Energy Systems Today and Tomorrow

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Learning Objectives

- Be able to understand the importance and types of energy systems,
- Be able to grasp the drivers, barriers, and challenges of the ongoing sustainable energy systems transition,
- Be able to classify and identify dimensions of smart grids (special role of power systems and ICT),
- Be able to describe the relevance of technological diffusion (social welfare perspective, path dependence/lock-in, complexity, supply-push/demand-pull),
- Be able to explain key policy aspects related to energy systems transition (policy instruments, regulation, market failure, uncertainty)

The energy systems are under tremendous change, driven both by technical change (digitalization) and climate protection policy. Overall, it is expected that the future energy system will be decarbonized, digitalized, distributed—and thus also democratized (the four "Ds"). An increased digitalization and the vast system transformation also bear new risks, some of which are related to cybersecurity.

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C. Dinther et al. (eds.), *Smart Grid Economics and Management*,
Lecture Notes in Energy 51, https://doi.org/10.1007/978-3-030-84286-4_1

1 Energy Systems—An Essential Element of Society

Energy is a key factor for human development and economic growth (Stern 2011). It appears in different forms (e.g., potential, chemical, electric, kinetic, or thermal energy). Apart from its physical characteristics, energy has also an economic, societal, and environmental dimension. No matter which area we look at in our everyday lifes, energy plays an important role.

The downside of massive (fossil) energy consumption is the increasing emission of carbon dioxid (CO_2) or greenhouse gases (GHG), respectively, as well as environmental pollution. The Intergovernmental Panel on Climate Change (IPCC) published a First Assessment Report in 1990 IPCC (1990, p. xi) stating that "there is a natural greenhouse effect which already keeps the Earth warmer than it would otherwise be" and "emissions resulting from human activities are substantially increasing the atmospheric concentrations of greenhouse gases [...]" enhancing "[...]the greenhouse effect, resulting on average in an additional warming of the Earth's surface." Twenty-five years later, 195 nations have fixed an agreement on the mitigation of GHG emissions. This agreement is known as the Paris Agreement (European Union 2016) and seeks to limit the global mean temperature increase to 2 °C and mitigate the increase at 1.5 °C. In order to reach this objective, each country presented comprehensive climate safety plans. As a result, most Western industrial countries have pledged to radically transform all energy-consuming sectors. This transformation process that goes well beyond changing the technical systems is known as sustainable energy transition. This has major effects also on the electricity system where conventional electricity generation from fossil fuels needs to be replaced by generation from renewable resources.

The need for a sustainable energy transition has implications for many areas of the energy industry. In this book, we focus on the ramifications for the electricity sector by looking at the future of distribution grids, the so-called *smart grid (SG)*. In the context of this transition, it is often referred to the Ds of the energy transition. There is no clear original scientific source for these Ds. However, there typically is an agreement on the first three Ds (e.g., Agora 2017)—decarbonization, digitalization, and decentralization. Other Ds include democratization, the dominance of fixed costs, or degression of technology costs (cf. also Chapter 6).

The *decarbonization* of electricity generation leads to a more *decentralized* structure of the electricity system, as the renewable energy generation plants, i.e., wind turbines and PV, are smaller and are installed across many locations. Generation-led system control is insufficient in this setting and in turn we need more flexibility on the demand side. This flexibility will not be achieved with manual processes or behavioral changes. New technology is necessary to control devices, to meter actual consumption or monitor the grid. This calls for *digitalization* to make the distribution grid smart. Controllable devices, consumer-side generation, and the need for demand-side flexibility empower consumers and turn them into prosumers. In turn, we see a *democratization* of the electricity system. The latter is not only a technical challenge. In fact, while the structure of the system is changing and new players are emerging, regulators will need to adapt market mechanisms to reflect changing cost structures. Similarly, network management is changing, new regulation is required and new business models are emerging. Renewable power generation is characterized by the *dominance of fixed cost*, although we observe a *decrease of the technology cost* due to technological progress and scale effects.

