Global
Sustainable Electricity
Partnership

New electricity frontiers

Harnessing the role of low-carbon electricity uses in a digital era

GSEP REPORT | May 2018

ABOUT GSEP

The Global Sustainable Electricity Partnership (GSEP) is a unique international organization dedicated to electrification and sustainable energy development. We are a not-for-profit comprising the leading companies in the global electricity sector. Together, our companies serve 1.2 billion customers, and generate and deliver about one-third of the electricity used in the world, over 65% of which is generated with no direct carbon emissions.

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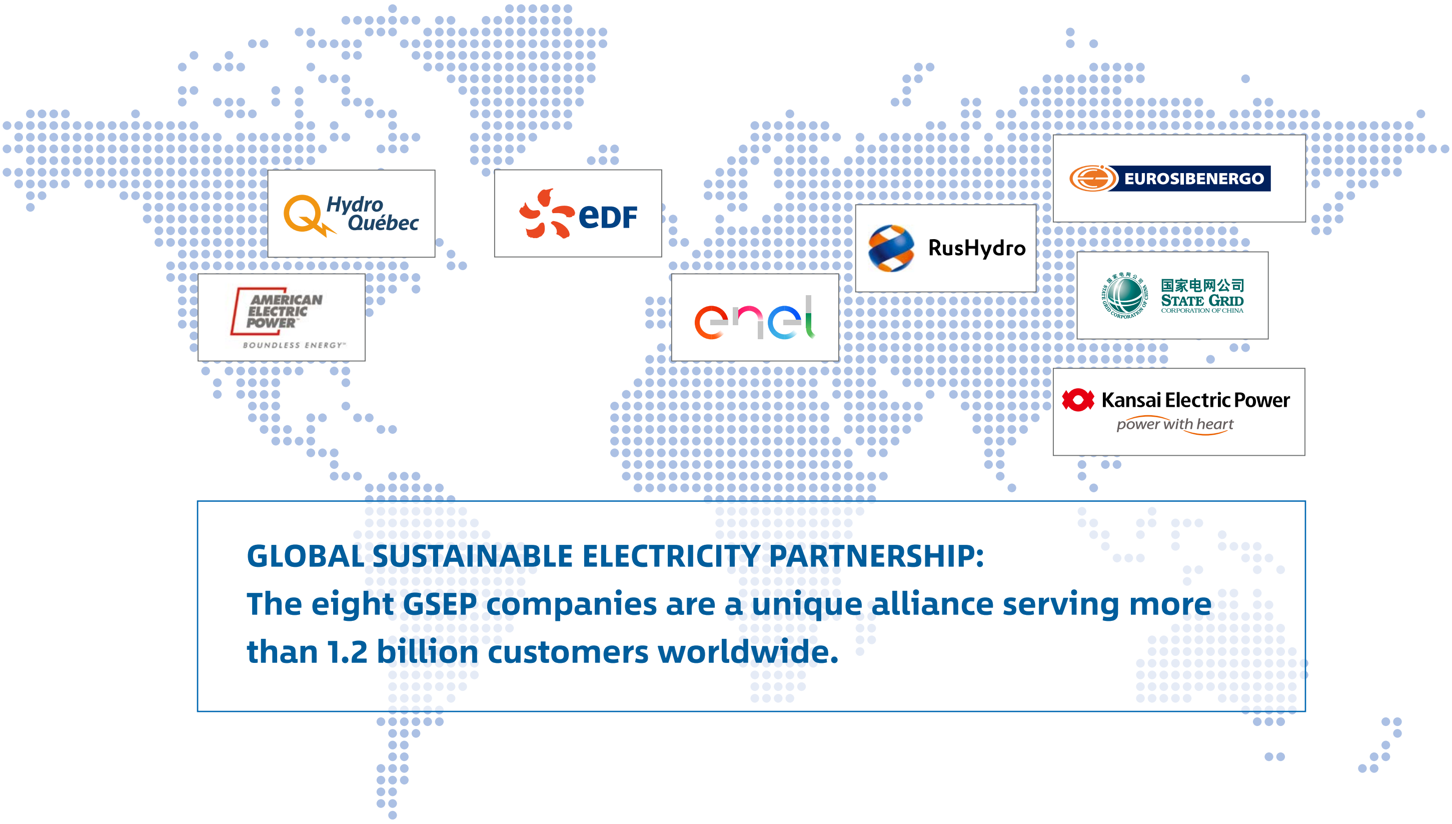
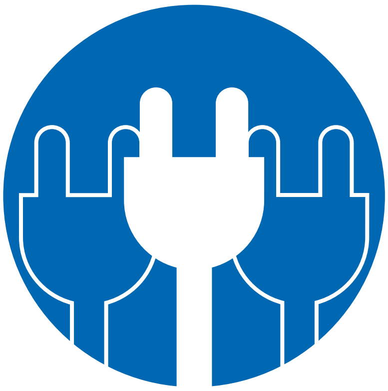
GSEP: COMMITTED TO SUSTAINABLE ELECTRIFICATION

This report is the collective work of the Global Sustainable Electricity Partnership's (GSEP) members, global leaders in the radical transformation of today's electricity industry. The GSEP companies believe that electricity is the energy of the future. Cleaner electricity generation, energy efficiency and massive electrification of end-uses will be needed to decarbonize the economy and to reach the world's development and climate goals.



GLOBAL SUSTAINABLE ELECTRICITY PARTNERSHIP:
The eight GSEP companies are a unique alliance serving more than 1.2 billion customers worldwide.

Our collective expertise in power systems and electricity technologies is unparalleled.



APPROXIMATELY

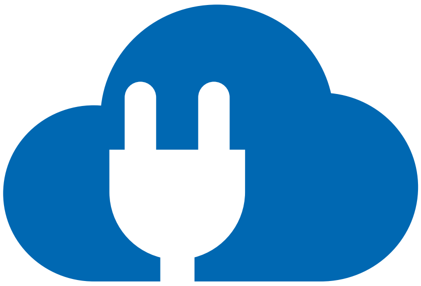
1/3

OF THE ELECTRICITY CONSUMED
IN THE WORLD IS PRODUCED
BY THE EIGHT COMPANIES
OF THE GSEP

- Our companies invest more than $120 billion US per year in generation, transmission, distribution and energy services
- Our companies own and operate more than 5.9 million km of transmission and distribution lines around the world

We are actively tackling climate change, reducing the environmental impact of our operations and moving towards lower-carbon solutions

- Together, our companies have more than 400 GW of installed capacity in all generation technologies (of which 31% hydro, 23% nuclear, 4% other renewables, 19% coal and 7% natural gas)



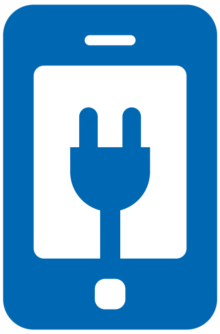
OVER

65%

OF OUR ELECTRICITY
IS PRODUCED WITH
NO DIRECT CO_2 EMISSIONS

We are investing in innovation and digital solutions to shape a cleaner, brighter future

- We are deploying new digital and mobile solutions that empower our consumers, offering them new electricity services for every aspect of their daily lives



MORE THAN

$2.2 billion US

INVESTED BY OUR COMPANIES
EACH YEAR IN RESEARCH
AND DEVELOPMENT TO DEVELOP
CUTTING-EDGE INNOVATIONS
AND NEW TECHNOLOGIES

EXECUTIVE SUMMARY

The size of the environmental challenge in front of us is unprecedented. As we rise to this challenge, electrification is an absolutely vital pathway to decarbonizing energy. For GSEP, electrification is part of the journey to a safe future. This report provides an overview of the conditions that must be met to achieve electrification. It outlines six fundamental convictions about the future of electricity.

1. Electricity fostered development in the 20th century. It will be the energy of the 21st century.

Electricity was a major driver of development and economic growth in the 20th century. It is set to play an even more important role in the 21st century, given four key qualities that make it indispensable to meeting the growing need for reliable, affordable and clean energy.

Electricity is efficient: Electrical technologies have very efficient output. Heat pumps in buildings and electric vehicles for transportation are up to three to five times more efficient than traditional fossil fuel boilers or internal combustion engines. Thanks to its efficiency, electrification results in a significant reduction in overall energy consumption, which also reduces the cost of use and limits the impact of new types of consumption on infrastructure.

Electricity is flexible: The electrification of end-uses enhances overall energy security of supply, thanks to a diversified portfolio of energy sources in the power mix. The diversification of sources and technologies makes the electricity system more resilient. At the same time, electrification provides more flexibility in demand management between sectors, allowing the optimization of renewable generation by coupling power, heat and mobility. The parallel development of electricity end-uses is required as volumes of variable renewable energy increase, in order to facilitate their integration at the lowest possible cost.

Electricity is an essential tool for climate protection: With well-balanced policies, emissions from the power sector can be reduced while keeping costs in check. Low-carbon electricity can then easily replace fossil fuels in transport, buildings and industry. Technologies already exist for efficient and competitive electricity end-uses. Electrification enables economies to get on track to meet ambitious decarbonization goals without having to wait for hypothetical future technologies, thus avoiding the lock-in to emitting technologies and associated stranded costs, and making the transition to a low-carbon society more affordable.

Electricity is the energy of the digital and urban eras: Electricity is at the heart of the two megatrends sweeping our societies: urbanization and digitalization. One in three people lived in cities in 1950, rising to one in two today and set to reach two in three by 2050. People in cities consume 2.5 times more electricity than their rural counterparts. Urban development is thus driving up the electrification of end-uses and it should therefore be accompanied by the construction of smarter infrastructure. Digitalization is also gathering momentum at an extremely fast pace, with electricity at the heart of this trend: the number of gigabytes produced per second worldwide has risen from 100 in 1992 to almost 50,000 today. This boom in big data is creating the need for more electricity, which could be offset by significant energy efficiency gains.

The four unique attributes of electricity listed above mean that it has major potential to help solve the energy challenges that lie ahead. However, several conditions mentioned in this report will have to be met if it is to play this role. One crucial prerequisite will be the ability to keep it as affordable and reliable as possible while steadily reducing emissions. In a previous report drafted in preparation for COP 21, *Powering Innovation for a Sustainable Future*, GSEP described the main conditions that would have to be met.[1]

2. Electrification needs to shift gears, rapidly doubling its pace compared to recent trends

We need to speed up electrification. Governments can shift gears by promoting the electrification of end-uses in all sectors. Electrification has two major knock-on benefits for the climate: improving energy efficiency and decarbonizing power generation. In order to reach zero net emissions in the second half of the century, the efficient and cost-effective electrification of end-uses must be enhanced at the same time as the power mix is decarbonized, in order to avoid lock-in effects and stranded investments from the overdevelopment of fossil-fuel infrastructures.

Electricity will become the world's leading energy source by 2050, according to most projections, with a share in final energy demand that should double, from 18% today to about 36% in 2050. This represents a major shift in the energy sector. As long as electricity prices are kept affordable, and bearing in mind the current decreases in electricity technology costs, higher electrification rates should be possible, reaching over 50% of final energy by 2050.

- In buildings, electricity's share in global final energy (for lightings, appliances and thermal uses) could go from 30% today to 75% in 2050.
- In transportation, electricity and other carbon-free energies (biofuels, hydrogen) must rise from 4% today to above 40% in 2050, with virtually all light-duty vehicles being electrified.
- In industry, electricity's share could double from 23% today to about 50% in 2050.

Thus the pace of electrification worldwide needs to double at least from the current rate of increase of 1.2% per year of total energy consumption to over 2.5% per year. Efficient electrification of end-uses should spread quickly in all sectors, thanks to already-available technologies, thus contributing to achieving the below 2°C target.

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[1] https://globalelectricity.org/content/uploads/final_powering_innovation_for_website_and_usbs_2.pdf

3. The momentum for efficient electrification is building, thanks to competitive technologies that are ready for mass deployment now

Many technologies capable of making end-uses efficient, competitive and better for the environment already exist. One example is light electric vehicles (EVs). Battery costs are dropping rapidly, indicating that the total cost of ownership of EVs could be the same as for internal combustion engines in the near future. Gains in the energy density of batteries, the efficiency of electric motors and more electricity-specific vehicle designs all point to electric vehicles becoming more competitive going forward. Furthermore, autonomous vehicles will mostly be electric. Though it is still not clear when that technology will mature, greater use of these vehicles through car-sharing suggests an additional reduction in the cost of electric mobility.

In the building sector, heat pumps are a competitive solution for producing heat and cold when consumption per square meter is medium to high. Thanks to mechanical vapour recompression, heat pumps are also suitable for certain industrial processes that do not require very high temperatures. Thermodynamic water heaters make it possible to supply hot water in buildings at a competitive price and to store energy, making the electricity system more flexible. When consumption per square meter is low, electric heating is a competitive solution, one that in combination with low-carbon electricity contributes to climate protection.

Digital and the role it can play in managing demand will be a key facilitator for all these end-uses: smart homes and smart cities will enhance the efficiency of technologies, increase the flexibility of the electricity system and thus encourage the integration of intermittent renewable energies while further lowering the cost of energy services for users. It will also play a vital role in ensuring the reliability of networks and optimizing infrastructure needs (i.e. via smart grids).

In short, efficient electrification is at hand, thanks to available and mature technologies: action is called for now.

4. Innovation and technology improvements will, in the longer term, enlarge the current portfolio of uses that run on efficient electricity

Over the longer term, R&D and demonstrations should add new technologies to the portfolio and allow for emissions reductions in sectors of activity where decarbonization is still expensive.

In the transportation sector for instance, electrifying long-distance freight calls for R&D starting now on electric trucks (battery or catenary systems) or hydrogen produced using low- or zero-carbon electricity and fuel cells, two feasible paths for which competition is currently open.

In buildings, larger heat pumps will be needed for collective heating as higher temperatures are required than with individual heat pumps. The relevant technologies have been clearly identified and the first full-scale demonstrations are being carried out in some countries, for example in Scandinavia. The challenge is to facilitate the emergence of a market and to create the structure for a competitive industry for these products.

R&D efforts are required on some industrial processes to lower the cost of technologies that could potentially result in their electrification, either directly or indirectly via hydrogen produced with electricity via electrolysis. Two examples of areas with significant potential are the direct reduction of iron ore in steel and heat pumps for industrial processes requiring very high temperatures. "Power-to-X" technologies that enable the production of hydrocarbons from hydrogen and CO_2 is another potential avenue for R&D. However, the low efficiency of power-to-X technologies and their impact on prices are such that they can only complement direct electrification. Targeted R&D and demonstration programs should make it possible to manage and guide the decrease in the cost of electrolyzers and carbon capture and synthetic hydrocarbon manufacturing techniques.

5. Electric utilities are moving forward and evolving

This shift toward an efficient electrification of our economies will change the role played by electricity companies. Utilities must ensure a reliable and affordable electricity system while facing new challenges: (i) more intermittency from renewable generation, (ii) integrating a more decentralized, customer-oriented approach, and (iii) new and diversified end-uses. These challenges are causing them to evolve. One key characteristic of their transformation is that they are now providing new services to prosumers and managing flexibility as a new source of value for the electricity system.

The declining cost of digital together with the spread of communication devices are paving the way for personalized and more fine-tuned management of comfort in homes, cities and mobility. Electric utilities will play a role in the emergence of these new services aiming to deliver increasingly specific solutions to each customer, while also locking in economies of scale to ensure the lowest possible prices. They will accomplish this by forging partnerships with new players from other sectors (particularly construction and mobility), which are also being impacted by electrification and digitalization trends.

With more variability in electricity systems, flexibility and adaptive management will be crucial in guaranteeing the reliability of systems around the clock, seven days a week. The digitalization of networks and infrastructure and new digital services to increase comfort in homes (smart homes), efficiency in cities (smart cities) and mobility (vehicle-to-grid, vehicle-to-home) will pave the way for an optimization of electricity infrastructure and cost reductions, while complying with the most stringent system reliability requirements.

Electric utilities have a vital role to play by continuing to find new ways to foster these personalized services while ensuring the efficiency and reliability of electricity systems as a whole. These changes will be a challenge for utilities. GSEP companies are already moving in the right direction. The present report provides many examples of the progress members have made in this area: it highlights the wide range of models that can be developed to address the uncertainties surrounding these new activities, differences between the circumstances of individual regions and the importance of public policies.

6. Moving toward effective public policies regarding electrification: key enablers

Public policies will play a central role in enabling electricity to make economies more competitive, improve quality of life in a more urbanized world, and better protect the environment and climate. GSEP has identified five key enablers, amongst others, for effective policies regarding electrification:

a. **Set clear and efficient sector-specific electrification goals in line with economy-wide policies targeted at energy efficiency and emissions reduction.** Public policies should make it possible to give sector actors sufficient visibility to develop their products/services and infrastructure. This requires identifying the potential for competitiveness (cost-effectiveness) in different sectors (buildings, transport, industry) and over different time horizons, based on the specific characteristics of countries and their climate and environmental targets.

b. **Establish a level playing field for all energy carriers.** Efficient electrification requires fair competition between energy carriers. Key actions in this regard will be reducing or eliminating subsidies when appropriate, removing inappropriate charges on electricity bills (i.e. taxes or levies) and taking into account environmental externalities, such as a carbon value.

c. **Update energy efficiency codes.** Efficiency standards for buildings should also allow for fair competition between energy solutions, while guaranteeing efficiency gains for consumers and a reduction in greenhouse gas emissions. To this end, standards for final energy rather than primary energy should be the norm.

d. **Set up regulation and support for the development of infrastructure.** This is crucial for electric mobility charging infrastructure as well as for the digitalization of cities, homes and industries. Norms and standards guaranteeing the interoperability of charging systems and the development of vehicle-to-X technologies should facilitate consumer choices and promote flexibility. Effective standards on security and transmission protocols between IoT systems should address the privacy and cybersecurity concerns of citizens.

e. **Expand R&D and demonstrations to accelerate technology development.** Existing electricity technologies can be leveraged to meet a very large share of countries' economic and environmental targets. Additional solutions must be developed for ambitious objectives (notably climate targets). To ensure that the electrification solutions of the future will be available on time and on budget, specific technology roadmaps must be drawn up. These roadmaps, drafted jointly by research labs and industry, should set cost targets for different timeframes and allow them to be monitored. This is a more cost-effective path than rolling out solutions still far from commercial deployment.

