3) are improvements in the management of energy infrastructure maintenance. Sensors and near real-time analytics are being used to monitor and predict early-stage problems with individual items of equipment before a mechanical failure can interrupt operations. In this way, digitalization can help to reduce unplanned outages. Close monitoring of equipment can also help to spot human error and can quickly identify the exact location of damage due to external factors such as extreme weather.

Other digitalization elements that can help energy security are on the demand side (Chapter 2). Energy saving has underpinned energy security efforts since the 1970s, and digitalization offers a significant chance to further strengthen these efforts, notably in residential and commercial buildings, where a 10% reduction in total energy demand to 2040 could be achieved by means of smart controls on heating and cooling, lighting, and appliances. Better matching of energy demand to supply fluctuations by means of smart demand response also improves energy security, and is of increasing importance as electricity systems integrate larger shares of variable wind and solar (Chapter 4).

Digital tools to improve the policy-making process

Digitalization is not only a powerful tool to achieve a myriad of policy objectives, it can also help improve the policy-making process itself. This section discusses the impact of digitalization on energy statistics, followed by specific examples of how new digital tools can assist policy makers with standards for energy-efficient appliances.

Better energy statistics

Collecting and harnessing digital data (Box 7.2) has the potential to revolutionise our understanding of energy and shed new and vital light on how and why energy is used. With access to digital data and new methods for collecting and combining data, the quality, timeliness and availability of energy data can be transformed. This, in turn, can help improve the decision-making process of policy makers, companies and other actors.

Take the example of electricity production and consumption. If power generators collect real-time information in a digital form, potentially this could be supplied, under the right conditions, to official energy statistical institutions. This could help make possible the ability to have near real-time official generation and fuel input data.[6]

Box 7.2 Types of digital data

Data is a widely used term with many meanings. In the context of digitalization, it is worth considering three interlinked but separate definitions:

- **Statistics** are facts such as a country's annual energy balance, or more formally, "numerical statements of facts in any department of inquiry placed in relation to each other."*
- **Structured data** are organised large datasets, usually generated by state administrations, for example, information about feed-in-tariffs or energy audits. Structured data can also come from the energy industry, for example from electricity meter readings.
- **Big data** are large amounts of data gathered from a range of diverse sources, often in near real time. Because the data may be collected through business or control processes that have not been specifically designed for data analysis, ICT consultancy Gartner defines big data as "high volume, high velocity, and/or high variety information assets that require new forms of processing to enable enhanced decision making, insight discovery and process optimization."

Note: * Lyon Bowley, Sir Arthur (1915), *An Elementary Manual of Statistics*.

Digital data can also revolutionise an evolving process known as "data fusion", in which datasets are created which are far more powerful than a simple sum of their parts. Currently there are two main trends in data fusion with relevance to energy analysis: geographical information systems (GIS) and data aggregation. GIS allows different data to be combined as layers into a single map.[7] The map can be used to display average wind speeds at different heights together with solar radiation, the plan of the electricity grid, transport infrastructure, cadastre information, and protected areas. Combining these data into a single map means that the evaluation of a potential new energy project takes much less time, with very precise results, facilitating investment and decreasing risks.

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[6] However, this supply-side data would still be insufficient to track electricity demand trends, as data from grid operators and electricity retailers does not capture energy use by self-consumers – such as households which have solar photovoltaic (PV) panels or batteries installed behind-the-meter (see Chapter 4). Current data collection procedures need to be adjusted to be able to cover this market segment.

[7] Examples of energy-related GIS include: the Swiss Confederation Geocatalog (https://map.geo.admin.ch); the Australia Renewable Energy Mapping Infrastructure (AREMI, http://nationalmap.gov.au/renewables/); the Netherlands National Energy Atlas (www.nationaleenergieatlas.nl/en/kaarten); Natural Resources Canada's GeoApp (http://geoappext.nrcan.gc.ca/GeoCanViz/map/nacei-cnaie/en/index.html); Indonesia's ESDM One Map (http://geoportal.esdm.go.id/monaresia/home/); and the International Renewable Energy Agency's Global Atlas (IRENA, https://irena.masdar.ac.ae/gallery/#gallery).

Data aggregation, as the name suggests, aims to merge and manage different data sources and use them to provide an enhanced understanding of the energy system. One example is work in the United Kingdom to combine data for local areas about annual consumption of electricity and/or gas with information on building stocks (type of buildings, floor area, age of buildings), energy audits, and socio-economic indicators. The resulting analysis can both be commercially useful and help understand the impact and targeting of energy efficiency policies, as shown by the UK National Energy Efficiency Data framework (NEED).[8] A second example are data hubs that are being established in the Nordic countries with the objective of enhancing competition in electricity retail markets by bringing all data to one access point in order to make supplier switching and other market processes easier for consumers and other market players. Denmark's electricity grid operator, EnergiNet.dk, is currently securely storing anonymised highly granular near real-time data on their Energi Data Service. This is then made available as aggregated open data on electricity consumption, production by source, trade, CO_2 emissions, transmission line capacity and prices on wholesale markets with the goal of supporting new product development and statistical analysis.[9]

An essential part of any data fusion is a rigorous validation process, which in turn generates high-quality data for further use. Datasets created through the integration of different sources of data need to be repeatable, and statistics of this sort require metadata to explain how they have been constructed and where there is uncertainty. Attention to the representativeness and completeness of data remains vital.

The opportunities provided by digitalization to improve energy statistics can only be realised if policy makers and industry enable access to these new sources of data. Much work still needs to be done to develop the guidelines and mechanisms that will allow this (Masanet et al., 2017). Recent policy papers from the European Commission provide a good overview of key issues and some possible ways forward (European Commission, 2013; 2017a; 2017b).

Data on energy efficiency standards for appliances

Minimum energy performance standards for appliances, buildings and vehicles have proven to be among the most cost-effective measures used by governments around the world to improve energy efficiency. Yet these standards are sometimes less effective than they might be because of information asymmetries between manufacturers and regulators, as well as a lack of effective compliance regimes.

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[8] www.gov.uk/government/collections/national-energy-efficiency-data-need-framework.

[9] www.energidataservice.dk/.