1

OVERVIEW

Electricity is the energy of tomorrow's world

Electricity drives development: In emerging countries it boosts productivity and in developed countries it is a vital condition for modernization. Around 1.1 billion people still need access to clean energy, whether from networks when urban and industrial development is sought, or via off-grid systems in remote areas. Recent technological advances have opened the way to smarter power grids, which can empower customers, enhance system reliability and resilience, and reduce long-term costs. Affordability of electricity, guaranteed by adapting technologies and regulations to regional contexts, is the key condition to deep electrification.

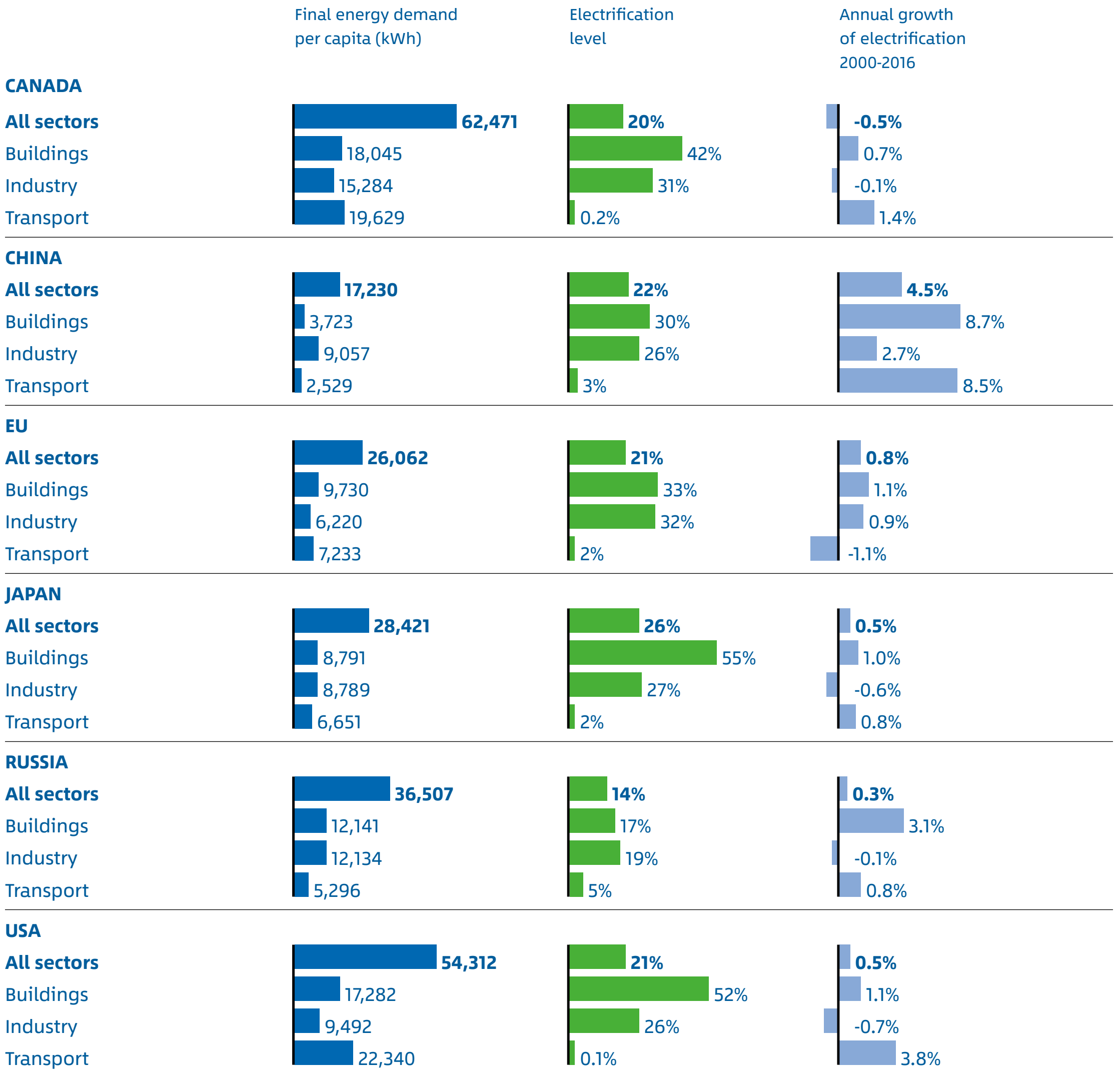
Electricity is set to become the world's leading energy source by 2050. Electricity's share of the final energy mix is already on an upward trend, going from 9% to 18% between 1970 and today. Now the pace of electrification must double in order to meet the Paris Agreement's targets and help protect the world from climate change. Governments can shift gears by promoting the electrification of end-uses in all sectors. It has two major knock-on benefits for the climate: it improves energy efficiency, as electrical technologies have a higher output than fossil fuel equivalents; and it facilitates the decarbonization of power generation, as it provides more scope to manage demand, thus allowing more variable renewables to be brought into the mix.

Clean, efficient electricity is the lifeblood of the modern city. Cities are on the rise: by 2050, two-thirds of the world's population will live in urban areas, up from already 50% today. Cities consume 1.3 times more energy and 2.5 times more electricity per person than rural areas, making urbanization a major contributor to electrification. In the near future, electricity has the power to transform cities for the better. It will radically reduce local pollution by replacing fossil fuels in transportation and heating, and facilitate a digital revolution that will deliver a huge range of new services to citizens.

OVERVIEW

Right from its origins in the 19th century, electricity has been at the heart of economic and social development. Looking to the future with the will to bring modern levels of quality of life to everyone worldwide, efficient and clean electricity has a vital role to play, especially as urbanization and digitalization increase. In the coming decades, electricity will become the energy of choice for most end-uses, thanks to three major trends: economic development (see sub-section 1.1), global momentum to tackle climate change (1.2) and urbanization and local initiatives on air quality and noise reduction (1.3).

FIGURE 1.1 **Great scope for electrification in all GSEP countries**

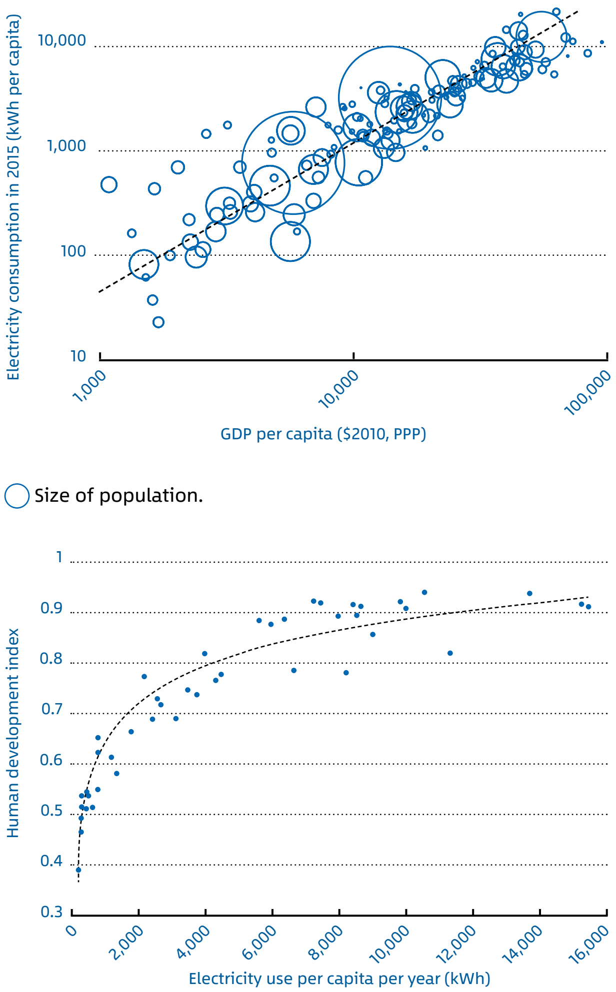


Breakdown of electricity share in main energy-consuming sectors, GSEP countries, 2016.

Source: Enerdata.

1.1 Electricity fuels economic and social development

FIGURE 1.2 **Economic and human development goes hand in hand with electricity**



Source: IEA database and World Bank 2013.

Electricity is at the heart of economic development, industrialization and urbanization. The US National Academy of Engineering identified societal electrification as the "greatest engineering achievement" of the 20th century. Over the same period, aided by the benefits brought by electricity, the global population grew by over 50%. As metropolises developed, transportation was revolutionized, medical care improved dramatically and a vast system of electronic communications emerged. Electrification was accompanied by a marked increase in the efficiency of primary energy consumption, and therefore with a reduction in energy intensity.

Well beyond the Second Industrial Revolution of the late 19th and early 20th century, electricity electricity has been closely correlated with GDP growth. For instance, when electricity spread rapidly in the USA in the early 20th century, electricity contributed from one-third to one-half the productivity growth per capita.[1] Today, we can see a strong correlation between electricity consumption per capita and both revenue levels and the Human Development Index (which incorporates other measures of well-being), as shown in Figure 1.2.

Developing countries have expanded access to electricity, but we can go faster. There are positive signs: over 100 million people per year have gained access to electricity since 2012 compared with around 60 million per year from 2000 to 2012. However, 1.1 billion people still do not have access to electricity and 40% of the world's population (2.8 billion people) rely on wood, coal or animal waste for cooking and heating. Household air pollution from these sources is currently linked to three million premature deaths per year.[2] Meeting the United Nations' Sustainable Development Goals (SDGs) and providing electricity access to all by 2030 would correspond to 188 GW of new power generating capacity by 2030,[3] equivalent to around 3% of the world's current power generation capacity.

Industrialization and urbanization levels determine best way to expand access to electricity.

In areas with high population density and a fast-growing economy, large capacities and stable generation are needed, strengthening the case for network solutions that incorporate centralized as well as decentralized generation. As far as renewable generation is concerned, large interconnected grids address the intermittency of generation by pooling resources and flexibilities in both production and demand, allowing more renewable capacity.

For more isolated rural areas far from power grids and with little energy demand, off-grid electricity systems, generally based on PV-battery combinations, are new ways of delivering clean energy. Most off-grid solutions sold today provide only basic, low-power energy services, such as lighting and mobile phone charging. Under-electrified households often cannot either afford or access enough energy to power additional services, such as cooling, refrigeration and entertainment. Nonetheless, energy efficiency can open up commercial opportunities in this sector by enabling off-grid households to run more appliances from a limited amount of electricity. This in turn fuels consumer demand for new types of products. Off-grid appliances are poised for significant growth, and have the potential to become a $4.7 billion global market by 2020.[4]

ENEL'S MICROGRID IN MARCUS GARVEY, USA

New York City is one of the most energy-intensive urban environments in the world. As loads grow over time, different networks become constrained. The Marcus Garvey Village microgrid developed by DEN - Demand Energy (Enel Group) is a perfect example of how a major city can build an intelligently controlled distributed digital power grid, provide local resiliency and other grid-supporting capabilities. The owners of the 625-apartment Marcus Garvey Village are deploying a first-of-its-kind microgrid integrating solar PV, storage and a fuel cell with Demand Energy Network's intelligent software to manage these distributed energy resources. A key aspect of the project is the ability of DEN.OS to ensure that the Village self-consumes all the energy it generates, without exporting to the grid. In particular, the Garvey Village Apartments Microgrid includes 400 kW of solar PV, a 400 kW fuel cell and 300 kW/1.2 MWh of energy storage (fully managed by DEN.OS). Furthermore, the project has won the prestigious ESNA Innovation Award for distributed storage.

Access to clean electricity for all is a springboard for many SDGs. With respect to the 17 SDGs adopted in 2015, much remains to be done, especially in sub-Saharan Africa and Central and South Asia.[5] In total 10-11% of the world population was still beneath the poverty line in 2016, undernourished and without access to clean drinking water, while 9% of children lack primary education and at least twice that secondary education. Decarbonized electricity makes a significant contribution to SDG 7 (access to energy for all) and SDG 13 (tackling climate change). However, electricity also correlates positively to all the other goals, and especially to the eradication of poverty, food security, access to water and sanitation, industrialization, innovation and sustainable cities.[6]

Smart infrastructure empowers customers, enhances reliability, reinforces resilience and reduces long-term costs. Examples include effectively deployed advanced digital technologies, improved power lines and substations and cyber and physical security measures. The grid is the enabling platform for clean and distributed energy resources, smart meters, storage, microgrids, visibility, management, reliability, resilience, security, analytics, customer solutions and digital sensing, monitoring and controls.

1.2 Electricity is at the heart of tackling climate change

Electricity is essential to energy decarbonization. In order to reach the Paris Agreement goals on climate change, the global economy will need to reach peak greenhouse gas emissions as soon as possible and then aim for zero net emissions in the second half of the century. Energy is responsible for around two-thirds of global emissions, and electricity will play a key role in decarbonizing it. Major studies on decarbonization consistently emphasize three essential actions with regard to electricity:[7]

1. **Enhance energy efficiency**
2. **Decarbonize generation for electricity**
3. **Electrify end-uses.**

Electricity is set to become the world's leading energy source by 2050. In both the IEA and the IPCC's trajectories for 2°C scenarios, the share of electricity in global final energy demand is expected to nearly double by 2050 (from 18% to 32-38%),[8] becoming the largest final energy carrier after 2050. Looking at carbon-free energy objectives for 2050, for which clean electricity should constitute the vast majority, the ambition is even higher. Electricity should therefore represent a major share in final energy demand in various sectors by 2050:[9]

- In buildings, electricity's share of final energy demand worldwide needs to more than double from 30% today to 50-75% in 2050;
- In transportation, a major transformation is required to raise the share of carbon-free energies (electricity, biofuels and hydrogen) in final energy demand, from 4% today to above 40% of in 2050;
- In industry, the share of carbon-free energies in global final energy demand should double from 23% today to around 50% in 2050.

To achieve those targets, the pace of electrification worldwide (which is to say, the growth of the share of electricity in global energy consumption) must double from the current rate of increase of 1.2% per year (2000-2016) to over 2.5% per year.

Momentum behind the electrification of end-uses is needed now. Ambitious actions are required on the three pillars at the same time. Governments and NGO are deploying a wide range of initiatives on the first two (energy efficiency and decarbonizing the power mix) but seem to be postponing real action on the third pillar (switching from fossil fuels to electricity in all sectors) until such a time that the power generation mix is mainly carbon-free. Given the delays in renewing assets downstream (about 10 years for cars and 20 to 30 years for heating systems), setting up industrial sectors (batteries, electric vehicles, etc.) and establishing infrastructure (charging stations, railways, electricity networks), we should not wait until 2050 before deploying suitable solutions to electrify end-uses, in order to avoid massive lock-in effects, including stranded assets.

The electrification of end-uses fosters energy efficiency and decarbonization. Electrical technologies can be as much as three to five times more efficient than fossil fuel ones. For example, electric cars have an output of about 80-90% compared to 15-25% for internal combustion engines (ICEs), while heat pumps have a coefficient of performance (COP) of above 300% compared to 80-90% for gas or fuel boilers. To decarbonize the power mix, electrification combined with new digital services such as home management brings more flexible electricity demand, which in turn facilitates the growth of renewable capacity.

KANSAI'S "VIRTUAL POWER PLANT" EXPERIMENTATION OF COUPLING POWER, HEAT AND MOBILITY

Sector coupling is using electricity from renewables for heating and cooling and for electric vehicles (EVs). This transfer of clean electricity is made possible by two factors. First, the growing use of digital technologies (especially connected devices and smart-home management systems) in end-uses increases the electricity system's flexibility. Second, smart grids, which allow a more precise management of the electricity system as a whole, matching variable renewable energy generation and flexible demand more efficiently.

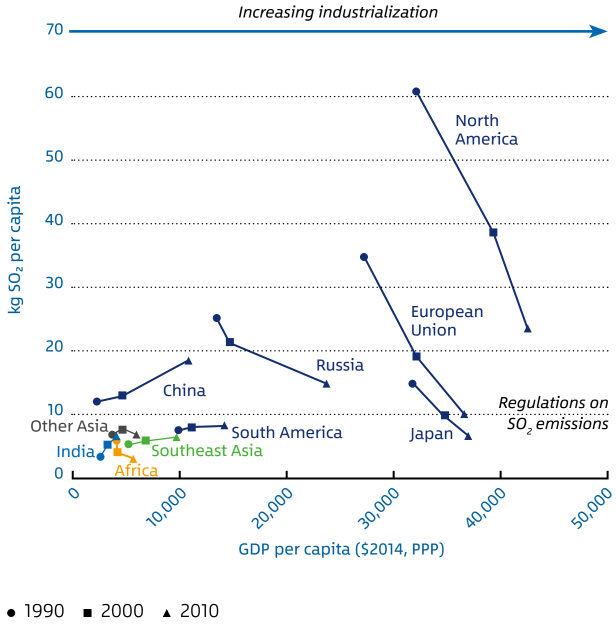
In Japan, Kansai Electric Power Company (KEPCO) is leading a large-scale demonstration project, along with 15 firms (Fuji Electric Co, Sumitomo Electric Industries, Nihon Unisys, etc.). Named the "Virtual Power Plant", it is a network of decentralized energy resources such as batteries, electric vehicles, heat pumps and generators as well as flexible consumers (for heating, cooling, etc.), up to 15 MW. All these interconnected units are dispatched through a central system which aim to smartly distribute the power generated by individual units and relieve the load on the grid during peak hours. Thanks to the optimization of the central system, this project brings new value for customers and at the same time, achieves low-carbon power generation.

In 2018, the project went into a new step with KEPCO, Sumitomo Electric Industries and Nissan Motor starting a full-scale study on remote-controlled charging of electric vehicles, in order to improve their use as energy resources. For the first time in Japan, a newly-developed EV switch, to remotely control the charging of 60 EV units, has been launched at KEPCO offices and general households. Based on the EV information given via the VPP server, the charging of EVs is adjusted to the need of power storage. In addition, the use of smartphone apps in order to confirm the availability of EVs by the owners is being monitored. Data collected during this study will be analyzed, and the value of EVs as a VPP energy resource will be evaluated.

The technical information accumulated in this demonstration project should contribute to decarbonize both building and transportation sectors due to broad use of EVs and electric thermal systems in the future, powered by a reliable and low-carbon electricity supply, improving energy efficiency.