Three low-cost digital technologies and techniques can significantly improve data collection and analysis about appliance energy performance, providing better information to consumers and greatly improving the policy-making process:

- **Online registration systems** are web-based facilities where the manufacturers or importers of equipment and appliances register eligible products with a regulatory authority before they can be sold in a market. Typically, registries require the submission of technical documentation to demonstrate product compliance with programme requirements. This database also allows the regulator to track changes in the market over time. Overall, registration systems can facilitate programme development, reduce the costs and resources needed to develop compliance mechanisms, provide a more streamlined and transparent system for manufacturers to interface with, and provide information that can help consumers make informed energy-efficient purchasing decisions. A number of countries have successfully implemented these online systems, including Australia, Brazil, Canada, the People's Republic of China (hereafter, "China"), India, Japan, Saudi Arabia, Thailand, New Zealand, Viet Nam and the United States.
- **Web crawling** (also known as web harvesting or web scraping) is a technique that uses search algorithms to automatically collect information from websites. Crawling can be used to collect online data on sales, prices, efficiency levels and types of products. Easy and cheap access to this data can be helpful to policy makers as they develop standards or evaluate the impact of energy labelling programmes. Swedish and US policy makers have achieved promising results when compared to traditional forms of market research. This is still a new technique, but web crawl data is becoming increasingly relevant as more appliances and equipment are sold online. The sharing of international knowledge and experience on web crawling, as the technology and methodologies develop further, would be a valuable exercise for policy makers worldwide.
- **Quick response (QR) codes** are a type of machine-readable optical label, resembling a two-dimensional barcode (Figure 7.2). The code contains information about the item to which it is attached. Applications include product tracking, identification, document management, and general marketing. QR codes enable information to be accessed in a consistent format. Their use improves the quality of registration systems. For example, imported appliances and equipment can be easily checked by customs officials by simply scanning labels, so that non-compliant manufacturers are easily detected when cross-checked against the registration database.

Figure 7.2 Example of a QR code on an appliance energy efficiency label in China

Key message: QR codes contain an efficient way to access additional information about the labelled item.

Source: China National Institute of Standardization (2015). *QR Codes for Appliances and Equipment – Enabling Access to Information and Facilitating Compliance*.

China is at the forefront of using new technologies for managing mandatory energy performance standards and labelling programmes. In particular, China has led the way in using QR codes to guide consumers to information that can support energy efficient purchasing decisions.

Observing that ordinary (non-digital) energy labels were having a limited impact on consumers, who tend to rely on retailers to advise on purchase decisions, the China National Institute of Standardization in 2016 introduced QR codes on 16 types of appliances.[10] These QR codes allow consumers to easily access relevant information via smart phone apps. The information available is updated daily based on the product registry, and includes comparisons of different appliance prices and running costs, manuals, repair options and end-of-life recycling options. Additionally, the scannable codes are expected to enhance compliance checks without needing large numbers of technical experts; local compliance authorities can see whether a product or manufacturer has performed badly or well in tests in other parts of the country.

QR codes are a good fit for China, where about 1.2 billion people have access to a mobile phone, of which more than half are smartphones with some form of scanning capability. In addition, QR codes are not patented, are easy to use and low cost. To

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[10] China National Institute of Standardization, 2017. *Best Practice of QR Code Application in China Energy Label*. Presentation by Dr. Yujuan Xia. Resources and Environment Branch. CNIS.

date, more than 4 000 appliance models have QR codes and in a nine-month period there have been 85 million scans.[11]

There is a growing risk that different countries might opt to design their own different QR code protocols. International collaboration to develop common data requirements or a QR code protocol would enable wider use and, in the future, international adoption by regulators and manufacturers.

Policy frameworks and market design

In many parts of the energy system, digitalization can facilitate positive change, but only if policy makers undertake efforts to understand, channel and harness digitalization's impacts and to minimise its risks. It should first be acknowledged that policy makers have different starting points – country by country and jurisdiction by jurisdiction – with respect to energy resources, digital and energy infrastructure, and market designs. Furthermore, certain countries have already adopted general policy goals seeking rapid digitalization of their economies and societies as a whole. The Singapore Smart Nation Vision can be viewed as a useful case study of a holistic digitalization strategy which encompasses energy and transport (Box 7.3), although this specific model may not be replicable or suitable in other countries. Other leaders in e-government include Estonia.

A key common theme emerging from this report is that many potential benefits of digitalization need policy support and frameworks in order to be fully realised. Transport is a key example. Smart, connected EVs and shared mobility could potentially transform cities, but a host of technical, legal, regulatory and other policy-related hurdles first need to be overcome (see Chapter 3, and in particular, Figure 3.1).

Similarly, as Chapter 4 discusses, digitalization is contributing to a complex transition in the structure of electricity systems and in business models. Here also, governments may want to consider how far standard-setting (see Box 6.3), market design and regulatory frameworks can help to shape the process of change toward preferred outcomes. For example, digitalization of grids might require a revision of the rate-basing rules to facilitate ICT investment and purchase of software services on an equal basis with copper-wire investment. Digitalization of utility companies might be supported using a range of measures, including regulatory pilot schemes, subsidies for demonstration projects and standard-setting.

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[11] China National Institute of Standardization, Personal communication in 2017.

Box 7.3 Singapore's Smart Nation Vision

Launched in 2014, Singapore's Smart Nation Vision aims to use digital technology to make Singapore "the world's first smart nation". While Singapore differs in many ways from other governments – including the fact that Singapore's status as both a city and a country allows its government to bring to bear a full range of both municipal and national policy levers – its integrated efforts offer an interesting case study and raise many policy issues other governments may face more of in the future.

Singapore's digitalization efforts focus on a range of infrastructure, regulation and innovation support:

- Singapore has invested heavily in a robust digital backbone, including a high-speed broadband network to improve connectivity rates. Singapore has constructed a common platform, joining up various sensors distributed across the island with a data-sharing gateway and video and data analytics capabilities, allowing real-time data to be quickly collected and processed for analysis, incident response and policy making.
- To facilitate interoperability of digital devices, Singapore is working to develop standards for network system architecture, communication and security protocols for sensors and the IoT. In the financial sector, Singapore has introduced a regulatory sandbox to allow fintech solutions and business models to be tested outside existing regulations for a limited duration.
- To build up human resource capabilities in data analytics and cybersecurity, the Singapore government is training 10 000 public servants in data science, while allowing military service conscripts to serve in cybersecurity functions, learning skills that they can carry over to their future careers.
- Singapore has committed approximately USD 14 billion in funds through to 2020 to support private- and public-sector R&D, predominantly in developing technological and digital capabilities and sustainable urban solutions.
- More public data and maps are being made available to the private sector. For example, real-time public transport data available online were used to create "Bus Uncle", a Facebook Messenger chatbot that tells the waiting time for the next bus in the distinct local creole Singlish.