1.3 Electricity delivers better quality of life in an urbanizing world

FIGURE 1.3 **Major SO_2 emissions reductions achieved by industry and power generation**



Source: IEA, Energy and Air Pollution, World Energy Special Report, 2016.

Global urbanization trends are driving electricity growth. Today, 54% of the world's population lives in urban areas, compared to 30% in 1950. In 2050, with 2.5 billion additional people living in cities, essentially in India, China and Nigeria, two out of every three people on the planet will live in urban areas.[10] Electricity demand per capita in urban populations is 2.5 times higher than for rural ones, although final energy demand is only 1.3 times higher.[11] The global trend toward urbanization is therefore a strong driver of electrification. The rise of smart cities is another driver: digitalization is improving quality of life in cities, as more and enhanced digital interactions are built into daily life (smart lighting, real-time car and parking management, digital interactive walls in public places, etc.). Add this to the exponential growth of data use, and the share of electricity in cities' final energy demand is set to rise.

Switching to electricity creates sustainable, livable cities. Big cities today face issues of congestion and local pollution, especially noise and air pollution from ICEs and fossil-fuel heating systems. There are approximately 3.5 million premature deaths each year from outdoor air pollution, notably from fine particulate matter, sulfur oxides (SO_X), nitrogen oxides (NO_X) and ozone.[12] Almost all SO_X and NO_X emissions to the atmosphere are energy-related, as are some 85% of particulate matter emissions. Within the energy sector, oil use in vehicles and power generation are the leading emitters of NO_X. Consumption of biomass, kerosene and coal in the buildings sector, along with industrial use, are responsible for the bulk of the particulate matter reaching the atmosphere. Power generation and industry are the main sources of SO_X, mostly from coal use.[13]

Electricity – efficient, cost-effective, clean – is the answer for cities. Power generation has made substantial progress over the last decades in reducing SO_x and NO_x emissions (see Figure 1.3), with measures such as using low-sulfur fuels, improving combustion methods and installing sulfur and nitrogen scrubbers. With low-SO_x/NO_x emissions generation, by spreading those measures or by switching from coal to other sources of generation for the power mix, electricity can play a major role in depolluting cities from NO_x and particulate matter. Electrification of heating and cooling systems for buildings removes the air pollution from fossil fuel combustion, while electric cars and electric mass transit (trams, buses, subways, etc.) reduce air and noise pollution significantly. Furthermore, in the coming decades the development of autonomous electric vehicles represents the best option for reducing congestion in large cities, with less vehicles needed to ensure the same volumes of passenger journeys (in addition to freeing up space previously used for parking).

In the following chapters of the report, we will be looking at four major avenues for electrification:

1. **Lighting and appliances in buildings,**
2. **heating and cooling in buildings,**
3. **transportation and**
4. **industry.**

MUSE®, THE URBAN SPACE MANAGEMENT PLATFORM, LEADS A DIGITAL REVOLUTION IN DIJON (FRANCE)

Thanks to the collaborative urban space management platform MUSE® developed by EDF's subsidiary Citelum, towns can now list all of their connected equipment and manage operations undertaken by different service providers with the greatest of transparency.

Dijon Metropole, a gathering of 24 municipalities for 250,000 people in France, is using the MUSE® platform for its urban space connected management. The platform is connecting all the city's actors to control and manage in real-time all of the municipalities' various equipment (street lighting, traffic light systems, CCTV cameras etc.). On the platform, the city's public services have access to information about all the infrastructures of the municipality, and can efficiently plan maintenance interventions, optimize cost management and inform their partners on the progress of their work. Thanks to MUSE®, citizens can contact the city's public services from their mobile phone and signal any event on the streets requiring quick and coordinated management.

The platform meets the ambitions of Dijon Métropole regarding coordination, equipment management, inhabitants' safety and urban attractiveness development.

EFFICIENT ELECTRIFICATION IN THE US: REDUCED COST, BETTER ENERGY EFFICIENCY AND FEWER EMISSIONS

Electricity delivers a growing share of final energy use in the US, from 3% in 1950 to 21% at present. In parallel, power is becoming much cleaner: over the last decade, the US power sector has decarbonized (2005-2015: -21% CO_2) and continued to reduce air pollution (1990-2015: -87% SO_2 and -79% NO_x).[14] Today, the nation is approaching a tipping point, at which the use of electricity causes fewer greenhouse gas (GHG) emissions than the direct combustion of fossil fuels. Combined with more energy efficient end-use devices, these factors are driving interest in further electrification and have given rise to numerous studies on "environmentally beneficial electrification".[15]

The Electric Power Research Institute (EPRI) has developed four scenarios of efficient electrification in its US National Electrification Assessment (USNEA), published in April 2018.[16] Findings indicate that economy-wide electrification over the next three decades is set to reduce energy consumption, increase grid efficiency and flexibility, foster electric load growth and reduce GHG emissions.

All USNEA scenarios predict reductions in final energy consumption of at least 20% by 2050. However, while energy consumption would decline without electrification, electric load grows by a total of 24% to 52%, or up to 1.2% per year, in USNEA. The share of electricity rises to between 32% and 47%. Electrification of transport is the strongest driver, prompted by a cost advantage in electric vehicles before 2030 in all but the most conservative scenario. Innovation in technologies such as heat pumps in buildings and induction furnaces in industry lowers costs, drives higher adoption, and amplifies consumer benefit. Natural gas use also grows in industry and in power generation, where gas and nuclear provide balancing capacity to compensate for the growing share of variable renewables.

A 67% reduction of CO_2 emissions is achieved in the most ambitious scenario, based on a carbon value of $50 per short ton from 2020. Yet even in the scenario without any additional carbon policy, efficient electrification and efficiency gains reduce CO_2 emissions by 19%. A previous EPRI study also showed reduced air pollution, especially in cities.[17]

Recent reports from the Brattle Group indicate that coupling 100% electrification of heating and surface transport with power sector decarbonization could reduce US energy-related GHG emissions by more than 70% in 2050 compared to 2015.[18] Brattle sees electricity demand nearly double between 2015 and 2050, reversing the trend of declining utility sales. Even fulfilling the full technical roof-top photovoltaic potential would not reduce US grid electricity demand and CO_2 emissions by more than 9%, whereas electrification would increase demand by 105% and reduce GHG emissions by 72%.

The National Renewable Energy Laboratory (NREL) has also launched a major research initiative on electrification, the "Electrification Futures Study" (2018-2020). Results are not yet available, but a 2017 predecessor report indicated that electrification of the transportation, building and industrial sectors, coupled with power sector decarbonization, would reduce carbon emissions from fossil fuel combustion by up to 74% below 2005 levels.[19] NREL also predicts a 41% emissions reduction through electrification even without additional carbon policies.

Full electrification of energy end-uses will not come without a cost. The farthest-reaching electrification scenarios require a carbon value between $12 and $50/ton of CO_2 in 2050, as well as significant investment in new generating capacity, grid and charging infrastructure, and technologies to enhance power system flexibility, reliability and resilience.

NREL's maximum decarbonization scenario results in an increase of power demand of about 60% and average electricity prices $11/MWh (+23%) higher in 2040 than in its baseline case. Without a carbon policy, the average power price increase is $7/MWh in 2040 (+15%). However, Brattle sees electrification as the most obvious decarbonization pathway, as it requires fewer technological and cost improvements than other pathways such as biofuels or synthetic natural gas.

CHINA'S ELECTRICITY DEMAND INCREASES THANKS TO ECONOMIC GROWTH AND A SHIFT FROM FOSSIL FUELS

In 2017, total electricity consumption in China was 6.3 trillion kWh, 6.6% higher than in 2016. Agriculture's consumption increased by 7.3%, industry by 6.6%, services by 10.7% and the residential sector by 7.8%. China's power generation mix in 2017 has 37.8% of non-fossil capacity (+11.2% since 2010), generating 29.1% of its electricity (+9.8% since 2010).

China's electricity demand in 2020, 2030 and 2050 is predicted to rise to 7.5, 10.3 and 13.6 trillion kWh respectively. In total, the share of electricity in final energy demand in 2020, 2030 and 2050 will be 25.2%, 30.4% and 40.4% respectively.

In industry, the share of electricity in total energy demand will increase from 22.6% in 2015 to 27.6% in 2020, 33.1% in 2030 and 39.8% in 2050. In transportation, the share of electricity in total energy demand will increase from 3.9% in 2015 to 6.1% in 2020, 14.1% in 2030 and 33.2% in 2050. In the commercial sector, the share of electricity in total energy demand will increase from 34.7% in 2015 to 37.8% in 2020, 40.5% in 2030 and 47.3% in 2050. In the residential sector, the share of electricity in total energy demand will increase from 25.6% in 2015 to 28.4% in 2020, 34.0% in 2030 and 47.3% in 2050.

In the period from 2015 to 2030, industry will be the main driver for electricity demand growth, contributing 40% of the total growth. In the period from 2030-2050, the contribution from the industry sector will become negative, while the residential, transportation and commercial sectors will make contributions of 52%, 42% and 39% respectively to the total growth.

Thanks to its electrification initiative, involving nearly 100,000 projects, State Grid replaced 115 GWh of other energies with electricity in 2017. The period 2013-2017 saw an acceleration of State Grid's achievements with a total electrification figure of 358 GWh. State Grid's target for 2018 is 130 GWh, mainly from the installation of electric furnaces and replacing oil furnaces in airports and ports.

State Grid believes that the trends of electrification in both energy supply and demand side are speeding up, so called *re-electrification*. The supply side shows large-scale development and utilization of clean energy, especially new energy. The demand side witnesses deep substitution of fossil fuels by electricity, such as transportation electrification, electric motors, electric heating. The next-generation power system, as the fundamental platform of the energy transition, will become interconnected, intelligent, flexible, and controllable.

2

LIGHTING AND APPLIANCES

Efficiency opens avenues to the future

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Energy efficiency encourages the uptake of electricity over other energies, by expanding the goods and services that can be run on electricity. Energy demand from appliances grew by 50% from 1990 to 2016, a figure which would have been twice as high without energy efficiency improvements. There is still considerable potential growth in traditional household appliance rates, which are currently 60-80% in OECD countries and 35% in non-OECD countries. Connected devices are another source of growth for electricity, with devices having gone from 500 million in 2005 to eight billion today and predicted to rise to one trillion in 2030.

The growth of digital will generate new business models. A multi-use digital landscape, with the Internet of Things (IoT), new services and greater energy demand management, is drawing in new actors (GAFA, telecom operators, manufacturers, etc.) to the energy system. This raises questions about how value chains will evolve and what partnership models might emerge for energy utilities in the transformed ecosystem.

Only flexible regulation will keep step with the astonishing pace of innovation, as new digital technologies emerge with incredible rapidity. Both the number of devices and the volume of data are expanding exponentially (for example, 90% of all data were created in the last two years). Regulation can encourage wider consumer adoption of connected devices by ensuring standards on privacy, cybersecurity and system resilience. Finally, regulation can foster a favorable market for demand response and the necessary development of smarter infrastructure.

2.1 CONTEXT

Constant progress in energy efficiency fosters new electric end-uses

Except for a few situations, electricity is the only energy source used for lighting and appliances. However, other major building end-uses (space heating, cooking and water heating) can use other sources of energy. Recently, electricity has fed the development of electronic devices and ICTs (information and communication technologies). In developing countries, some other energy sources (mainly oil) are used for lighting and some appliances work with gas, but these are very particular cases. Given that with these exceptions electricity is practically the only source of energy for lighting and appliances, levels of electricity demand depend on a combination of equipment rates and progress on energy efficiency.

Positive energy efficiency trends are set to continue, moderating the effects of electrification. Between 1990 and 2016, global energy demand for appliances grew by 50%, or around 1.6% per year. The great strides made in energy efficiency in the past few decades in many countries have been offset by factors such as population growth and growing access to electricity in developing countries, resulting in a net increase in demand. Since 2010, global energy use for lighting, appliances and equipment in buildings has grown steadily at 1% per year. This growth is driven by non-OECD countries, where the annual rate is twice the global one, thanks to improved access to electricity, increasing household wealth and greater demand for comfort.[20]

Energy savings from efficiency standards are expected to reduce OECD residential electricity consumption by 2025 by nearly 10% compared to current levels. Further research is needed for China and other non-OECD countries.[21]

FIGURE 2.1 **Final energy demand worldwide**

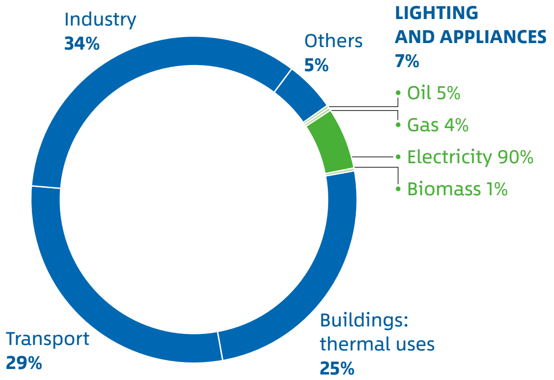
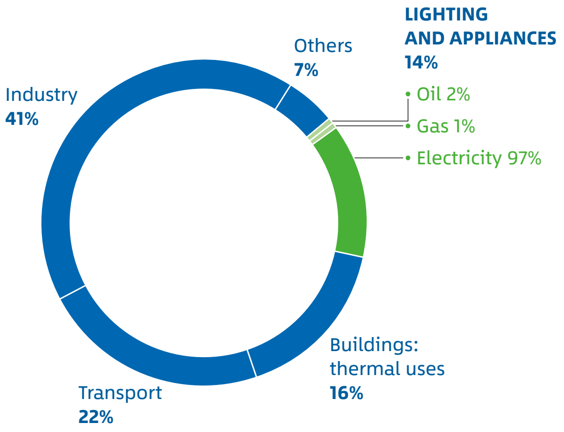


FIGURE 2.2 **CO_2 Emissions from energy combustion**



CO_2 emissions for electricity are calculated from total emissions in proportion to each sector's electrical demand.

Source: IEA ETP 2017

Energy efficiency makes electricity more attractive. Gains in efficiency ensure cost reductions in the services provided by electrical appliances, which in turn encourages the development of newer electrical services. People will see reductions in their energy bill as they renew their assets, so they can turn to new devices and new services. Illustrations of these effects are given in sub-section 2.2.

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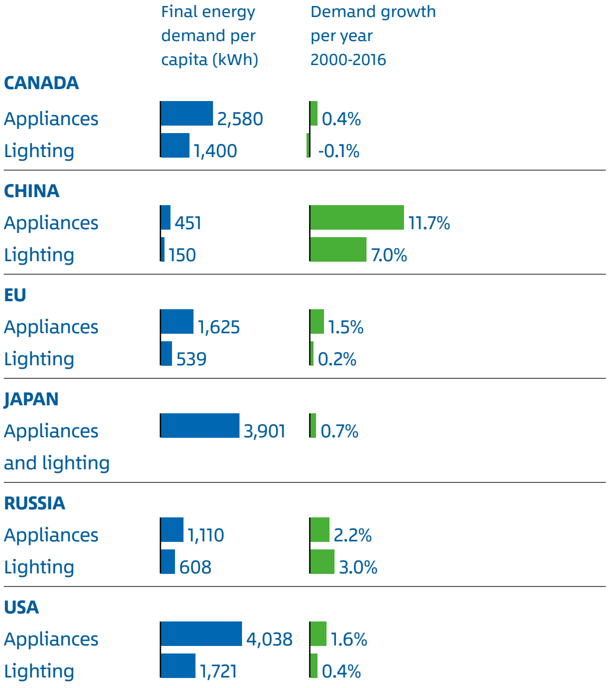
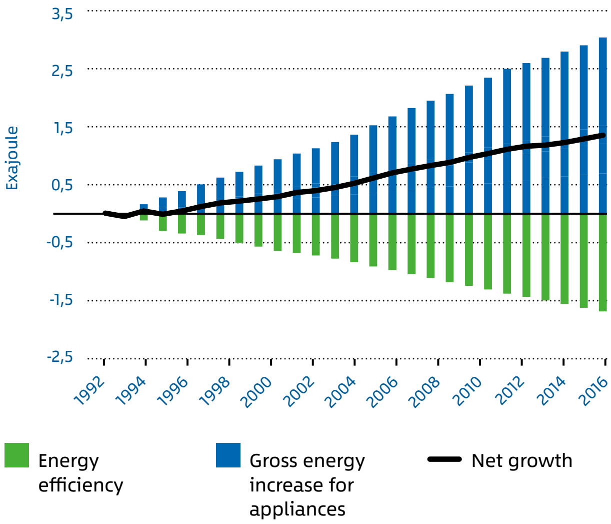
FIGURE 2.3 **Demand for appliances and lighting on the rise**



Demand for appliances and lighting in buildings (residential and commercial) for GSEP countries, in 2016.

Source: Enerdata

FIGURE 2.4 **Energy efficiency moderating energy demand growth of major appliances**



The figure shows the final energy growth decomposition of major appliances in buildings worldwide. Despite major progress in energy efficiency (EE), factors such as population growth, reduction of household occupancy, electrification (especially in emerging countries) and other energy demand factors (such as the increase in appliance ownership) have more than compensated for EE effects. It results in a net growth of energy consumption by major appliances over the last 25 years. Source: chart from IEA Energy Technology Perspectives 2017.

2.2 CASE STUDIES

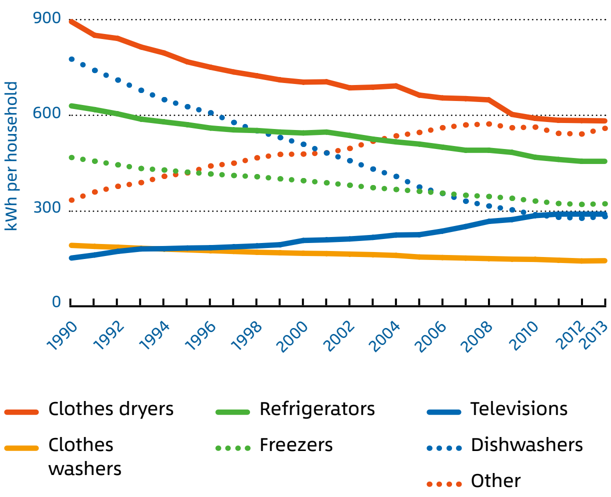
Energy efficiency for lighting and appliances boosts equipment rates

A transformation in lighting. The switch from oil to gas and then from gas to electricity has reduced the price of lighting over the last two centuries nearly 3,000-fold. Over the same period, the use of lighting has increased nearly 40,000-fold (see box p. 27). More recently, the use of LEDs has been an important step forward, as they are nearly ten times more efficient than traditional incandescent light bulbs, and have longer lifespans, making them five to seven times less expensive over their lifespan. In 2015, high-efficiency LEDs represented 15% of total residential lamp sales and were estimated to have grown to nearly 30% in 2016. Around 90% of indoor lighting worldwide is expected to be provided by compact fluorescent lamps (CFLs) and light-emitting diodes (LEDs) in five years' time.[22]

Scope for greater equipment rates as people aspire to better comfort.

If we look at traditional household appliances (white goods), the equipment rates in OECD show potential margins for Europe and Asia, and very strong potential margins for growth markets (see Figure 2.6). Progress in energy efficiency is helping the deployment of new electrical appliances in emerging countries as well as in advanced economies (Figure 2.5).

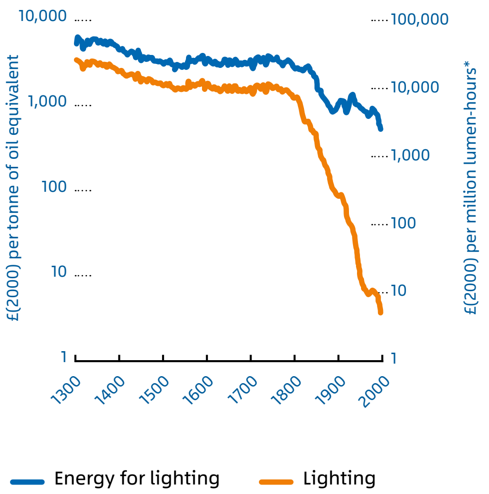
FIGURE 2.5 **Progress in energy efficiency for household appliances**



Source: IEA'S ETP 2017 report.

ENERGY EFFICIENCY HAS LED TO EXPONENTIAL COST REDUCTIONS IN LIGHTING SINCE THE 1800s

Trends in the price of energy for lighting (left axis) and in volumes of lighting (right axis)

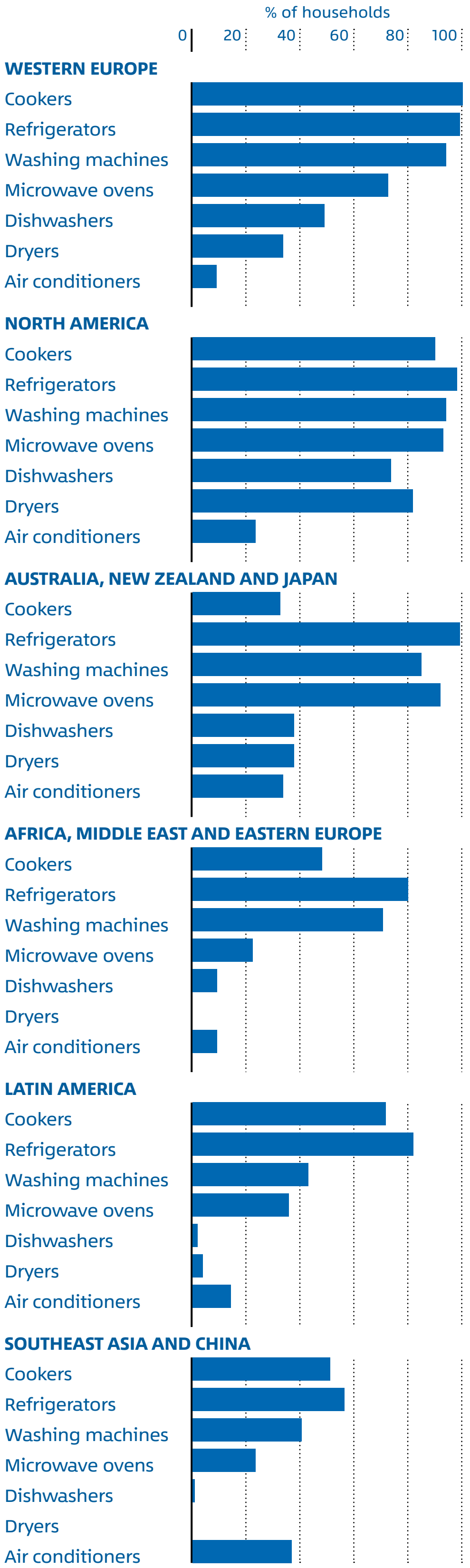


Five years averages

The use of gas for lighting since the early 1800s and then of electricity since the beginning of the 1900s have enabled a fall in lighting service's price of more than 3,000-fold between 1800 and 2000. During the same period, real income per capita increased from £1,750 (2000 prices) per year in 1800 to £17,000 in 2000 – nearly a ten-fold rise in 200 years. Total lighting consumption soared from less than 20 billion lumen-hours in 1800 to nearly 800,000 billion lumen-hours in 2000 – a 40,000-fold rise in 200 years.

Source: R. Fouquet et P. Pearson, "The Long Run Demand for lighting", 2012

FIGURE 2.6 **Large remaining potential for household appliances**

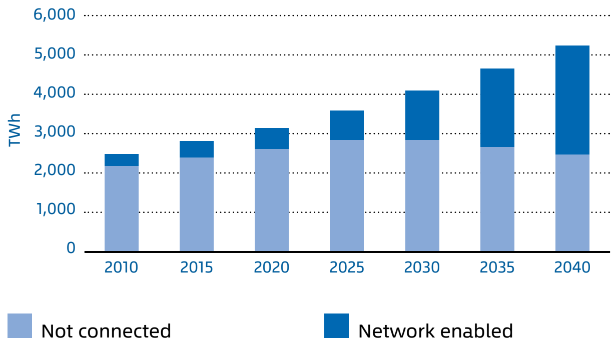


Source: Electrolux Annual Report 2015 – Market overview.

2.3 DIGITAL DRIVING GROWTH

Exponential energy needs moderated by improving efficiency

FIGURE 2.7 **Household electricity consumption from connected devices on the rise**

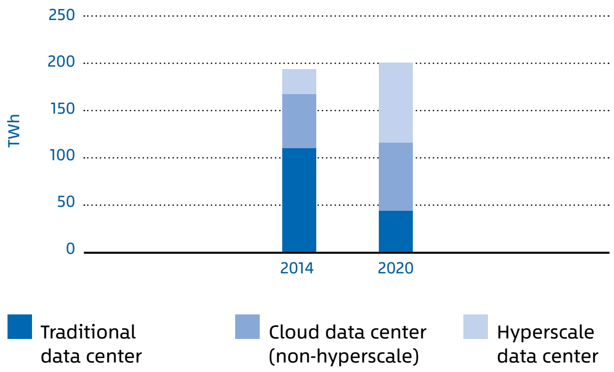


The share of connected "network-enabled" appliances in total household electricity consumption is set to grow rapidly, presenting opportunities for smart demand response but also increasing the need for standing power consumption.

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.

Source: IEA's Digitalization and Energy report 2017.

FIGURE 2.8 **Data center electricity use**



Sustained efficiency gains could keep energy demand largely in check over the next five years, despite exponential growth in demand for data center and network services.

Source: IEA's Digitalization and Energy report 2017.

The extensive development of digital tools over the last decades has brought significant gains in comfort and services, but also significant growth drivers for electricity demand. Increasing connectivity is driving demand for data center services and electricity, as is the development of the Internet of Things (IoT).

The number of connected devices and appliances is set to rocket, with an exponential impact on the volumes of data transmission. If the Internet began by connecting people with each other, we are now at the beginnings of an era in which people and objects will be connected (through an app on a smartphone for example), and moreover in which connections between objects will represent the bulk of connected object transmissions. In 2005 there were 500 million connected objects; today there are eight billion. The World Economic Forum estimates that there will be 100 times more in 2030, or around one trillion.[23] The decrease in cost and the increase in the quality of local or zonal radio networks will be one of the key enabling factors. 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.

Connected devices aren't just about electricity from the plug. Connected devices consume electricity for their day-to-day use, but they also involve electricity consumption in data transmission and other energies in their initial manufacture. We can anticipate growth in electricity demand in households from the increase in connected devices (see Figure 2.7). It should be emphasized, however, that the manufacture of devices and data transmission are both significantly more energy-hungry than their operation, especially given that the devices are getting smaller and consume energy efficiently. To take one striking example, more than three-quarters of the lifecycle energy use for a tablet is associated with its manufacture, and only one-quarter for use-phase energy (charging the battery). Moreover, the energy used to provide its Internet services is estimated to be over ten times greater than the energy needed for the production, use and disposal of the device.[24]

Efficiency will allow data centers to triple workloads for the same energy consumption, but major question marks remain on the evolution of total consumption beyond 2020. Global data center electricity demand in 2014 was estimated to be around 194 TWh, or about 1% of global final demand for electricity.[25] Despite large increases in demand for data center services, major efforts to improve energy efficiency have restrained electricity demand growth in recent years. Based on current trends in the efficiency of hardware and data center infrastructure, the IEA expects global data center energy demand to remain around 200 TWh in 2020, despite a projected tripling of data center workloads, a 22% increase in the number of servers and a 46% increase in storage drives. The shift to much greater shares of cloud and hyperscale data centers, which are more efficient than traditional data centers, is one of the main reasons for this predicted flat demand in coming years[26] (see Figure 2.8).

For example, Google recently announced a 40% reduction in the amount of electricity needed to cool its data centers, thanks to its DeepMind artificial intelligence (AI) system's management of power usage. According to Google, they are now able to draw around 3.5 times the computing power from the same amount of energy compared to five years ago.

Internet data transmission networks consume as much as data centers, around 190 TWh worldwide, making them the second major source of energy demand driven by connected devices. Two-thirds of their demand comes from mobile data networks and one-third from fixed networks. Depending on the rate of efficiency, there is a wide range of possible outcomes for demand in 2020: it could rise by 70% to around 320 TWh or drop by 15% to around 160 TWh.[27] Development of new infrastructure for mobile networks, such as 5G, should help to increase efficiency while allowing more network traffic.

A wide range of trajectories looking beyond 2020. In recent years, worldwide electricity consumption for ICT grew at an estimated annual rate of 7-8% against 2-3% for global electricity consumption. Staying on the same trends, ICT's share in global electricity consumption could rise from an estimated 10% in 2010 to 20-30% in 2030. A recent study on global ICT electricity demand expects it to grow from 2,000 TWh in 2010 to over 8,000 TWh in 2030, although the different scenarios show a wide range of trajectories.[28]

SMART METERS IMPROVE CUSTOMER SERVICES AND GRID OPERATION

In its new development strategy, State Grid aims to become a world-leading energy internet enterprise, by employing advanced Information & Communication technologies and "Internet + Energy" innovation.

In China, by the end of 2017, the coverage rate of automatic information collection by State Grid smart meters was over 99%, and 70% of customers chose to pay their bills by direct debit, online payment, smart phone apps and telephone. 3.3 million households were covered by "N in One" meters, which provide integrated metering services for electricity, water, gas and heat. Smart meters improve service and billing and also system operation and grid planning.

2.4 BUSINESS OPPORTUNITIES

A shift to services on a wider scale

Digitalization is generating new business models, as companies develop new services in addition to the core business of energy supply. Competition will increase as non-energy actors arrive on the scene. In many sectors, competition will intensify in energy supply due to technological innovation and related regulatory changes, which tend to blur the lines between energy utilities and their upstream partners, and even with clients as they become producers. For example, some building constructors have already set up subsidiaries specializing in energy systems for smart buildings, while some online general retailers are using their e-market platforms to sell gas and electricity to customers. As such movements among the different actors in the value chain increase, energy utilities can capitalize on their expertise in energy management by developing new services to complement energy supply. As the number of connected devices grows over the coming years, they will be able to manage customers' energy demand flexibility at a low marginal cost, therefore providing competitive energy services: autonomous light or ventilation control, low-cost smart-charging of home devices, all possibly optimized in combination with PV generation and storage. Services are being focused increasingly on multi-use management to boost added value, associating energy management with comfort, entertainment or security in the house, which is bringing non-energy players into the sector via digital (GAFA, telecom operators, etc.). This multi-use approach raises vital questions about defining the right partnerships among the various players.

SOWEE: EDF'S START-UP FOR THE SMART-MANAGEMENT OF CONNECTED HOMES

With its connected hub and a range of services, EDF's subsidiary SOWEE allows its customers to control their heating down to the last degree and see exactly what they're spending. Sowee includes the control, sensors and a smart thermostat that works with the home's smart meters. An app allows customers to manage their energy from their phone. Sowee provides different temperature configurations throughout the day and/or budget control, and an "Away" setting to save energy. Sowee's smart-management system can help customers to reduce their energy bill up to 15%.

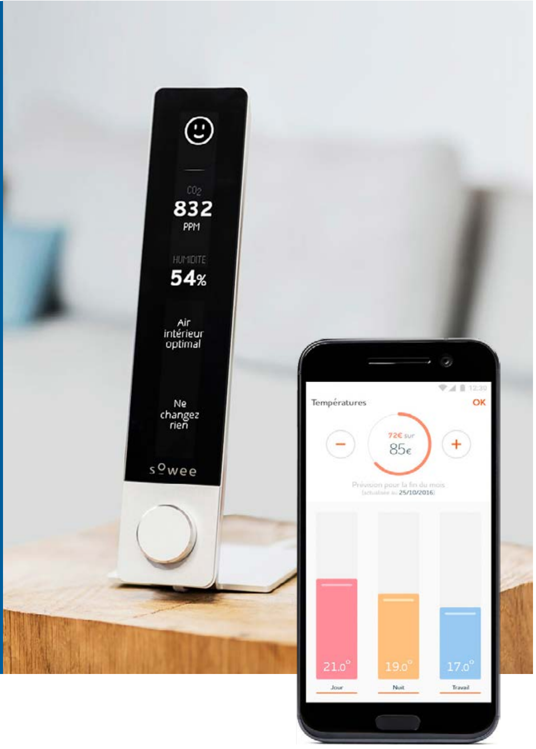
Sowee also allows customers to manage all the smart appliances in their home, with features such as weather forecasts, journey planning, humidity and CO_2 readings, providing simplicity and comfort. Sowee will soon be able to manage the energy production of photovoltaic panels and the charging of electric cars, driving the development of self-generated power and renewable energy solutions.

2.5

REGULATORY CONTEXT AND ENABLING POLICIES

A major role for policy-makers ahead

Governments can resolve asymmetries of information between companies and customers. Information on the electricity consumption of devices is hard to obtain for customers. Better customer information and the promulgation of best practices can be encouraged through regulation, policies and programs for more efficient devices, such as minimum energy performance standards, information campaigns and energy labeling. It should be stressed that standards on energy efficiency will be more effective if they are determined in line with state-of-the-art technology, so as not to slow down innovation. A systems-led approach, taking into account the potential impacts on economic development and people's security and comfort, would be optimal.



The pace of innovation in digital technologies is astonishing, so regulations will have to be flexible in order to adjust to rapid changes. The policy challenges in addressing energy use from connected devices are inherently different from those related to other historically important appliances such as refrigerators, freezers, air conditioners and televisions, which have been on the market for decades. With such 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 rate, with new types of devices with complex operating modes coming into use almost daily. In this new, rapidly moving reality, policy-makers will need to make creative use of the tools available to them.

Policy can help stimulate the uptake of smart appliances and equipment, especially by ensuring more flexible market conditions and regulation on privacy and cybersecurity. The most important issues are standards on security and transmission protocols between IoT systems, to address the privacy and cybersecurity concerns of citizens. At a system level, regulators need to allow the implementation of favorable market conditions for demand response, as well as the associated infrastructure for the electricity system, in order to ensure resilience. Electricity's expanding role in the energy system heightens requirements for resilience with respect to both natural forces (e.g. extreme weather) and physical or cyber-attacks. As electricity systems "go digital", from generation all the way through to the billions of connected devices, the points of vulnerability increase exponentially. However, that same digital capability can also be harnessed to locate, isolate and recover from both natural disruptions and malicious attacks.

3

BUILDINGS

Electricity provides smart and competitive solutions for heating and cooling

Huge potential to electrify buildings. Around 80% of buildings' energy consumption is used in thermal uses (and half of that is used for space heating). Today, 70% of buildings' heating consumption is produced by fossil fuels, yet modern and cost-competitive electricity technologies already exist for every thermal use. Many of these technologies are far more efficient than those they replace: for example, electric heat pumps use four times less energy than oil or gas boilers. Moreover, they can be used for both heating and also air conditioning, which is particularly susceptible to high growth given the very low current equipment rates and the reality of global warming. To help achieve the world's climate goals, electricity for buildings' thermal uses should rise from 14% today to over 50% in 2050.

Digitalization in buildings will boost both comfort and efficiency. The integration of supplier and user networks can and will lead to more reliable, flexible and affordable energy services. Smart thermostats will optimize thermal comfort while simultaneously delivering energy savings. Smart-home systems will allow more personalized services for customers. At the same time they will enhance the decarbonization of power generation by increasing demand flexibility, reducing the need for fossil fuel peak generation. Standards to ensure systems' reliability, privacy and cybersecurity are important preconditions.

Prompt action will pre-empt lock-in effects. Building renovations and heating/cooling systems last for decades, which means that choices based on small, short-term improvements in emissions can trap systems for decades to come. Good decisions now, on the other hand, will pay off for years. Governments can facilitate the transformation of the buildings' sector by ensuring an affordable electricity price through a generation mix optimized in line with available technologies and resources, and a level playing field for different energies (with a carbon value and the elimination of extra taxation on electricity). Definition of clear standards for customers is key to avoid the bias inherent in using indicator calculations based on primary energy.