Singapore's integrated approach can be particularly seen in the multitude of efforts undertaken in energy and transport. Singapore is pioneering advanced urban congestion pricing with the introduction of a global navigation satellite system, allowing more flexibility to shift charges and applicable zones to respond to changes in traffic flow, and better refinement in charging for exact distances travelled on congested roads. An initial pilot project co-ordinated by various government agencies helped assess usage patterns of electric vehicles (EVs), different charging technologies and their impact on the grid, and cybersecurity concerns. It culminated in new larger-scale pilots for EV car-sharing and taxis, and hybrid and electric buses, testing out viable business models. Various autonomous vehicle testbeds are being explored and deployed, ranging from on-demand cars and buses, to truck platoons, to multi-purpose vehicles for road cleaning and refuse collection.

Likewise, digitalization can technically achieve significant gains in demand response, providing useful flexibility as well as energy savings. However, market reforms may be needed in order to provide the incentive for this to happen. For example, solar PV-with-battery prosumers could be useful participants in demand response and grid balancing at local level. But if charging and discharging batteries into the grid entails large tariffs or is taxed at each transaction, then prosumers will not to want to join in demand response, and will prefer to keep the energy that they generate and store for use behind-the-meter in their own buildings.

Meanwhile, regulators will need to be alert to the impact of rapidly increasing volumes of automated transactions as these are carried out within grids, putting pressure on physical system controls (Vasconcelos, 2017). Decisions about these issues will also have implications for the emergence of new business models in the energy sector.

Digitalization has also already resulted in large upheavals in many sectors and markets (see Chapters 1 and 6). In energy, some uses of digital technologies are long-standing – for example, mainframe computing in oil and gas and electric utilities' operations. Other uses of ICT deployed at scale more recently have uncertain impacts.

Consequently, flexibility in policy frameworks will be needed to accommodate hard-to-predict future developments. With the enormous speed of change in business models and the way services are provided, governments with overly rigid frameworks may risk being slow to react to, and to take advantage of, the opportunities that digitalization offers.

Chapter 6 has also highlighted how digitalization carries a number of potential risks as well, in particular digital security, privacy, and changes in jobs and skills. Further challenges will certainly emerge. Balancing an open approach – open data, openness to new market entrants – with the management of these issues will require both foresight and collaboration with experts from beyond the energy sector.

No-regrets policy recommendations

Based on the analysis presented throughout this report, a preliminary set of no-regrets recommendations has been drawn up to help policy makers navigate the opportunities and challenges brought about by greater digitalization in the energy sector. This list is not intended to be exhaustive or definitive, and recognises that national circumstances and contexts vary between countries.[12] It is hoped it will foster further discussion among governments, companies and other stakeholders.

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[12] For instance, in energy resources and infrastructure; digital readiness, and economic development.

Governments should:

- **Build expertise.** Energy policy makers need to make sure they are well-informed about the latest developments in the digital world, its nomenclature, trends, and ability to impact a variety of energy systems (both in the near and longer term). A major part of this endeavour consists of ensuring that energy policy makers have access to staff with digital expertise. Education policies and technical training to ensure an adequate pool of relevant expertise for both the private and public sectors will also be critical. Conferences, workshops and exercises can also help.
- **Ensure appropriate access to data.** Opportunities provided by digitalization to improve energy statistics can only be realised with access to data. For example, these could include: electricity consumption data at a high level of detail in both space and time; information on installed distributed energy resources; and data about energy infrastructure. Ensuring timely and robust, verifiable and secure access to the necessary data, from business and across government, while protecting privacy, is critical. Policy makers should consider how guidelines and mechanisms can enable sharing of data.
- **Build flexibility into policies.** While energy infrastructure can be expected to last 50 years or more in many instances, software, applications, and even ICT hardware turns over quickly. As policy makers design a range of energy policies, they should ensure appropriate flexibility to deal with new developments in digital and communication technologies, while these continue to rapidly evolve, often in hard-to-predict ways.
- **Experiment.** As explored throughout this report, there is no way to predict with certainty how particular digital technologies will interact with specific energy system applications, especially in complex real-world situations that involve multiple policy objectives and uncertain (and sometimes unintended) feedbacks. Accordingly, governments should consider setting up and exploring a wide variety of real-world experiments that can yield “learning by doing”. California’s programme of pilot projects in electricity demand response and smart grids is a good example. Governments may also consider setting up equivalent digital “sandboxes”[13] along the lines of fintech test zones developed

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[13] A sandbox is a type of “safe house” where pilots of specified types of innovative products, services and market arrangements can take place, with the support of sector regulators. In the sandbox, there may be relief from regulatory requirements which would otherwise prevent the pilot taking place.

in Australia, Indonesia and Singapore. Such sandboxes, for example, could be set up to enable testing of peer-to-peer transactive energy markets or autonomous vehicle experimental zones.