3.1 CONTEXT

Smart competitive electricity technologies can reduce the volume of fossil fuels

Space heating, air conditioning, water heating and cooking mostly run on fossil fuels. The average share of electricity in final energy for thermal uses in buildings is only 14% worldwide. Thermal uses account for nearly 80% of the energy demand of the building sector worldwide, ranging from 56% to 86% in the different GSEP countries. The main use is heating, accounting for 40% of buildings' consumption, of which 70% is produced by fossil fuels.[29]

FIGURE 3.1 **Final energy demand worldwide**

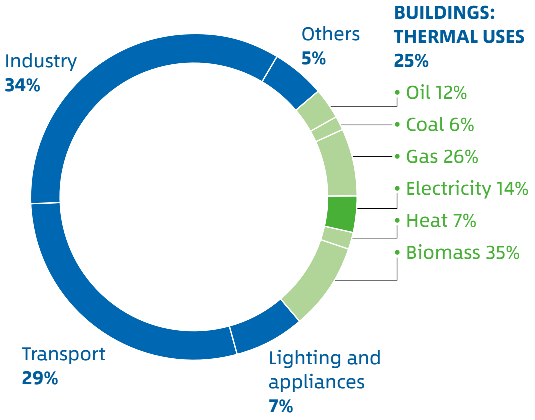
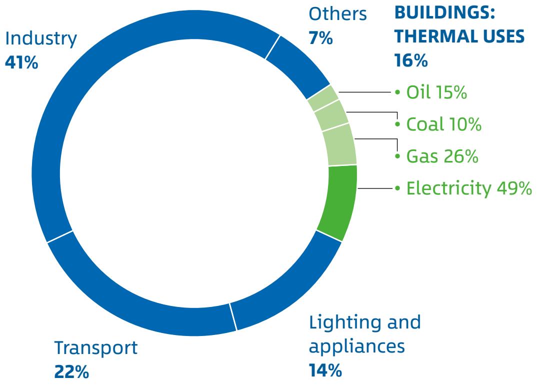


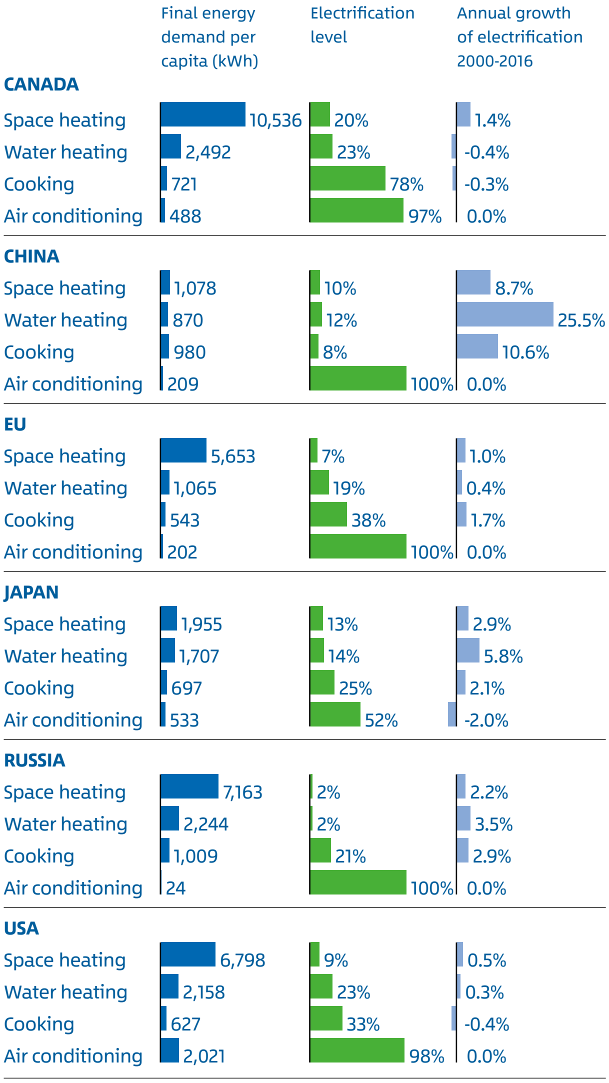
FIGURE 3.2 **CO_2 Emissions from energy combustion**



CO_2 emissions for electricity are calculated from total emissions in proportion to each sector's electrical demand.

Source: IEA ETP 2017.

FIGURE 3.3 **Space and water heating: the main target for electrification in buildings**



	Final energy demand per capita (kWh)	Electrification level	Annual growth of electrification 2000-2016
CANADA			
Space heating	10,536	20%	1.4%
Water heating	2,492	23%	-0.4%
Cooking	721	78%	-0.3%
Air conditioning	488	97%	0.0%
CHINA			
Space heating	1,078	10%	8.7%
Water heating	870	12%	25.5%
Cooking	980	8%	10.6%
Air conditioning	209	100%	0.0%
EU			
Space heating	5,653	7%	1.0%
Water heating	1,065	19%	0.4%
Cooking	543	38%	1.7%
Air conditioning	202	100%	0.0%
JAPAN			
Space heating	1,955	13%	2.9%
Water heating	1,707	14%	5.8%
Cooking	697	25%	2.1%
Air conditioning	533	52%	-2.0%
RUSSIA			
Space heating	7,163	2%	2.2%
Water heating	2,244	2%	3.5%
Cooking	1,009	21%	2.9%
Air conditioning	24	100%	0.0%
USA			
Space heating	6,798	9%	0.5%
Water heating	2,158	23%	0.3%
Cooking	627	33%	-0.4%
Air conditioning	2,021	98%	0.0%

Share of electricity for main thermal end-uses in buildings, GSEP countries, 2016.

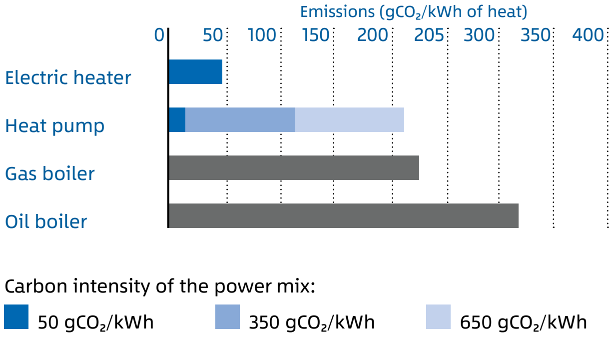
Source: Enerdata.

The climate needs faster deployment of low-carbon electricity solutions for thermal uses in buildings. The electrification trends of the past decades need to be enhanced to meet the electrification targets of the 2°C scenarios. In GSEP countries, the share of electricity in energy demand from buildings' thermal uses (air heating and cooling, water heating and cooking) has grown from less than 8% in 2000 to over 11% in 2016, representing a rate of electrification of 2.3% per year over the last 16 years. Keeping the same pace would mean a 24% share for electricity in 2050, still below trajectories for the 2°C scenarios, where electricity represents around 50% of energy for thermal uses in buildings in 2050.[30]

Showing the way to electrifying heating systems. Many countries have high electrification rates, but still have potential for the development of electricity in space heating:

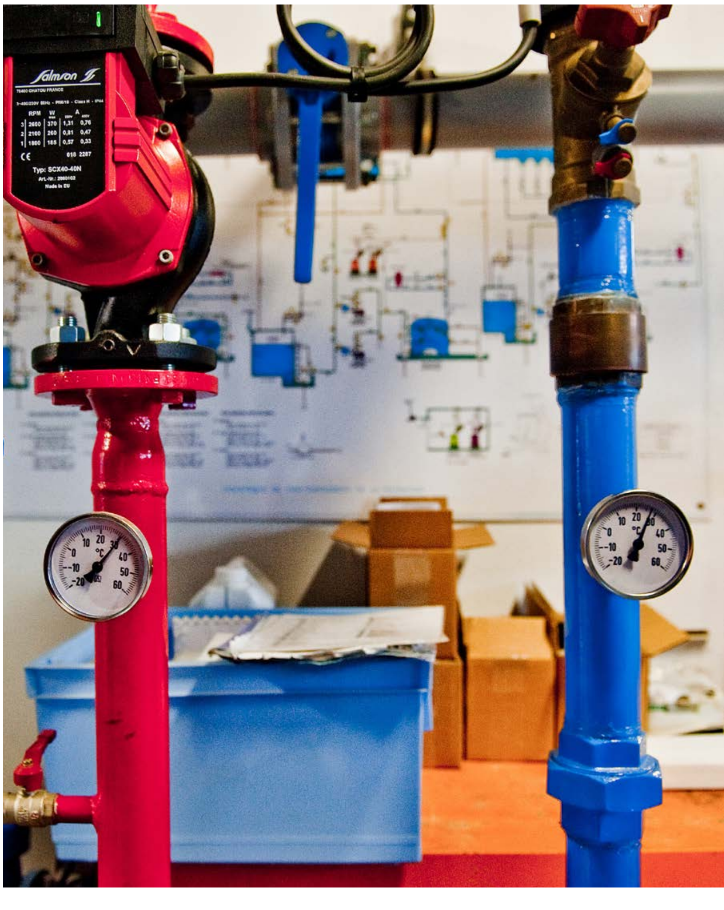
- In France, the market share of electricity for space heating is about one-third of households and for water heating nearly 50% of households.[31]
- In the US, electricity is the main heating source for more than one-third of households. More than 12 million households use electric heat pumps (over 10% of households).[32]
- In Norway, electricity is the main heating source for about 73% of households, either through electric space heaters (48%), electric floor heating (7%), air-air heat pumps (21%) or central heating run on electricity.[33]
- In Québec, a province of Canada, 78% of households use electric heating, 13% bioenergy, 4% fuel, 4% gas and 1% another source.[34]

FIGURE 3.4 **CO_2 emissions for different heating systems**



Electric heaters are an efficient solution for reducing CO_2 emissions of buildings with a low-carbon power mix (50 gCO_2/kWh). With more carbon-intensive power mix, electric heat pumps remain the most climate-friendly solution, at the EU average (350 gCO_2/kWh) or even at the world average (650 gCO_2/kWh).

Source: calculation by authors with an output of 85% for oil boiler, 90% for gas boiler, 300% (COP 3) for heat pumps and 100% for electric heater.



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3.2 CASE STUDIES

Efficient, cost-effective solutions for decarbonization exist already

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Electric heat pumps generate around 3 to 4 kWh of heat for every kWh of electricity, with a triple advantage: two-thirds of heat generation comes from renewable generation, high energy efficiency and big reductions in customers' energy bills. This energy performance of 300-400% is far in excess of the maximum of 90%-100% reachable by a top-class gas or oil boiler. Moreover, most heat pump systems are reversible as they work for space heating and cooling, and are easy to control, enabling more comfort and efficiency. Fed by the average electricity mix in Europe, heat pumps emit less CO_2 than any other heating device. If heat pumps were widely adopted for space and water heating applications in buildings, they would reduce 2050 global CO_2 emissions by 1.25 billion tonnes.[35]

There are different types of heat pumps, depending on requirements:

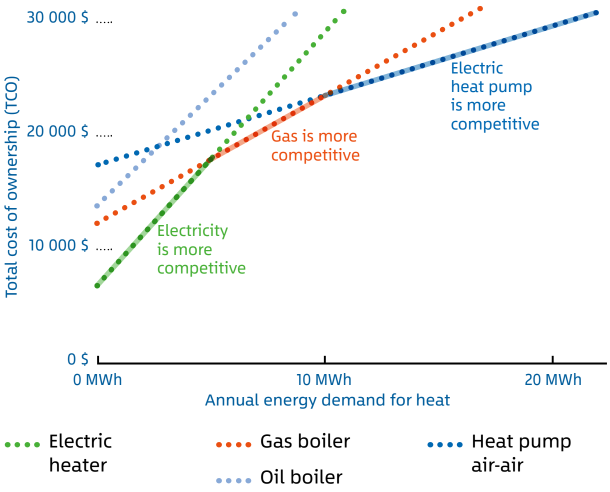
- Air-to-air central, split and room air conditioners are the standard technology for air conditioning (either one room, or the entire dwelling/building) in many regions. They can be reversible, allowing them to provide heating as well. Among heat pump systems, they have the lowest capital cost, are easy to install and are well-suited for modern or renovated buildings with median to high energy consumption.

- Air-to-water or water-to-water systems provide sanitary hot water and space heating. As they require water-based heating systems, they are more capital-intensive and expensive to install in existing buildings (factoring in the cost of changing the existing heating system). However, they are well-suited to new buildings. In France, 50% of new houses are equipped with electric water-based heat pumps for heating.

Technological advances should boost the market share of heat pumps. The investment cost of heat pumps for water or space heating can be higher than the cost of traditional boilers in some cases, but with major savings on energy bills. Nevertheless, the technology cost is decreasing. While heat pumps are a mature technology, their efficiency is expected to increase by 30-50% for heating by 2030, reaching a coefficient of performance (COP) of 4 to 5.[36] Cost reductions are expected as a consequence of technology improvements, market penetration and synergy with thermal storage systems.

Heat pumps are usually particularly well-suited to the relatively mild winters in hot-humid areas and some mixed-humid areas. However, advances in heat pump technology, including cold-climate heat pumps, have enabled more efficient electric space heating in areas with lower winter temperatures. For instance, 1.3 million – or 3% – of US households in the cold/very cold climate region in 2015 had electric heat pumps. Furthermore, the development of hybrid energy systems with heat pumps can assure grid efficiency by lowering peak demand while minimizing cost by assuring best price arbitration for consumers.

FIGURE 3.5 **Competitiveness between electric and gas heating varies with consumption levels**



Competitiveness of technologies for space and water heating depends on the household's consumption level: in this example, with US residential prices, electricity is more competitive for an annual energy demand lower than 5MWh per year or over 10 MWh per year.

Calculations made by authors, from DOE EIA for US data: Electricity $125/MWh, Gas $45/MWh, Oil $8/MWh. Oil & Gas prices include a future Carbon Tax of $40/t (IEA WEO, NP scenario in 2030 for WCI Market). Total costs are calculated over 20 years.

ENERGY EFFICIENCY MEASURES REDUCE ENERGY INTENSITY IN QUÉBEC

The Government of Québec's real estate portfolio includes approximately 14,900 buildings comprising 43.5 million m^2. From 2002 to 2012, energy intensity (energy consumption per m^2 of floor area) was reduced by 11.2% through energy efficiency measures.

Electric heaters are optimal for well-insulated households with moderate energy demand, with reduced investment costs and strong progress on comfort associated with heating diffusion for the latest generation of electric heaters. Moreover, they can easily be controlled remotely, allowing customers to manage the temperature in every room separately. For bigger houses with higher energy consumption, for a low additional investment, electric heaters can be used as an auxiliary, in addition to a main heating system running on biomass.

Electric water heaters offer competitive storage capacity for renewable and nuclear generation. The electric water heater is a mature, profitable and efficient technology. It allows great flexibility in consumption, for a storage capacity equivalent to a basic Tesla Powerwall battery (around 5 kWh). This flexibility is especially valuable under a smart tariff system and with smart low-cost automation. For example, in France nearly 80% of domestic hot water electrical demand is now settled on a smart tariff signal that enables around 15 TWh (11% of residential electricity demand) to be shifted from peak hours to off-peak hours. The development of connected devices and the IoT should further enhance the flexibility potential associated with electric water heaters.

MULTIPLE USE OF RECYCLED SEWAGE WATER TO SUPPLY HOT WATER AND AIR CONDITIONING WITH HEAT PUMP TECHNOLOGY (Sakai city, Japan)

In Sakai city, Kansai Electric Power Company (KEPCO) has led a project which utilizes heat pumps in the sewage water recycling center to provide heat in winter and air conditioning in summer to the nearby shopping mall operated by Aeon Corporation. Power consumption was reduced by 11% and running costs by 25%. KEPCO is now promoting this first-of-a-kind project for municipalities and local communities.

NORTHERN CHINA, A MAJOR SHIFT FROM COAL TO ELECTRIC HEATING: 150 TWH ADDED ANNUALLY IN 2030?

By the end of 2017, State Grid had completed 18,000 electric heating projects in Northern China, reducing the coal burned in one heating season by 15 million tonnes.

At the end of 2017, ten government agencies jointly issued a plan for 2021 on clean heating in Northern China, including heat pumps, biomass, solar energy, natural gas, electricity, clean coal and industry waste heat. The main targets are for the penetration level of clean heating in Northern China to reach 50% by 2019 and 70% by 2021. National targets for electric heating will reach 150 million m^2 in 2021 (distributed electric heating, electric boilers and heat pumps) implying 110 TWh of added electricity consumption.

State Grid estimates that if all household heating in Northern China was transferred to electric heaters by 2030, the added annual electricity demand would be 150 TWh.

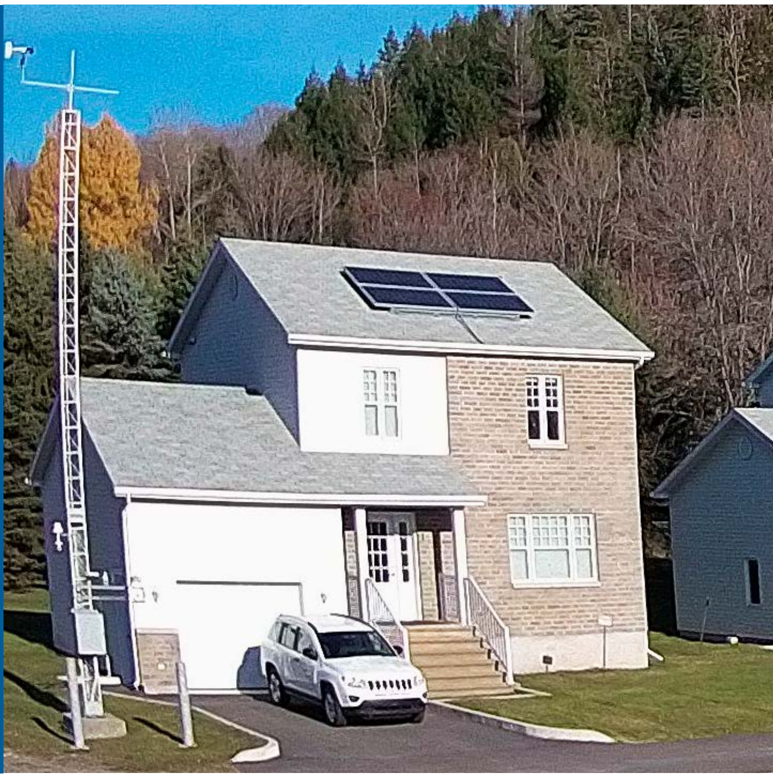
3.3 DIGITAL DRIVING GROWTH

New smart tools deliver comfort and efficiency in the home

Digitalization in buildings will improve comfort, with new services and the automation of heating and cooling management, resulting in an expansion of electrical devices. According to the IEA, global consumption in active control devices should rise from nearly zero in 2010 to 275 TWh/year in 2040 (this figure includes a predicted 50% efficiency gain). At the same time, digitalization will enable better management of energy through real-time measurements and adjustments, which will enable substantial efficiency gains. The IEA estimates 4,650 TWh of energy can potentially be saved through such active controls by 2040.[37] Digitalization will also facilitate demand response to reduce peak loads, and by monitoring real-time performance of buildings it will allow consumers and building managers to identify where and when maintenance is needed and where energy savings can be achieved.

HYDRO-QUÉBEC'S SMART HOME CONCEPT

In Shawinigan, Hydro-Québec experiments with the smart home concept. These homes of the future were adapted into net-zero-energy houses to understand the issues related to the growing popularity of advanced smart houses, electric vehicles – including vehicle-to-grid (V2G) and vehicle-to-home (V2H) applications – and distributed generation. Technologies being tested on these houses include smart home systems, a bidirectional EV charging station, and photovoltaic solar panels.



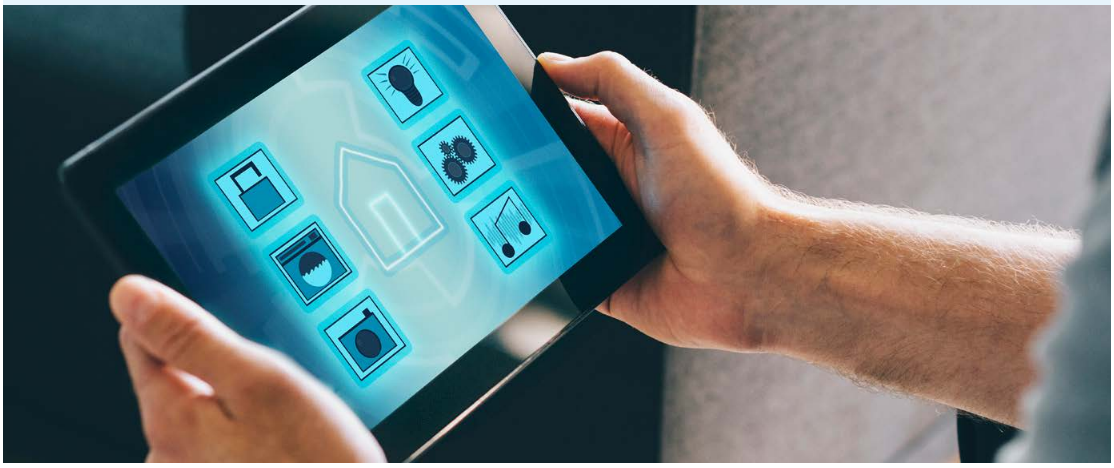
Smart thermostats improve the management of heating and cooling loads, allowing automated management and remote control of temperatures throughout a building. They ensure thermal comfort when and where it is needed while enabling energy savings when heating and cooling are not needed, thus making those systems more competitive. Increasingly, learning algorithms in smart thermostats can adapt the management of thermal comfort to customers' lifestyles, automatically pre-heating or pre-cooling a building space relative to expected occupant presence, user preferences, forecasted weather conditions and other inputs, such as energy prices.

In the United States, sales of smart thermostats doubled between 2014 and 2016, going from 3% of total residential thermostat sales to 6%. Globally, revenue from the sale of connected smart thermostats and their software and services is projected to increase from $1.1 billion in 2016 to $4.4 billion in 2025 (including $1.6 billion in North America, $1.3 billion in Asia-Pacific and $1.1 billion in Europe).[38]

CHINA IS EXPLORING SMART CITIES AND SMART INDUSTRIAL PARKS

In its 12th Five-Year Specific Plan, China planned to construct 5-10 demonstration projects for smart cities and 50 demonstration projects for smart industrial parks.

By the end of 2015, State Grid had built 32 smart communities or smart buildings in Beijing, Chongqing and Hebei. Smart communities and smart buildings not only created an interface between public utilities and consumers, but also enabled interaction between buildings and consumers. Based on the interactive processing of information, both public utilities and consumers can control electricity utilization in air conditioning units, electric boilers, lighting and smart appliances, improving comfort. Moreover, based on detailed online and off-line data and behavior analysis, electricity suppliers can provide consumers with advice on how to improve the efficiency of their energy use.



3.4 BUSINESS OPPORTUNITIES

Transitioning towards a wider service offer

Demand response is helping power utilities ensure the balance between supply and demand. For utility providers, beyond helping to secure a competitive advantage by offering better control to customers, encouraging the use of smart thermostats could also enable them to draw on customers' demand flexibility instead of adding power generation and network capacity.

Energy services companies have been helping businesses for many decades, for instance by providing services in heating and cooling operations and maintenance for industry and for public, commercial or large residential buildings. In the recent context, where new competitors are taking up positions in the energy supply sector, this expertise is more than ever an important asset for utilities to add value for their customers.

Now digital platforms are opening the way for energy services for the mass market. Such options for the retail market are already in place in many countries, having digital platforms with certified experts for the repair and maintenance of thermal systems. A variety of systems are feasible, such as open platforms or all-inclusive offers on energy services via a subscription fee.

ENEL X'S DEMAND RESPONSE

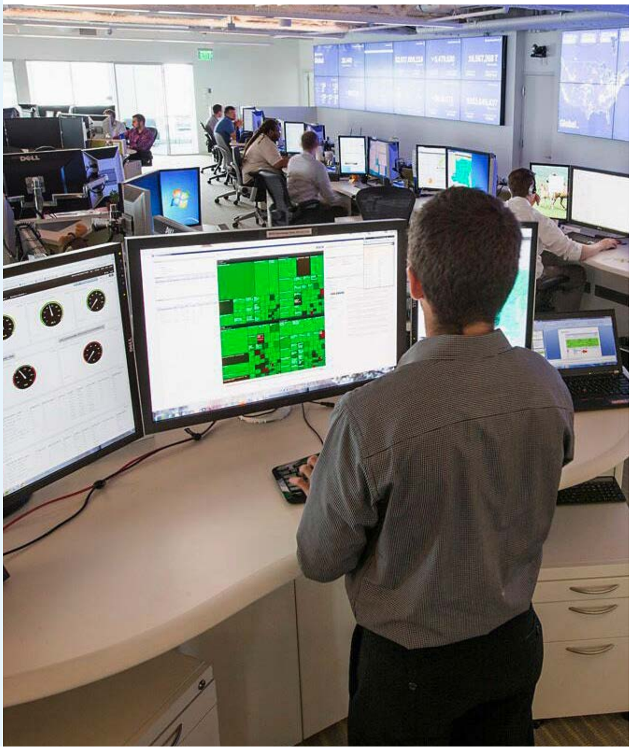
In August 2017 Enel finalized the acquisition of EnerNOC, the world's largest provider of demand response and energy intelligence software. EnerNOC partners with enterprises to reduce costs, manage risks, increase sustainability, and maximize the value of emerging energy technologies through customized energy management strategies. EnerNOC is the global leader in demand-side flexibility services, providing large energy users access to more demand response and demand management programs worldwide than any other provider. In addition to its flexibility solutions, EnerNOC's technology-enabled advisory solutions help large energy users create value through strategic energy procurement, energy management, and utility bill management software as well as services.

EnerNOC has more than 8,000 customers, 14,000 sites under management and a total of 6.2 GW of demand response capacity currently managed all around the world. Demand response programs are conceived for large energy customers, such as manufacturing facilities, data center and commercial real estate companies that are willing to adjust their energy consumption by either reducing or increasing their power consumption to stabilize the grid and earn money. Demand response provides grid flexibility, stability and more efficient use of power infrastructure in order to help maintain electricity prices as low as possible for all consumers and postpone investments on the grid. Enel X's demand response commercial and industrial clients are paid for the flexibility they provide to the system by staying ready in the event of a grid emergency and they obtain additional payments when they are effectively dispatched.

3.5 REGULATORY CONTEXT AND ENABLING POLICIES

Investments in infrastructure needed

Electricity needs a level playing field between energies to remain competitive: When deploying incentives that shape the generation mix (by influencing technology choices upstream) and influence the sizing of related networks, regulators should consider the price impacts on electrification. The decarbonization effort of the electricity mix should not penalize the penetration of electricity in end-uses, which would be a counterproductive in tacking climate change. The introduction of a carbon value would be a good incentive to create a level playing field between energies, helping guide consumers' investment choices towards sustainable electric solutions.



Get efficiency standards right: A review of efficiency measurements is needed to remove fuel bias and frame regulations that enable efficient electrification and continue to encourage energy efficiency. The use of indicators based on primary energy in thermal regulations should be avoided. While primary energy is a good indicator of security of supply in a fossil fuel era, it does not help in assessing the efficiency of end-uses in terms of competitiveness and CO_2 emissions. In some countries, the use of such indicators is encouraging gas heating systems instead of low-carbon electricity. Regulators should introduce clear indicators for consumers, with standards targeted on final energy efficiency and environment for new buildings, i.e. in price/m^2 and CO_2/m^2, and should ensure that customers can access neutral and efficient advice on the most cost-effective solutions.

For renovations, reliable diagnosis is needed on final energy consumption, with incentives to switch out equipment based on energy performance and related emissions, rather than on technology. This will increase competition between technologies, enhance innovation and reduce costs. It is also necessary to train installers in these new electrical technologies in order to ensure quality and further reduce costs.

We need to act quickly since cycles are long: heating systems have renewal cycles of around 20-30 years (against 10-15 years in transportation or industry). Ambitious renovation programs are therefore needed in order to avoid lock-in effects resulting from short-term choices for decarbonization (such as gas systems). States and communities have a wide range of existing tools (especially tax incentives) they can use to accelerate the transition. As long as it is cost-effective, renovation can be a rich creator of local jobs in the long run.

4

TRANSPORTATION

Electrification now within our reach

Massive electrification is ahead, advisable and achievable. Today, oil dominates transportation (95%). Among GSEP countries, between 50% and 70% of oil used for transportation fuels light-duty vehicles (passenger and freight), which can be easily and rapidly electrified in the coming decades. The key driver in this trend is the drop in battery prices, from $1,000/kWh in 2010 to $200/kWh today. Further falls of two-to-three-fold are anticipated in the coming decade, bringing light-duty electric vehicles (EVs) to competitiveness. Appropriate development initiatives for electric trucks and more R&D for electrically-generated clean hydrogen could also bring cost-effective solutions for electric heavy and long-distance road freight in the medium term.

Rapid EV deployment will drive optimization of the grid. Smart charging will ensure the reliability of the power grid and keep infrastructure costs in check by smoothing out capacity demand. Furthermore, “vehicle to grid/vehicle to home” (V2G/V2H) services will mobilize the storage capacity of hundreds of millions of EVs. This new resource will enable grid operators to integrate more variable renewable energies by balancing supply and demand. V2G/V2H services will also foster new partnerships between utilities and car manufacturers, creating synergies between the sectors.

Governments have a key role to play by ensuring (1) clear, shared, ambitious long-term objectives for electrifying transportation; (2) short-term support and common standards for electric mobility technologies and charging infrastructure; (3) affordable electricity, thanks to a level playing field among energies, the phase-out of fossil fuel subsidies and the inclusion of externalities (especially CO_2) in energy prices.

4.1 CONTEXT

Massive electrification potential for cars and trucks

FIGURE 4.1 **Final energy demand worldwide**

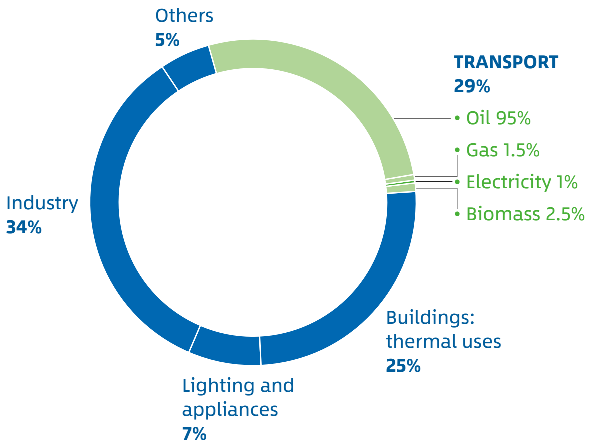
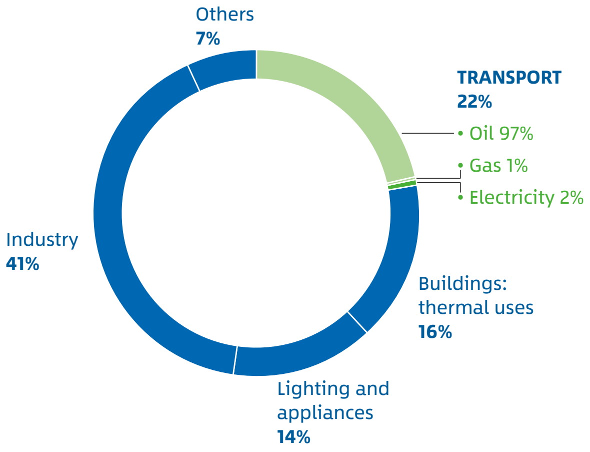


FIGURE 4.2 **CO_2 Emissions from energy combustion**



CO_2 emissions for electricity are calculated from total emissions in proportion to each sector's electrical demand.

Source: IEA ETP 2017.

The transportation sector massively relies on fossil fuels: the transportation sector is dominated by oil, which provides nearly 95% of transportation's energy demand, due to its high energy density and the ease with which it can be pumped and stored. Most of transportation energy demand comes from road passenger transport (50%) and road freight vehicles (30%), with major impacts of road transportation on CO_2 emissions and air pollution in cities.

The trend for electrification isn't fast enough: electricity represents barely 1% of the transportation sector, largely from the electrification of railways (trains, subways and trams). According to IEA and IPCCC projections, electricity's share will be around 4% in 2050 on current trends, whereas low-carbon energy ought to be ten times more than that under their 2°C scenarios, reaching over 40%. In the coming decades, the least expensive and fastest method of decarbonization is electrification, as the technologies exist already and are easy to implement on a mass scale. In addition, electrification does not put pressure on natural resources unlike biofuels which compete for arable land with food production.

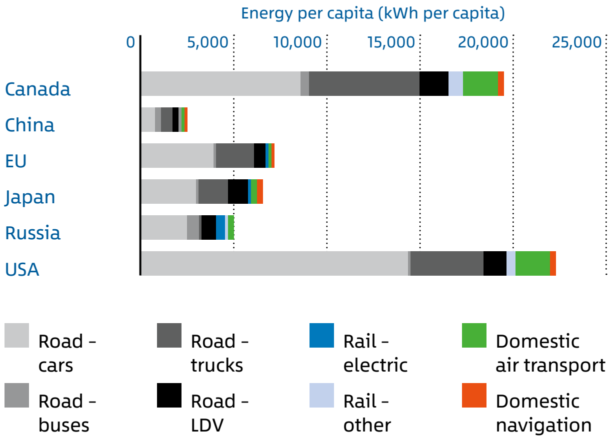
We can be more ambitious: some countries have put in place successful initiatives for the deployment of electric vehicles (EVs). In Norway the market share is already 39%.[39] The world electric car stock surpassed 3 million vehicles at the end of 2017 after crossing the one million threshold in 2015.[40] China is by far the largest market, accounting for more than 40% of EVs sold in the world. Despite those impressive numbers, the scale achieved so far is still small: the global electric car stock at the end of 2016 corresponds to just 0.2% of the total number of passenger light-duty vehicles in circulation.[41]

There is still a wide range of future projections although they are continually revised upward for the development rate of EV sales and the global EV fleet. Each year, stakeholders tend to review their projections upward because of the exponential progress on electric mobility, as we can see from Figure 4.4. Two main drivers explain these rapid changes of forecast: the continuing drop in lithium battery prices and the increase in government regulations and targets to support EVs.

Battery costs make up a large share of EV prices. Much progress has been made on this front in recent years, and the trend is expected to continue over the medium term (see Figure 4.5). The main factors that have driven battery costs down are industrialization and energy density. Over the 20 years between 1991 and 2011, cell density was increased three-fold and energy capacity seven-fold. Production of lithium-ion batteries has grown from 5 GWh in 2003 to 90 GWh in 2016 and recent estimates based on new factory buildings forecast 300 GWh in 2025.[42]

In November 2017 lithium-ion battery packs were selling at an average price of $209 per kilowatt-hour, down 24% from a year ago and about a fifth of the level in 2010 (see Figure 4.5).[43] There is also further room for improvement, with a predicted drop below $100 per kilowatt-hour by 2025, a price which is widely seen as a tipping point in the adoption of EVs, where total cost of ownership (TCO) parity between EVs and ICEs may be reached.

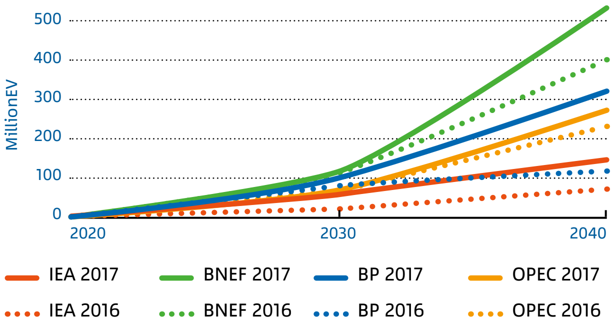
FIGURE 4.3 **Cars and trucks represent the bulk of domestic transportation energy demand**



Energy demand by transportation mode in GSEP countries for 2015. Navigation and air transport only take into account domestic transport (not international transfers).

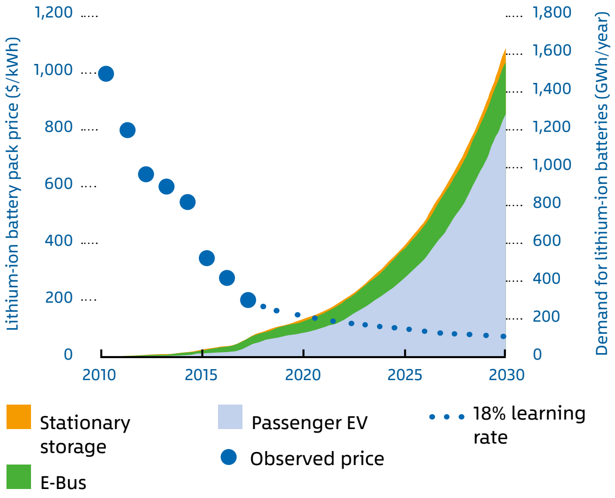
Source: Enerdata.