- **Participate in broad inter-agency discussions.** Many jurisdictions around the world are developing digital strategies for their whole economies. For example, since May 2015, the European Commission has delivered 35 legislative proposals and policy initiatives in its *Digital Single Market* strategy. Energy policy makers should be active in these inter-agency discussions to ensure energy sector perspectives and equities are taken into account.
- **Focus on overall system benefits.** In line with broader IEA recommendations, the costs and benefits of digitalization in energy should be considered not only per component or per individual consumer, but also in terms of overall net benefits to the security, sustainability and affordability of the system as a whole. This approach is particularly important in electricity where the transition to smart energy systems may require significant changes in market design.
- **Monitor the energy impacts of digitalization on overall energy demand.** Policy makers should be aware of the possibility that new digital devices and services have the potential to increase energy consumption, for example, as a result of growing quantities of smart household and consumer electronics. Understanding consumer behaviour and being always up-to-date in monitoring the energy efficiency of new energy-using devices will be increasingly important.
- **Incorporate security by design.** As an efficient way to reduce overall digital security risks, policy makers should include security considerations in all publicly supported technology research and design programmes, and in product manufacturing through standard-setting.
- **Provide a level playing field.** Governments should strive to provide technology-neutral and delivery-route-neutral policies and platforms for digital energy (for example in relation to the role of smart meters or other energy management systems), to allow a variety of companies to compete to find new business models and to serve consumers better. Considerations of security, privacy, economic disruption and other concerns will also need to be taken into account.
- **Learn from others.** It is acknowledged that each country is different in many ways that are relevant to digitalization's increasing impact on energy systems; nonetheless, there are lessons to be learned from the experiences of other

governments and jurisdictions. These lessons can include both positive case studies as well as more cautionary tales. Useful collaborations and best policy sharing can take place in a variety of fora, including the Connected Devices Alliance and a wide range of IEA Technology Collaboration Programmes.[14]

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[14] See www.iea.org/tcp/.

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Glossary

3D printing	3D (three dimensional) printing, or additive manufacturing, is a computer-controlled technology that builds objects by depositing consecutive layers of material.
4G	The fourth generation of mobile telecommunications, succeeding 3G. A 4G system provides faster broadband internet access to mobile devices, with peak speed requirements defined by the International Telecommunications Union (ITU) of 100 Mbps for high-mobility communication (such as from trains and cars) and 1 Gbps for low-mobility communication (such as pedestrians and stationary users).
5G	The proposed fifth generation of mobile telecommunications, succeeding the current 4G standard. 5G is expected to feature faster speeds, increased reliability and improved security, underpinning key technologies such as connected cars and the IoT. 5G is expected to be deployed from 2020.
Additive manufacturing	See 3D printing.
ACES	Automated, connected, electric and shared (referring to vehicles and mobility).
Active controls	Automated devices or hardware systems which collect, process and adapt to real-time data using sensors, for example in a building, and which can be automated or managed from a single front-end dashboard (e.g. a smart phone app or building energy management system). Active controls can also integrate and intelligently link building energy services with information from the grid, allowing for better management across supply and demand.

Aggregator	Aggregators, also known as demand response providers, gather consumer demand of any type, as well as energy supply from distributed producers such as renewables-based power plants, in order to provide balancing services to the grid by adjusting power demand and/or shifting loads at short notice. The aggregated load is managed as a single flexible consumption unit and sold to the markets or to the grid operator. In this way, the aggregator provides an interface between large numbers of individual consumers/producers and power markets/grid operators.
Analytics	The use of data to produce useful information and insights.
Application program interface (API)	An API is a list of commands that allows software programs to communicate with each other and use each other's functions.
App-based ride hailing	Prearranged transport services that use an online-enabled application or platform (such as smart phone apps) to connect drivers using their personal vehicles with passengers. Companies that provide these services are known as transportation network companies (TNCs), such as Uber, Lyft, Didi Chuxing and Grab.
Artificial intelligence (AI)	The simulation of human intelligence processes by machines, especially computer systems. These processes include learning, reasoning and self-correction. One subfield or application of AI is machine learning. (See also learning algorithm.)
Automation	The use of various control systems to allow equipment, a process, or a system to operate automatically, with minimal or no need for human input.
Autonomous vehicle	Often referred to as "driverless" or "self-driving", an autonomous vehicle is capable of sensing its environment and navigating safely and effectively with no or minimal human intervention. In this report, "autonomous vehicles" refers to vehicles with high levels of automation, specifically levels 4 and 5 in the Society for Automotive Engineers International Standard J3016.
Autonomous closed-loop industrial control	Where digital meters and sensors collect data on system performance, with optimisation actions determined by control algorithms and automatically implemented by digital systems.

Bandwidth	The volume of data that can be sent through a network connection, typically measured in bits per second (bps). Greater bandwidth supports faster transfer of data.
Behind the meter	On the customer's side of the utility meter.
Big data	Large amounts of data gathered from a range of diverse sources, often in near real time.
Blockchain	Also called distributed ledger technology. A decentralised data structure in which a digital record of events (such as a transaction) is collected and linked by cryptography into a time-stamped "block" together with other events.
Botnet	Automated programs that run over the internet, short for (ro)botnet(work). Some botnets run automatically, others only execute commands when they receive specific input. Often used to launch spam email campaigns, denial-of-service attacks or online fraud schemes. Not all botnets are malicious.
Broadband	A term applied to high-speed telecommunications systems (i.e. those capable of simultaneously supporting multiple information formats such as voice, high-speed data services and video services on demand).
Central Scenario	The IEA Central Scenario describes the pathway for energy markets and technological progress based on the continuation of existing energy and climate policies and measures, and to a certain extent announced commitments and plans. It is broadly in line with the New Policies Scenario of the IEA *World Energy Outlook* and with the Reference Technology Scenario in *Energy Technology Perspectives 2017*. The Central Scenario should not be interpreted as a forecast.
Cloud computing	The practice of using a network of remote servers hosted on the internet to store, manage and process data, rather than a local server or a personal computer.

Connected device	Connected devices – also referred to as networked, edge or end devices – are consumer electronics, appliances and other devices that can be connected to networks and interact with the network or other devices. Examples include smartphones and tablets, as well as other consumer electronics, household appliances, machines, and objects (e.g. televisions, washing machines, security cameras, industrial equipment, cars, clothing). The primary function of some connected devices is data storage or use ("electronic edge devices", e.g. smartphone; smart TV), while the primary function for others is not data-related ("other edge devices", e.g. home appliances, lighting). (See also the Internet of Things.)
Connectivity	Exchange of data between humans, devices and machines through digital communications networks.
Computer emergency response team (CERT)	Organisation devoted to ensuring that appropriate technology and systems management practices are used to resist cyber-attacks on networked systems and to limiting damage; it also ensures continuity of critical services following successful attacks, accidents or failures.
Curtailment	The practice of temporarily decreasing electricity supply due to grid constraints or other causes, for example decreased electricity supply from a variable renewable energy (VRE) generator at times when total supply from those sources exceeds demand.
Critical infrastructure	An asset, system or part of a system which is essential for the maintenance of vital societal functions, such as the health, safety, security, economic or social well-being of people in a country, and the disruption or destruction of which would have a significant impact as a result of the failure to maintain those functions.
Cryptocurrency	A digital asset designed to function as a medium of exchange, e.g. Bitcoin. Cryptography is used to secure the transactions and to control the creation of additional units of the currency.
Cyberspace	A global domain within the information environment consisting of the interdependent network of information system infrastructures including the internet, telecommunications networks, computer systems and embedded processors and controllers.