FIGURE 4.4 **Forecasts for electric vehicle fleet size increase rapidly**



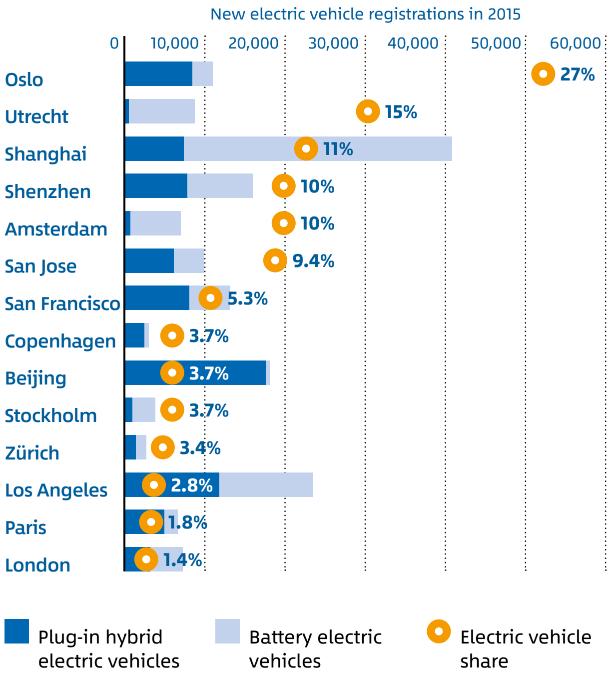
Source: Bloomberg New Energy Finance, BP, Exxon, OPEC, IEA.

FIGURE 4.5 **Lithium-ion battery prices keep dropping as demand rises**



Source: Bloomberg New Energy Finance.

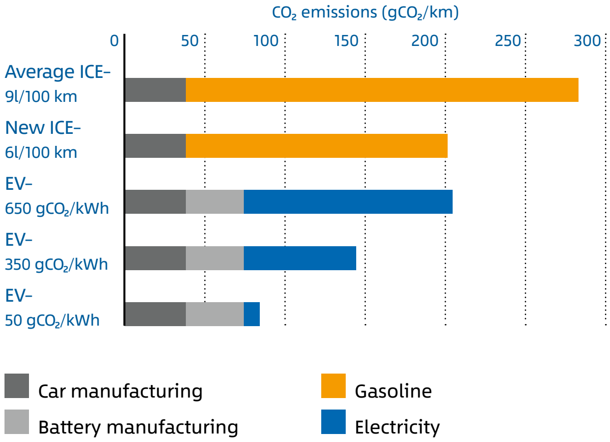
FIGURE 4.6 **Significant EV penetration in 14 pioneering cities**



New registrations and market share of EVs for the 14 most advanced cities in 2015.

Source: International Council on Clean Transportation White Paper, 2017.

FIGURE 4.7 **EV is cleaner than ICE especially with a decarbonized mix**



Electric vehicles (EVs) produce less CO_2 emissions than traditional vehicles with an internal combustion engine (ICE), even when conducting an analysis of the whole life (direct and indirect emissions from energy, and emissions for car and battery production). The chart above shows the life-cycle emissions (over 150,000 km) of ICEs, depending on their efficiency (average and new, efficient vehicle), and EVs depending on the power mix, from a low-carbon mix (50 gCO_2/kWh), to the EU average (350 gCO_2/kWh) and the world average (650 gCO_2/kWh). Life-cycle emissions due to car and battery manufacturing are taken from ICCT's Briefing "Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissions", February 2018.

Policy is a key driver in the uptake of EVs. Numerous countries have adopted financial incentives to increase the consumer uptake of electric vehicles. In 2015, nearly all European countries subsidized the purchase of electric vehicles, and the vast majority provided additional support to annual operational costs and infrastructure development, complemented by additional local measures in cities, such as access to public transport lanes or free parking.[44] California provides major incentives for charging infrastructure. Many studies show that fiscal incentives, easy availability of charging stations and access to otherwise restricted areas are the most important support measures to promote electric vehicle ownership,[45] and of these, access rights to restricted zones seem to be the most effective.[46]

Nearly one-third of global electric vehicle sales are concentrated in 14 cities, which have applied an efficient mix of policies, especially those tailored to local conditions, such as their geography (e.g. waiving tunnel tolls in Oslo), city layout (e.g. congestion zones in London, carpool lanes in Los Angeles) or vehicle licensing policies (e.g. exemption from registration lotteries in Beijing and Shanghai).[47]

Looking ahead, several cities and countries will ban ICEs: Paris will ban all gasoline and diesel-powered cars by 2030, a decade ahead of France's 2040 target. Copenhagen plans to ban diesel cars from 2019, while London has proposed banning all non-electric vehicles from its center from April 2019.

4.2 CASE STUDIES

The coming electrification of public transportation, freight, boats and planes

Efficient electric solutions for passenger transportation exist already. While private cars are the main form of passenger transportation, it should not be forgotten that efficient solutions exist for electrifying public transportation. The main drivers are: economic visibility, with identified journeys and thus known distances and traffic levels; easy installation of infrastructure; and the drop in battery prices for electric buses. Even more importantly, electric public transportation is a valuable tool for cities and local governments that want to tackle air pollution, noise and congestion.

With more than 200 million electric two-wheel vehicles and more than 300,000 electric buses, China is by far the global leader in the electrification of other transportation modes. Many cities are putting in place initiatives to electrify their public transport infrastructure, with railways (subways, tramways) or electric buses. For example, Paris has decided that its entire 4,500-strong bus fleet will run on clean energy by 2025: 80% on electricity and 20% on biogas.

THE ELECTRIFICATION OF RAILWAYS, HARBORS AND AIRPORTS IN CHINA

In 2015, the share of electrified railways in China was about 40%. It is forecasted that this figure will increase to 60% in 2020 and 90% in 2050.

Ships and boats in ports and harbors are encouraged to use electricity rather than diesel. In airports, all vehicles and equipment are encouraged to be driven by electricity. In 2017, State Grid built 44 high-voltage and 507 low-voltage power supply systems along the Beijing-Hangzhou Grand Canal, eastern coast and Yangtze River. 50% of ports along the Beijing-Hangzhou Grand Canal now are able to provide electricity supply.

Development will bring electricity solutions for freight closer. The technologies developed for light-duty vehicles pave the way for solutions to be found for long-distance transportation in the near future, particularly for freight. Last November, Tesla launched its electric truck division, which could manufacture as many as 100,000 vehicles per year. Tesla has announced that the trucks would have an 800 km range on a full charge, and would recharge up to 80% in 30 minutes. Earlier this year, the Swedish group Volvo Trucks announced that from next year it will be selling 16-tonne electric trucks with a range of up to 300 km.

For air transportation, short-distance fully electric options will emerge in the coming years with drones or VTOL (vertical take-off and landing) aircraft, while more R&D is needed for electric regional planes and plug-in hybrid continental planes. For large boats (ferries, container ships, etc.), electricity is already being deployed for short distances (up to several kilometres) and under study for distances up to 100 km.[48] For long distances, plug-in hybrid systems would still be necessary.

For heavy loads and long-distance journeys, hydrogen technologies could emerge, thanks to hydrogen's high energy density. Because of environmental concerns, hydrogen would be produced via electrolysis, which will involve electricity consumption. One key challenge will be to develop an infrastructure network for the distribution of hydrogen at the same time as electric charging infrastructure, while addressing related financing needs.

Smart charging is helping grids manage demand, but the right business models for developing charging infrastructure are yet to be found for massive deployment. Increasing use of EVs should not be an issue over the medium term for power grids, which can handle the additional consumption, notably thanks to smart-charging solutions and "vehicle to grid" (V2G) systems, which make it possible to leverage the flexibility of EV batteries to the benefit of networks. In the longer term, potential changes in transportation needs and modes, such as the development of autonomous vehicles and shared mobility, could bring new opportunities for EV charging optimization.

DEVELOPMENT OF EV IN CHINA: 40% OF SALES IN 2030, 50 MILLION VEHICLES, 200 TWH DEMAND

According to a State Grid study, the share of electricity in the transport sector of China could reach 10% in 2025, 15% in 2030 and 25% in 2040, compared to 5% in 2015.

Electric vehicle (EV) sales in China jumped from 5,600 units in 2011 to 45,000 in 2014 and 740,000 in 2016. In 2017, China's EV production was about 770,000 and its total EV holdings about two million.

China's electric vehicle holdings in 2030 are projected to be high as 50 million, which will lead to an annual electricity demand of 200 TWh for EV charging. According to projections by the Society of Automotive Engineering of China, the country's car sales in 2030 will be 38 million, of which the sales of EVs will be 15 million, or 40%.

Public transportation is being increasingly electrified, with 4,500 electric buses in Beijing (and a target of 10,000 by 2020, or 60% of the total) and 16,000 in Shenzhen in November 2017, with the ambition of achieving 100% electric buses by the end of 2017.

CHARGING NETWORKS ARE RECOGNIZED AS THE KEY INFRASTRUCTURE TO PROMOTE THE SPREAD OF EV

By the end of 2017, China had over 450,000 charging posts, a 14-fold increase since the end of 2014.

As the leader in China's EV development, State Grid implemented the Smart EV-to-Grid Service Network (SEGSN), providing an EV charging service and charging-post information. Moreover, SEGSN also provides EV sales and rental, EV insurance and finance and charging-post maintenance. SEGSN is the information hub for EV drivers, electricity grids and charging station operators, facilitating efficient communication among EVs, posts and grids and contributing to the foundation of a smart EV ecosystem.

SEGSN now covers 19 provinces and 150 cities. It also provides charging services along over 310,000 km of highways, at intervals of only 50 km.

By the end of 2017, 170,000 charging posts were connected and over 800,000 consumers registered. In 2017, electricity consumption from EV charging in SEGSN reached 390 GWh, of which about 100 GWh was during off-peak periods, accounting for 26% of the total.

SEGSN is capable of real-time operation monitoring and efficient maintenance: 90% of faults are fixed in one hour and the availability of charging posts is as high as 99%.

4.3 DIGITAL DRIVING GROWTH

Shared and autonomous transportation will be electric

Digitalization will revolutionize road transportation, as ubiquitous connectivity and automation technologies fundamentally transform how people and goods are moved. The first step of this revolution is the expansion of shared mobility, with a potential leverage effect on the transportation asset utilization rate, thus making mobility cheaper. This leads to the concept of mobility as a service (MAAS), which aims to simplify the range of shared mobility services by offering a unified routing and payment platform, allowing 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. The world's first such service, Whim,[49] was introduced in Finland in 2016.

The second step in this revolution is the deployment of connected automated vehicles in road transportation, a promising prospect thanks to rapid advances in key technologies (machine vision and 3D cameras, laser-imaging detection and ranging – LIDAR – and advanced GPS, and AI software) as well as their large potential cost savings and safety benefits (over 90% of crashes are attributable to human error according to the US Department of Transportation). Commercial applications, particularly where labor costs are proportionately high (e.g. buses and ride hailing) or where automation could enable higher vehicle utilization (e.g. trucks) are well-suited to be early targets. Major automakers have announced plans to introduce highly automated passenger vehicles as early as 2020, with some experts predicting widespread adoption in the period 2025-40.[50]

Shared mobility and autonomous vehicles are drivers for electric mobility. The combination of shared mobility and automation, by increasing the utilization rate of shared vehicles, will make passenger transportation cheaper. Automation will also lower the cost of road freight transportation. Both of these factors could encourage more travel activity, resulting in increased energy demand. On the other hand, shared and autonomous transportation could facilitate vehicle fleets' "right-sizing" and accelerate EV adoption and would result in energy efficiency gains, reduction of pollutant emissions and, assuming the electrical grid is progressively decarbonized, also result in lower greenhouse gas emissions. With higher utilization rates of automated and shared vehicles, the share of energy in the TCO will increase, which will make EVs even more competitive. Moreover, it will spur more rapid fleet turnover, accelerating the deployment of the latest and most efficient EV technologies.

4.4 BUSINESS OPPORTUNITIES

Who will manage the e-mobility charging system?

The impact of EVs on power grids is becoming an optimization driver for utilities. Assuming that cybersecurity and reliability issues are solved, "smart charging" will increasingly deliver value to the electricity system, by helping manage the charging of EVs while taking into account the mobility needs of customers (time and duration) and the near-term prices on spot electricity markets (looking for the lowest prices when variable renewable energy generation is high). Secondly, EV could bring services to the electricity system with "vehicle to grid" or V2G. For illustrative purposes, with a battery pack size between 40-80 kWh and with slow-charging points of around 6 kW, one million EVs connected to the grid would provide 6 GW of storage for 3 hours (assuming that one-third of the battery's capacity is available for charging/discharging).

The roles of car manufacturers and energy utilities will overlap in terms of the energy management related to the mobility needs of customers. Using car batteries to provide storage to the power grid will result in a new source of value for car owners. Depending on the number of EVs connected and price that this storage commands, this source of income could be integrated into mobility service offers, with companies offering lower energy costs in return for demand response capacities. But smart charging is also a good way to optimize cars fleets' charging needs and therefore charging infrastructure (both in terms of capacities and localization). Moreover, with the concept of mobility as a service, as outlined in section 4.3, the ownership model of vehicles might change drastically over the coming decades, with a transformation among all stakeholders (especially automakers and energy utilities), whose roles will eventually overlap.

One of the most famous examples of the evolving landscape is Tesla, which competes in the car and the battery manufacturing segments, as well as in the deployment of charging infrastructure and the electricity supply that goes with it. Looking further ahead, Tesla is now producing batteries and solar roof panels for buildings and supplying services to the grid with storage facilities.

The question is still open as to which actors will provide smart charging and V2G services. There are today many examples of both pilot projects and commercial platforms for smart charging by both energy utilities and automakers. One of the major questions is the relationship between the charging infrastructure network and the fleet of vehicles: which one will be "connected" to the smart-charging service platforms and thus to the ancillary services market, while responding to the cybersecurity, latency and availability requirements? In other words, is the gateway on the energy utility or the automaker side?

4.5 REGULATORY CONTEXT AND ENABLING POLICIES

Investments in infrastructure needed

Short-term support mechanisms will boost technological development. If the drop in battery costs is set to make EVs competitive with ICEs in the coming decade, short-term support in the meantime, with careful management of volumes, will help the development of EV sales and therefore the industrial scalability of production, allowing EVs to reach full competitiveness with the already mature ICE sector.

Government oversight is needed for charging infrastructure development, with some form of regulation required in addition to the market in order to guarantee profitability and thus rollout. The vast majority of charging happens at home or at customers' workplaces (see Figure 4.8). Public charging infrastructures are used very little, but their development is needed nonetheless in order to reassure customers of their car's autonomy and thus to support EV sales. Therefore, cities and states need to steer charging infrastructure development over their territories.

HYDRO-QUÉBEC'S ELECTRIC CIRCUIT INITIATIVE

The Electric Circuit, a Hydro-Québec initiative and business model, is Canada's first public charging network for electric vehicles (EVs). It offers both 240-volt and 400-volt charging stations. The stations are installed in the parking lots of the Circuit's numerous partners across Québec and in the northeast of Ontario.

Since its launch on March 30, 2012, the Electric Circuit has rapidly expanded to many of Québec's regions, with continued expansion into new urban areas. Electric Circuit charging stations are rolled out based on the geographical distribution of EV sales, users' needs and partners' business strategies.

While most electric vehicle charging takes place at home or at work, the public charging infrastructure allows EV drivers to travel worry-free, knowing they can top up their batteries on the road if necessary.

Common standards and interoperable solutions between charging stations will be needed for charging infrastructure, distribution networks and the electric cars themselves. Interoperability is necessary both in terms of the physical electricity network and equally for the ICT interface, where information will need to flow efficiently among the value chain's stakeholders. Interoperability and common standards are necessary to enable EVs to access flexible roaming platforms that enable consumers to drive and charge in different local distribution networks.

A level playing field between energies will encourage investments: to grant long-term visibility to the transportation and energy sector stakeholders, externalities from each energy source (CO_2 and CH_4 emissions, air pollution, etc.) should be taken into account in price signals.

FIGURE 4.8 **EV charging mainly happens at home and at work**

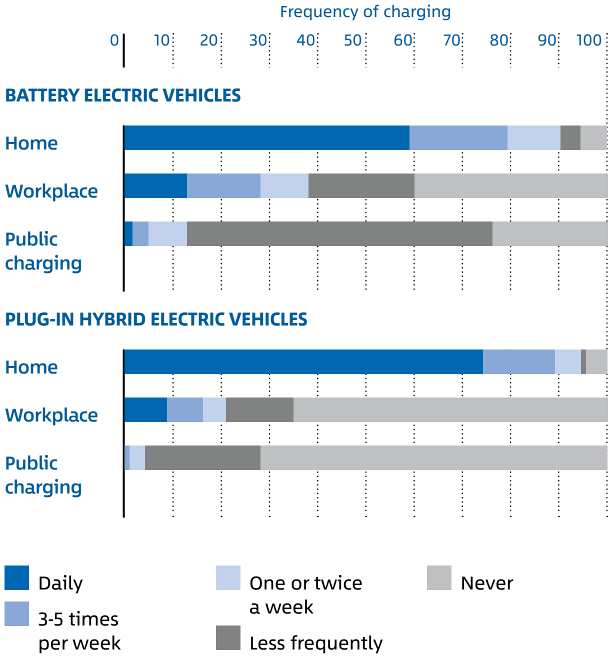


Illustration of charging habits for a sample of Norwegian electric car users in 2016.

Source: IEA Global EV Outlook 2017.

ENEL X E-MOBILITY

Enel X aims to become a technological leader in the e-mobility sector, to promote increasingly widespread and efficient electrical mobility with its charging infrastructure, Vehicle-Grid Integration (VGI) services and second battery life applications.