Cybersecurity	The ability to protect or defend the use of cyberspace from cyber-attacks and cyber incidents, preserving the availability and integrity of networks and infrastructure and the confidentiality of the information these contain. Commonly also refers to the safeguards and actions available to do this.
Cyber incident	Actions taken through the use of computer networks that result in an actual or potentially adverse effect on an information system and/or the information residing therein. A violation or imminent threat of violation of computer security policies, acceptable use policies, or standard security practices.
Cyber-attack	An attack, via cyberspace, for the purpose of disrupting, disabling, destroying or maliciously controlling a computing environment/infrastructure, or stealing controlled information.
Cyber-physical systems	Machines that sense their environment, collect, analyse and act on data, and collaborate with each other and with humans. System featuring a tight combination of, and co-ordination between, the system's computational and physical elements. Today, a pre-cursor generation of cyber-physical systems can be found in areas as diverse as aerospace, automotive, chemical processes, civil infrastructure, energy, healthcare, manufacturing, transport, entertainment and consumer appliances. This generation is often referred to as embedded systems. In embedded systems, the emphasis tends to be more on the computational elements, and less on an intense link between the computational and physical elements.
Data and text mining	Automated research in the digital environment for the purpose of discovering and extracting knowledge from unstructured data.
Data protection and data privacy	Data protection law or rules control how your personal information is used by organisations which collect, process or disseminate data about which there may be an expectation of privacy.
Data	A subset of information in an electronic format that allows it to be retrieved or transmitted.
Data centre	Facilities designed to house information technology (IT) equipment.
Data traffic	The amount and characteristics of data being transmitted on a network, e.g. quantity, timing, packet size, content. Also called network traffic.

Demand response	Demand response or demand-side response refers to the possibility for consumers to adjust their electricity consumption during periods of peak demand, when power supply is scarce or electricity networks are congested, in response to time-based financial incentives. Demand response can consist of interrupting demand for a short duration, or adjusting the intensity of demand for a certain amount of time by reducing or shifting loads, or storing energy. For connected devices, demand response functionality might enable a power utility or aggregator to remotely turn off air-conditioning units in customer homes to avoid peak load issues.
Digital	Signal transmission that conveys information through a series of coded pulses representing 0s and 1s (binary code).
Digitization	The conversion of analogue to digital.
Digitalization	Digitalization describes the increasing application of digital technologies (i.e. ICT) across the economy, including energy, to achieve desired outcomes such as improved safety, efficiency and productivity. The trend toward greater digitalization is enabled by advances in data, analytics and connectivity: increasing volumes of data thanks to the declining costs of sensors and data storage, rapid progress in advanced analytics and computing capabilities, and greater connectivity with faster and cheaper data transmission.
Digital technologies	See ICT.
Digital twins	Digital replicas of physical assets that can be used to simulate and optimise industrial design and oil and gas drilling.
Distributed energy resources (DER)	Small-scale energy resources, such as solar PV, wind power or batteries, generating or storing power at or near the point of consumption. DER are usually connected to the distribution level electricity grid. Also sometimes referred to as decentralised energy resources.
Drone	Also known as an unmanned aerial vehicle (UAV), a drone can either be piloted remotely by a human or else can be a fully autonomous vehicle.
Edge device	See connected devices.

eGovernment	Use of ICT tools and systems to provide better public services to citizens and businesses.
Energy efficiency	Something is more energy efficient if it delivers more services for the same energy input, or the same services for less energy input. For example, when a light-emitting diode (LED) uses less energy than a compact florescent lamp (CFL) or incandescent bulb to produce the same amount of light, the LED is considered to be more energy efficient.
Energy intensity	A comparative measure of total energy consumption relative to a specific indicator, such as primary energy use per unit of gross domestic product or final energy consumption per square metre.
Energy management system	A computer-based system that defines the practices, methods and structure for industrial or commercial firms, for example, to monitor their energy consumption and establish practices to improve efficiency within a defined perimeter, such as an industrial site or a building. A building energy management system, using computer software and equipment hardware (e.g. sensors and active controls), can monitor and control heating, cooling, ventilation and lighting systems, along with other buildings services such as fire and security systems.
Energy poverty	A lack of access to modern energy services. These services are defined as household access to electricity and clean cooking facilities (e.g. fuels and stoves that do not cause air pollution in houses).
Energy saving	The reduction or avoidance of energy use with respect to demand for energy services. Energy savings may result from energy efficiency measures (e.g. insulation of a building to reduce heating and cooling loads), improved energy management (e.g. use of sensors that turn off equipment when it is not being used) or user decisions, such as the choice to ride a bicycle rather than use a car.
Energy security	The uninterrupted availability of energy sources at an affordable price.

Electric vehicle (EV)	A vehicle whose powertrain includes both a battery (which can be recharged via an external power source) and an electric motor. Electric vehicles include battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and fuel cell electric vehicles (FCEVs). BEVs have no internal combustion engine. PHEVs combine a battery and an internal combustion engine. Charging of BEVs and PHEVs can be achieved by plugs, or by (stationary or dynamic) conductive or inductive power transfer. FCEVs have hybrid powertrains that use fuel cells, optionally together with a battery and supercapacitor, and an electric motor.
Firmware	Permanent software programmed into a digital device's read-only memory.
Flexibility (in electricity systems)	The capability of the electricity system to respond to upward or downward changes in the supply/demand balance in a cost-effective manner over a timescale ranging from a few minutes to several hours. Flexibility is often associated with the ramping capability of dispatchable power plants in the system, but it also refers to other resources including storage, demand-side management and grid infrastructure.
GW	Gigawatt (10^9 Watts). 1 Watt = 1 joule per second.
Hardware	The physical components of an information system. (See also software and firmware.)
Home or building automation	Refers to systems that integrate diverse electrical devices and energy-consuming equipment in a house or building, allowing control on site or remotely, e.g. through internet access or automatically in accordance with selected settings. Such automation has convenience, energy efficiency and safety benefits. (See also energy management system.)
Hyperscale (data centre)	Hyperscale data centres are very efficient, large-scale public cloud data centres operated by companies such as Alibaba, Amazon and Google.
ICT	Information and communications technology. Used in this publication in the broadest sense (i.e. digital technologies) to include all types of digital equipment such as sensors, connected devices, network equipment and infrastructure (e.g. data centres and network cables).