In November 2017, Enel X presented the Charging Infrastructure Plan for Italy. The plan will see the installation of about 7,000 charging stations by 2020, and 14,000 by 2022; the program calls for an investment between 100 and 300 million euro.

Furthermore, thanks to the recent acquisition of eMotorWerks, a California based start-up, Enel X's charging stations can interact with cars, customers and the grid. Indeed, JuiceNet, an integrated IOT platform developed by eMotorWerks, is able to remotely control and aggregate the distributed loads of thousands of EVs for grid balancing purposes, in addition to optimizing the cost of vehicle charging. Hence, thanks to VGI technology, Enel X smart charging stations can interact with the grid providing flexibility to the system, by modulating the process of charging according to the status of the grid. Additionally, customers can monetize their vehicle battery by participating to VGI program.

5

INDUSTRY

Trends in digital and automation favor electricity

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Industry should aim to double its share of electricity by 2050, from 23% to over 50%. Electricity will be central to decarbonizing industry and meeting the requirements of the IPCC's 2°C scenarios. Three-quarters of industry's energy needs are for heating, of which 90% is supplied by fossil fuels. Constant optimization of processes plus consumer pressure for environmental protection can transform this approach. In the meantime, digitalization is introducing new drivers of electricity demand, such as data analytics, robotization and, looking further ahead, additive manufacturing, which uses electricity rather than fossil fuels in its production processes.

Electrical technologies can optimize heat processes. Today, electricity can both improve heat loss recovery and enable more precise control of the temperature of industrial processes, thanks to technologies such as heat pumps, induction and mechanical vapor recompression. In the mid-term, investment in development should enable the emergence of electrical technologies for high-temperature processes, with industrial-sized advanced heat pumps. In the longer term, more R&D can allow clean hydrogen from low-carbon electricity to be cost-competitive.

To enhance the electrification and decarbonization of industry, governments have a key role to play, delivering R&D roadmaps, visibility on CO_2 ambitions and a level playing field among energies. International coordination will be needed to control "carbon leakage", in which energy-intensive industries relocate from countries that act to decarbonize industry. To push forward digitalization in industry, cybersecurity and privacy are issues that industry stakeholders must address.

5.1 CONTEXT

Industry's thermal energy needs currently largely provided by fossil fuels

Industry relies massively on fossil fuels: two-thirds of industry's energy demand comes from fossil fuels, with nearly 40% coming from coal. This large share of fossil fuels is mainly due to the dominance of thermal needs in industry, which represents three-quarters of its energy demand. Half of this energy is used to produce high temperatures (above 400°C), for which traditional fossil fuels are still more competitive than electricity (see Figure 5.4).

FIGURE 5.1 **Final energy demand worldwide**

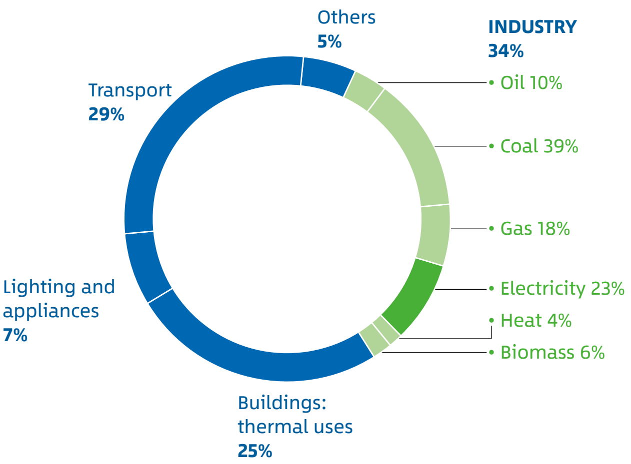
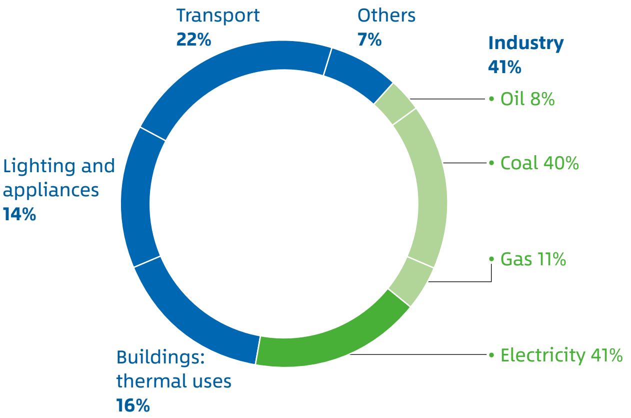


FIGURE 5.2 **CO_2 Emissions from energy combustion**



CO_2 emissions for electricity are calculated from total emissions in proportion to each sector's electrical demand.

Source: IEA ETP 2017.

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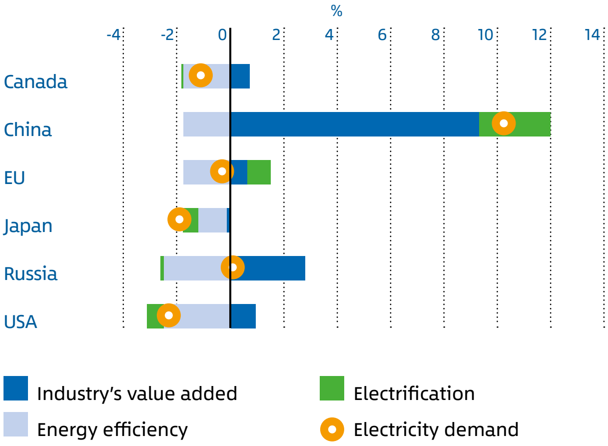
The trend for electrification is not fast enough: electricity represents about one-quarter of industrial energy demand, mainly to run motors, which represent 70% of industrial electricity consumption. The annual growth of electrification worldwide averaged 0.6% per year from 2000 to 2015, before accelerating to 1.7% per year from 2010, mainly due to the electrification of industry in China (see Figure 5.3). In the IPCC's 2°C scenarios, the share of carbon-free energies (electricity, biofuels and hydrogen) for 2050 has a median value above 50%. To reach this target, the electrification of industry needs to progress at a rate of at least 2.3% per year over the next 35 years.

We can be more ambitious: the share of electricity in industrial final energy demand is already much higher in some countries than the worldwide level (23%). For instance, it is on average 32% in the OECD, and about 35% in Germany, France and the United Kingdom, more than 40% in Switzerland and Korea, and above 67% in Norway, where there is abundant cheap, low-carbon electricity from hydropower. Naturally, there are industrial specificities depending on the country, yet even with large diversification among countries one can have high rates of electrification. For instance, looking at electrification rates for industrial sub-sectors, Portugal and Norway are above 60% for steel production, Ireland is above 60% for chemicals and at about 80% for paper production, while Israel uses 100% electricity for its steel, paper, textile and food industries.

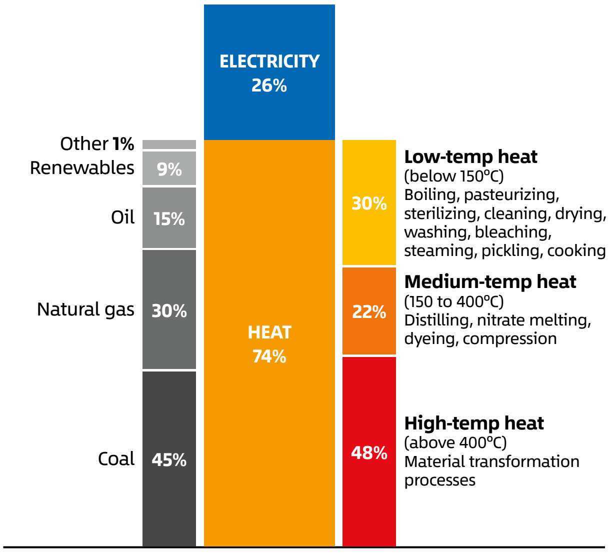
FIGURE 5.3 **Industry electrification needs to increase**



Annual growth of electric demand for the industry sector of GSEP countries over 2000-2015, with decomposition of main factors: the annual growth of electricity demand (orange dot) is the sum of the annual growth of the other 3 factors.

Source: Enerdata.

FIGURE 5.4 **Share and breakdown of heat demand in industry**



Three-quarters of industry's energy demand is for heating processes, more than half for medium to high temperature requirements. 90% of industrial heat comes from fossil fuels.

Source: IEA Renewable Energy for Industry, 2017 report.

5.2 CASE STUDIES

R&D pilots under way

Industry is driven by economic competitiveness at the international level, meaning that relocations to gain access to the cheapest resources (raw materials, energy, labor) are common and best-available technologies are generally adopted. In the coming decades, externalities and CO_2 values in particular will have a growing impact on the electrification of industrial processes. If based on low-carbon technologies, the electrification of industry offers great potential for CO_2 emissions reductions.

Today, the main challenge is to spread existing cost-competitive technologies. While electricity faces strong competition from fossil fuels for thermal applications, it has the advantages of precision and lower maintenance. Some electrical technologies for heat and steam production can be particularly effective, such as heat pumps, induction and mechanical vapor recompression.

Development efforts could deliver electricity technologies for high-temperature processes, by expanding the scope of existing efficient technologies in the mid-term. Technologies such as industrial-sized advanced heat pumps are especially promising. Heat pumps are currently able to reach temperatures of around 100°C and research is underway to reach temperatures of 140°C, which would double the installation potential.

IN CHINA, A MAJOR POTENTIAL INCREASE IN ELECTRICITY CONSUMPTION BY INDUSTRY

In 2017, China's electricity consumption from industry was 4.36 trillion kWh, an increase of 5.5% from 2016, contributing 58.4% to total annual growth of electricity.

In total, the electricity consumption of the manufacturing industry increased by 5.8%. Among subsectors, manufacturing for transportation and electrical equipment and general and specific equipment showed fast growth in electricity consumption, achieving a 10.3% increase when compared with 2016.

In industry, the promotion of electricity consumption includes electric boilers with or without storage in textile, wood-processing and aquaculture, electric furnaces for metal processing, casting and ceramics, electric motors for handling materials and electric pumps in agriculture. The Chinese government supports this shift towards electricity via public/private partnerships, cheap electricity during nighttime for electric boilers with storage, and measures against air pollution.

If all small industrial coal-fired boilers were replaced by electric boilers by 2025 the added annual electricity demand would be 750 TWh.

Prepare next-generation processes for the longer term: Many demonstration projects are being evaluated for the electrification of energy-intensive industries. For instance, the European project SIDERWIN for steel production is based on a breakthrough technology using electrolysis to transform any iron oxide (including those from by-products of other metallurgical processes) into steel plates, with a significant reduction of energy use. By creating a CO_2-free steel production process, the initiative will contribute to the reduction of the total greenhouse gas emissions. Compared to traditional steelmaking plants, this innovative technology has several positive impacts:

- A reduction of direct CO_2 emissions by 87%
- A reduction of direct energy use by 31%
- The capacity to produce steel from non-ferrous metallurgy residues rich in iron oxides
- Increased integration with renewable energies thanks to a more flexible process.

The production of clean hydrogen through water electrolysis from low-carbon electricity is a potential solution for decarbonizing industry, and should be further explored through R&D pilots. It can be used in segments as varied as precursors (e.g. for nitrogen fertilizers), process agents (e.g. for low-carbon emissions steelmaking) and fuels, as well as end-use sectors such as buildings and transport.[51] In regions where resources are especially abundant, the cost of hydro, solar and wind power can be very competitive, as can round-the-clock nuclear baseload electricity generation. Such low electricity prices could allow hydrogen to be produced on a cost-competitive basis with natural gas reforming, oil-cracking or coal gasification – and of course without their CO_2 emissions.

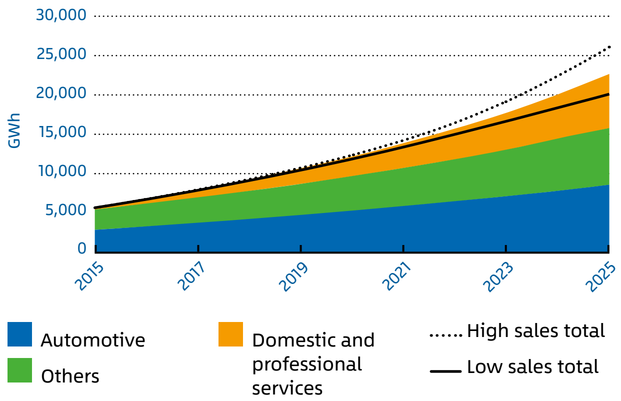
HEAT PUMP SYSTEM PROVIDING EFFICIENT HOT AND COLD WATER FOR A SAKE BREWERY IN KOBE

In a sake bottling plant which was newly built in 2012, hot and cold water is produced simultaneously by an electric heat pump system. An ice thermal storage system is also introduced for additional cooling capacity, limiting peak-hour power demand. Running costs and CO_2 emissions were decreased by 24% and 34% respectively compared to the conventional system. This system was suggested by Kansai Electric Power Company (KEPCO) to HAKUTSURU SAKE Brewing Company, the plant owner.

5.3 DIGITAL DRIVING GROWTH

Data analytics and robotization are on the way

FIGURE 5.4 **Electricity demand from robotics on the rise in the US**



Source: American Council for an Energy-Efficient Economy (ACEEE), 2017.

Growing electricity demand from data analytics. 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 optimize production processes, improve energy efficiency and reduce waste, apply to all production processes. The wide potential gains from digitalization should drive up demand for data centers and data transmission, and thus increase electricity demand.

Robotization is a potential driver of electricity demand. Since 2010, sales of industrial robots have grown by 16% per year on average, driven mainly by emerging economies, particularly China. The automotive and electronics industries are by far the largest sectors for robotization. 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). Few studies are available on robotization's impact on electricity consumption. However, a 2017 study by the American Council for an Energy-Efficient Economy (ACEEE) estimates that electricity consumption from robots in the US industry will grow from around 6 TWh in 2015 to above 20 TWh in 2025 (see Figure 5.4).

In the long run, an electrical revolution thanks to 3D printing?

3D printing can produce both plastic and metal parts by building up layers of the material, on demand and directly from digital 3D files. 3D printing is already competitive in small-series production in sectors such as automobiles, aeronautics and biomedics, thanks to the gain in precision and the reduction of waste of raw materials. But 3D printing also enables the manufacture of parts that were previously impossible to produce, and comes in perfect complement to the digital design methods used in high-tech industries. As an electricity-driven process, 3D printing can promote the electrification of thermal forming processes such as metal casting and forging in many manufacturing processes.

For example, GE uses laser fusion (injection through a nozzle of a metal powder which is then immediately fused by laser) for the manufacture of its LEAP aircraft engines. This process makes it possible to manufacture large parts of the engine as one piece rather than assembling multiple smaller parts, contributing to an increase in product lifespan and fuel efficiency. Airbus is considering the feasibility of manufacturing wings with 3D printing, thereby removing two tonnes' worth of rivets. 3D printing could also eventually circumvent warehousing and transportation issues, thanks to faster and more localized production.

5.4 BUSINESS OPPORTUNITIES

Developing energy services for industrial customers

Smart management can deliver energy savings to industrial customers. Energy services can help industrial firms to reduce their energy bill through a range of integrated services including individual assessments, streamlined supplies, operation and maintenance contracts, major maintenance and refurbishment work, and more. Energy utilities can also offer remote solutions to manage the energy performance of industries, based on a digital network that enables real-time data collection and analysis by experts, who can then request that work immediately be carried out by technicians on site where needed.

Heat recovery is a major source of savings from industrial facilities. Factories give off heat which in most cases is simply lost. Utilities can provide solutions to recover this heat for use either elsewhere in the factory to unlock energy savings or off-site to supply other plants, or homes and public buildings, creating an additional source of revenue. These solutions also provide a seamless fit with the circular economy model promoted by the energy transition.

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EDF'S SUBSIDIARY DALKIA RECOVERS SECONDARY ENERGY FROM ARCELORMITTAL'S SITE TO FUEL DUNKIRK URBAN NETWORK

EDF's subsidiary Dalkia specializes in supplying high-pressure steam, hot water, compressed air and cogeneration solutions. It also helps companies to reduce their energy consumption through an array of services ranging from individual assessments to optimization of sourcing and maintenance contracts.

In Dunkirk (North of France), Dalkia recovers the lost energy from ArcelorMittal's industrial site, and injects it into the city's district heating network. The 40 km long network heats the city hall, a swimming pool, the university, a shopping mall and thousands of housing units.

There is a two-fold economic and environmental benefit: for ArcelorMittal, a revenue stream from heat as a by-product of industrial processes while reducing its ecological footprint; for the city, stable energy costs for the heating network and a bill reduction of 15-20% compared to oil or gas, and 20,000 tonnes of CO_2 avoided each year.

Thanks to its "Eco-impact" solution, Dalkia helps to create value from previously unexploited energy. By recovering site waste, industrial actors contribute directly to the regional effort towards the energy transition. Waste becomes a new local source of renewable energy, helping to diversify the energy mix in the region.

5.5 REGULATORY CONTEXT AND ENABLING POLICIES

Governments can build R&D momentum

Affordable electricity is a key condition to deep electrification of the industry sector. Governments can facilitate the transformation of the sector by ensuring an affordable electricity price, thus helping it remain competitive at the international level. Regulators should consider the price impacts on the industry sector when deploying incentives that shape the generation mix (by influencing technology choices upstream) as well as how their choices influence the sizing of related networks. A level playing field is also required: industrial stakeholders need visibility on CO_2 ambitions at both national and international levels. International coordination will be needed to control "carbon leakage", in which energy-intensive industries relocate from countries that act to decarbonize industry. Border carbon adjustments can be implemented to encourage other countries to take actions on this matter.

Create R&D roadmaps in order to foster the development of non-mature industrial technologies, prepare those of the long-term future and encourage the indirect electrification of industry through clean hydrogen. Roadmaps should be developed in partnership with industry players, electricity utilities and R&D laboratories to set out cost targets, schedules and provide for demonstration projects, results monitoring and adaptive actions.

Government support for R&D can mitigate risks and crowd in private-sector investment. 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, thereby reducing the perception of risks and accelerating adoption.

Cybersecurity and data privacy are major challenges for industrial stakeholders, on which governments must give reassurance in order to push forward digitalization. While improved connectivity can increase productivity across firms, supply chains and industrial sectors, to fully realize 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.

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