Internet of Things (IoT)	Where everyday objects are connected to networks to provide a range of services or applications in areas such as cars, home automation and smart grids. The IoT encompasses both machine-to-machine (M2M) connection, where devices interact and share data without the direct involvement of people, and things connected to networks to enable people to remotely control processes or manage their devices.
Intelligent transport systems (ITS)	Intelligent transport systems include the use of sensors, communications technologies and advanced analytics to improve system operations, with the aim of improving safety, efficiency and service, as well as lowering costs. Examples of ITS include in-road detectors to control traffic lights, RFID to automatically collect tolls, and the use of the GPS and telecommunications for roadside assistance.
Internet	The internet is the single, interconnected, worldwide system of commercial, governmental, educational and other computer networks that share (a) the protocol suite specified by the Internet Architecture Board (IAB), and (b) the name and address spaces managed by the Internet Corporation for Assigned Names and Numbers (ICANN).
Internet Protocol (IP) traffic	IP traffic includes fixed and mobile internet traffic (IP traffic that crosses an internet backbone), corporate IP wide area network (WAN) traffic, and IP transport of TV and video on demand (VoD).
Interoperability	The ability of different computer systems or software to exchange and make use of information.
Last mile	In transport, the “last mile” refers to the stage of a trip or (in supply chains) delivery that is typically the most difficult to address in terms of perceived inconvenience or cost. In the case of goods delivery, getting merchandise from a final delivery hub to the customer is generally the most expensive and least efficient leg of product shipping. In the case of passenger services, the term refers to the perceived inconvenience of going from a public transit station to the final destination (often home or work). In the case of passenger transport, the term has an analogue: the “first mile”, which refers to the leg of a trip from home to the nearest public transport hub (and the difficulties in making this leg of a trip comfortable, convenient and cheap).

Learning algorithm	A process or method used to extract patterns from data collection (e.g. from building sensors and controls) to identify and adapt appropriate solutions or applications for a device or system. Examples include smart thermostats in buildings, that collect and process data on occupant presence, routine and preferences to adapt building energy services, such as lighting, heating, cooling and ventilation, in order to reduce total energy consumption while maintaining or improving the energy service and user comfort. (See also smart controls.)
Load	The level of network interaction of a network-enabled device, which influences its power consumption.
Low power wide area (LPWA) networks	LPWA networks provide low power draw and wide area coverage, and are designed for IoT and M2M applications that provide low data rates, long battery lives, and at low cost.
Machine learning	Machine learning, a subfield of artificial intelligence, is the science of getting computers to act without being explicitly programmed. Machines are given access to large data sets and allowed to learn for themselves. (See also artificial intelligence.)
Machine-to-machine (M2M)	M2M connections include energy sector applications such as smart meters and process sensors in power plants, GPS for logistics and vehicles, smart metering, and other IoT technologies.
Malware	A software (e.g. a virus, worm, rootkit, botnet or other code-based malicious entity) specifically designed to disrupt, damage, or gain unauthorised access to an ICT system.
Microgrid	Small electric grid systems linking a number of households or other consumers. Also sometimes called a mini-grid.
Mobility as a Service (MaaS)	MaaS identifies mobility solutions that are consumed as a service. This is enabled by platforms that integrate public and private, motorised and non-motorised mobility options and offer a unified trip-making and payment platform. MaaS platforms allow users to subscribe to an all-inclusive, multi-modal “mobility package” and access a variety of shared mobility services, including bicycles, buses, trains, cars, taxis and ride-hailing services. MaaS typically comes with a shift away from the conventional vehicle ownership paradigm.

Network (digital)	A digital structure that allows the transmission of data or information between two or more connected devices; networks can interconnect with other networks and contain subnetworks. Different types of networks include local-area networks (LANs) and wide-area networks (WANs), e.g. the internet.
Network (electricity or gas)	Electrical grid or gas pipeline.
Networked device	See connected device.
Node	An electronic device that can send, receive or forward information; nodes can be network devices (such as a modem) or edge devices (such as a digital telephone handset, a printer or a computer).
Open data	Free and widely available data for consultation and reuse, including reuse for commercial purposes, with a view to increasing transparency and stimulating economic activity.
Operation and maintenance (O&M)	Refers to monitoring and repair of equipment, utilities or other property (e.g. buildings and vehicles) to ensure operational performance, functionality and asset value. O&M may include scheduled or unscheduled service checks and repairs, where increasingly connected devices and sensors are helping to monitor and predict O&M needs. (See also predictive maintenance.)
Optical network	Optical networks transmit information in the form of light pulses through thin glass or plastic optical fibre, offering much higher transmission capacity than conventional copper-wire networks.
Patch	An update to an operating system, application or other software, issued specifically to correct particular problems with the software.
Peer-to-peer (P2P)	In energy, connecting system users and market participants with each other to enable direct trading.

Phishing / whaling	Trying to obtain sensitive information such as usernames and passwords by means of an email (or other electronic communication) which is disguised as a trustworthy communication, but which when opened or when a link is clicked on allows the sender a point of access.
Photovoltaic (PV)	One of the main technologies for producing solar power. PV cells directly convert solar energy into electricity; this is a semiconductor device.
Physical internet	An open, modular and shared global logistics system, inspired by the movement of data on the internet, in contrast to the proprietary logistics systems that are common today. Currently, nearly all logistics service providers and carriers maintain proprietary assets, both physical (e.g. warehouses and trucks) and operational (e.g. information on routes, customers and markets).
Platform	A layer of software that combines different kinds of devices, data and services, on top of which other firms can build their own offerings, e.g. search engines, social media, e-commerce platforms, app stores, price comparison websites.
Platooning	Platooning refers to the practice of driving vehicles (primarily heavy-duty tractor-trailers or rigid trucks) in a single line with small gaps between them to reduce drag and thereby save fuel during highway operations. Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technologies can enable trucks to drive in very close proximity without sacrificing safety or manoeuvrability.
Plug-and-play	Software or devices that are intended to work perfectly when first used or connected, without need for installation, reconfiguration or adjustment by the user.
Power	In the context of energy, refers to electricity (e.g. power plant).
Power purchase agreement (PPA)	A financial agreement/contract between two parties: one that generates electricity and one that is looking to purchase the electricity.
Power usage effectiveness (PUE)	A measure of how efficiently a data centre uses energy; the best global data centres have PUE values of around 1.1 (meaning 0.1 kWh used for cooling/power provision for every 1 kWh used for IT equipment).

Predictive maintenance	Predictive maintenance refers to the ability to perform targeted maintenance in order to address a potential issue before it happens or worsens, causing damage or downtime. Predictive maintenance is based on direct measurement of the real-time status of components.
Prosumers	Pro(ducer-con)sumers. Usually refers to small-scale, distributed generation which allows consumers to increasingly have the choice to buy electricity from a retailer or to produce at least part of it themselves.
Radio-frequency identification (RFID)	RFID uses electromagnetic fields to automatically identify and track tags attached to objects. The tags contain electronically stored information.
Ransomware	A type of malware which encrypts user data, asking victims to pay a ransom in order to obtain a decryption key.
Real time	Information is available simultaneous with an event, or immediately after collection. There is no delay in the timeliness of available information.
Rebound effect	The reduction in expected gains from the introduction of new technologies or policies that increase the efficiency of resource use, because of behavioural or other systemic responses, for example the increased consumption of energy following improvement in the efficiency of an energy-consuming product or service.
Ride-sharing	Ride-sharing refers to multiple passengers sharing a single vehicle to take a trip. These passengers may be making trips with different origins and destinations, or they may be starting and arriving at the same places, but use the same vehicle to economise on costs, resources or energy consumption. More recent innovations include “dynamic” and “app-based” ride-sharing.
Right-sizing	Improved resource and energy efficiency of service provision can be achieved by optimising the size of equipment, for example vehicles, to match utilisation patterns, for instance to match the number of passengers.
Sandbox	A type of “safe house” where pilots of specified types of innovative products, services and market arrangements can take place, with the support of sector regulators.

Self-consumption	When an energy producer, e.g. of solar power from PV, consumes or stores this directly, behind the meter, rather than feeding it into the grid.
Sensor	A device which detects or measures some type of input from the physical environment (e.g. daylight, temperature, motion or pressure).
Server	A server is a computer that provides functionality and services to other devices through network connections.
Shared mobility	A transport strategy that enables users to gain short-term access to vehicles, bicycles and other transport modes on an as-needed basis. Shared mobility services include car-sharing services, app-based shared ride-hailing services like LyftLine and UberPool, long-distance ride-sharing platforms like BlaBlaCar, and bike-sharing services.
Simulation	The use of computing to model the dynamic responses of a system to exogenous events.
Smart charging	A charging strategy for electric vehicles that uses connectivity and other digital technologies to automatically shift battery charging to times when electricity prices are low and/or when overall electricity demand is low.
Smart cities	A city becomes smart by virtue of strategically leveraging ICT infrastructures and applications towards better delivery of benefits to the citizens. These might include making a city more sustainable and greener through less energy consumption and more of it from renewable sources, or improving the efficiency of transport.
Smart controls (including smart lighting, smart thermostats)	ICT-enabled devices, such as building systems controls, that can take decisions in an adaptive or predictive manner based on sensors and data and possibly with the use of learning algorithms. For instance, smart LED lighting is connected to and can interact with building control systems to predict and control lighting services relative to occupant presence, routine and daylight conditions.
Smart device / appliance	Network-enabled devices or appliances (e.g. washing machines and televisions) with integrated information and communication functions that allow them to transmit and receive information.

Smart grid	An integrated electricity system that uses advanced software applications and communication network infrastructure, together with sophisticated sensing and monitoring technologies, to optimise the management of energy supply, demand and transmission. Smart grids use ICT to gather and act on data, so as to co-ordinate the needs and capabilities of all generators, grid operators, end users and electricity market stakeholders to operate all parts of the system as efficiently as possible, minimising costs and environmental impacts while maximising system reliability, resilience and stability.
Smart meter	A meter that records electricity consumption in intervals of an hour or less, and communicates that information at least daily back to the utility for monitoring and billing purposes. This type of advanced metering infrastructure differs from traditional automatic meter reading in that it enables two-way communication between the meter and the central system. Smart meter functionality includes remote reading, two-way communication, support for advanced tariff and payment systems, and remote disablement and enablement of supply.
Software	The programmes and other operating information used by a computer.
Solar PV	See photovoltaics.
Standardisation	The process of implementing and developing technical standards based on the consensus of different parties that include firms, users, interest groups, standards organisations and governments. Standardisation can help to maximise compatibility, interoperability, safety and repeatability.
Standby power	The power consumed by an appliance or device when it is not actively in use but is ready to be rapidly put into use.
Subcritical/ supercritical	Refers to the efficiency of fuel conversion by coal power plants. Supercritical (SC) refers to those thermal plants in which steam is raised above the critical point of water (221 bar and 374°C). Ultra-supercritical (USC) usually refers to those plants in which steam is raised at temperatures higher than 593°C (1 100°F).

System operator	The organisation responsible for operating part or all of the power system. Originally at high voltage only, active operation of low-voltage grids is emerging in order to manage a growing amount of distributed (mainly solar) power plants. System operation is ideally separate(d) from ownership of transmission and generation assets
Recovery (recoverable resources)	Remaining recoverable resources of oil and gas are comprised of proven reserves, reserves growth (the projected increase in reserves in known fields) and as yet undiscovered resources that are judged likely to be ultimately producible using current technology. Resources can be defined either as technically recoverable (i.e. producible with current technology) or as technically and economically recoverable, meaning that they are exploitable at current oil prices.
Robotics	The science of design, engineering and use of increasingly intelligent machines that sense, act purposefully and perform work autonomously, and their control and information processing systems.
Test bed	In engineering, an area equipped with instruments used for testing machinery, engines, etc. under working conditions.
Total final consumption (TFC)	Is the sum of consumption by the different end-use sectors. TFC is broken down into energy demand in the following sectors: industry (including manufacturing and mining), transport, buildings (including residential and services) and other (including agriculture and non-energy use). It excludes international marine and aviation bunkers, except at world level where it is included in the transport sector.
Transactive energy	The use of a combination of economic and control techniques to improve grid reliability and efficiency, in particular in a world with increasing numbers of independent prosumers. Often discussed in the context of market-based transactive exchanges between small prosumers.
Upstream oil and gas	The upstream sector includes production of oil and gas from all onshore and offshore oil and gas facilities (from either conventional or unconventional reservoirs) and gathering and processing of the produced hydrocarbons.

Unconventional reservoirs	Unconventional reservoirs include a variety of oil and gas resources that cannot easily be accessed using standard drilling technologies, where the hydrocarbons are trapped by the nature of the rock itself rather than by the geometrical arrangement of the rock layers (as in conventional structural or stratigraphic traps). Unconventional resources include extra-heavy oil and bitumen (oil sands), shale gas, and coal-bed methane.
Value chain	The complete range of activities comprising the development of network-enabled devices, which includes device and component manufacturing, software development, network design, network architecture, communication protocol development, technical standardisation processes and service providers. The network-enabled device value chain spans the computing and electronic sector, the appliance and equipment manufacturing sector, and the media and telecommunications sector.
Variable renewable energy (VRE)	Renewable energy technologies – including solar PV, onshore and offshore wind, concentrating solar power without storage and run-of-river hydropower – whose maximum output at any time depends on the availability of fluctuating renewable energy resources, such as wind or solar insolation.
Virtual power plant	A network of decentralised, small or medium-scale power generating units such as wind farms and solar parks, as well as flexible power consumers and batteries.
Vehicle-to-grid (V2G)	Technology by which an EV can both draw electricity from the grid and supply it back into the grid.
Web crawling	A technique that uses algorithms to automatically collect information from websites. (Also known as web harvesting or web scraping.)
Workload (data centre)	In computing, the workload is the amount of processing that the computer has been given to do at a given time.
Zettabyte	A measurement of data equivalent to 10^{21} bytes, or a billion terabytes.

Abbreviations and acronyms

ACES	automated, connected, electric and shared
AI	artificial intelligence
ANSSI	Agence nationale de la securité des systèmes d'information (France)
API	application program interface
ASEAN	Association of Southeast Asian Nations
BEV	battery electric vehicle
CAPEX	capital expenditure
CBECS	Commercial Buildings Energy Consumption Survey (United States)
CCS	carbon capture and storage
CDA	Connected Devices Alliance
CEN-CENELEC	European Committee for Standardization-European Committee for Electrotechnical Standardization
CERT	computer emergency response team
CFL	compact florescent lamp
CNPC	China National Petroleum Corporation
CO_2	carbon dioxide
CRISP	Cybersecurity Risk Information Sharing Program
DER	distributed energy resources
DOE	Department of Energy (United States)
DoS	Denial of Service
DSRC	dedicated short-range communications
EPEAT	Electronic Product Environmental Assessment Tool
ESCO	energy service company
EV	electric vehicle
FCEV	fuel cell electric vehicle
GCI	Global Cloud Index
GDPR	General Data Protection Regulation (European Union)
GIS	geographical information system
GPS	global positioning system
G7	Group of Seven
IAC	Industrial Assessment Center (United States)
ICT	information and communications technology
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IP	Internet Protocol

ISAC	Japan Electricity Information Sharing and Analysis Center
ISMS	information security management system
IT	information technology
ITS	intelligent transport systems
ITU	International Telecommunications Union
J-CSIP	Cyber Security Information-sharing Partnership of Japan
LBNL	Lawrence Berkeley National Laboratory
LED	light-emitting diode
LIDAR	laser-imaging detection and ranging
Li-Fi	light fidelity
LPWA	low power wide area
MaaS	Mobility as a Service
MAIT	Manufacturers' Association for Information Technology (India)
M2M	machine-to-machine
NATO	North Atlantic Treaty Organization
NEED	National Energy Efficiency Data Framework (United Kingdom)
NERC	North American Electric Reliability Corporation
NIS	Network Information Security Directive (European Union)
NIST	National Institute of Standards and Technology (United States)
NPS	New Policies Scenario
O&M	operation and maintenance
OECD	Organisation for Economic Co-operation and Development
OPEX	operating expenditure
OT	operational technology
PAYG	pay-as-you-go
PHEV	plug-in hybrid electric vehicle
PoE	Power-over-Ethernet
PPA	power purchase agreement
PUE	power usage effectiveness
PV	photovoltaic
QR	quick response
R&D	research and development
RECS	Residential Energy Consumption Survey (United States)
RFID	radio-frequency identification
RTS	Reference Technology Scenario
SAE	Society of Automotive Engineers
SCADA	supervisory control and data acquisition
UAV	unmanned aerial vehicle
V2G	vehicle-to-grid
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
yr	year
3D	three-dimensional

Units of measure

bps	bits per second
GB	gigabyte
Gbps	gigabits per second
GJ	gigajoule
GW	gigawatt
h	hour
kW	kilowatt
kWh	kilowatt hour
lm/W	lumens per watt
Mbps	megabits per second
Mt	million tonnes
m^2	square metre
PWh	petawatt hour
toe	tonne of oil equivalent
Twh	terawatt hour
W	watt

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Digitalization & Energy

Digital technologies are everywhere, affecting the way we live, work, travel, and play. Digitalization is helping improve the safety, productivity, accessibility, and sustainability of energy systems around the world. But it is also raising new security and privacy risks, while disrupting markets, businesses, and workers.

Digitalization & Energy is the International Energy Agency's first comprehensive effort to depict how digitalization could transform the world's energy systems. The report examines the impact of digital technologies on energy demand sectors, looks at how energy suppliers can use digital tools to improve operations, and explores the transformational potential of digitalization to help create a highly interconnected energy system.

This report seeks to provide greater clarity to decision makers in government and industry on what digitalization means for energy, shining a light on its enormous potential and most pressing challenges. It also lays out no-regret recommendations to help steer the world towards a more secure, sustainable, and smarter energy future.