In this new textbook, we cover these arising challenges and mitigation strategies. We thereby focus on economics and management, new trends, information processing, and entrepreneurship as well as on the modeling of "smart" energy systems, rather than on technical aspects.

Electrical energy is generated from different sources. These include primary energy sources such as oil, coal, gas, nuclear material, water, or renewable sources. Worldwide primary energy consumption increased rapidly in the last years, up to 14,126 million tons of oil equivalent (Mtoe) in 2017 (Worldbank 2018). Oil has the largest share with 34.2%, followed by coal with 27.6% and natural gas at 23.4%. Nuclear (4.4%), hydro-electric (6.8%) and renewable sources (3.6%) have smaller shares. In 2017, worldwide electricity production was 25,551.3 TWh (or 2,197 Mtoe). Therefore, presently about 15% of the world's energy consumption is electrical.

The knowledge of humans to physically transform (fossil) energy at large scale - in order to use it for industrial and manufacturing processes started the industrial revolution in the eighteenth and nineteenth centuries. This led to economic growth and an unprecedented societal development change of life. Today, Western economies as well as the developing and emerging economies cannot work without reliable energy supply. Although there is a relationship between energy consumption and economic growth, a synchronous development can no longer be observed since the 1970s. Instead, we have seen a decoupling of GDP and energy consumption (Banschbach 2003).

As already mentioned, energy can exist in different forms. Primary energy sources are crude oil, natural gas, coal (lignite and hard coal), nuclear raw materials, and renewable energy sources such as hydropower, solar energy, wind energy, geothermal energy, or biogas. The primary energy is transformed depending on the application, e.g., into electrical energy, heat (heating, process heat), or for the transport sector. The proportion of primary energy sources used varies in different regions of the world. According to BP's energy report, oil is the most frequently used primary energy, with a share of approximately one third of global consumption, followed by coal with a share of 26%. Asia is the largest consumer of coal and oil, while North America leads the rankings for nuclear energy and natural gas. Despite a steady increase, renewable energies still have the smallest share worldwide at 3.6%. In South and Central America, hydropower plays an important role. In Europe, the share of renewable energies is the largest across all industrialized nations.

In Germany, approximately 36% and in the USA 38% of primary energy is transformed into electrical energy. In Germany, electrical energy is the most important form for industry (31%), commerce/trade/services (36%) and households (19%) alongside natural gas. When we referring to the energy industry and the energy system in this textbook, typically the electricity system is meant.

The energy industry is faces with the challenge of providing electricity economically, ecologically, and reliably. We are therefore also talking about the energy policy trilemma of security of supply (social dimension), affordability (economic dimension), and environmental impact (ecological dimension). Since electricity, as an essential commodity for the economy and society, is vital for survival, all three dimensions are important. However, the question arises as to the political priorities, since the goals are interdependent. For example, redundancies in generation and transmission are necessary to reduce the risk of system failure. A high level of supply security leads to higher costs and thus has a negative impact on profitability. The ecological dimension also influences economic efficiency.

Electricity is a special economic commodity in several respects.

1. It is a *homogeneous good*, i.e., electricity cannot be distinguished physically. In principle, quality criteria can be defined, e.g., with regard to reliability or also with regard to generation source, frequency, voltage, and current, but electrons are electrons. In contrast to the homogeneous good "electricity," the electricity system is extremely heterogeneous. There are differences in the generation technology, in the structure of the system or with regard to the economic framework conditions which are laid down by law. Due to the heterogeneous system architecture/components, additional services and market mechanisms are necessary.
2. Power generation and consumption must be *continuously balanced*. For this reason, the electricity system was designed so that large power plants were built close to the consumption centres.
3. Electricity transport and distribution are *natural monopolies* due to the combination of high fixed investment costs and negligible marginal transport costs.[1]
4. Electricity *cannot be stored* easily or without losses.[2] In addition, electricity cannot be routed. Governed by physical laws, the current will flow along the path of least electrical resistance.

A working power system is indispensable. The structure of electricity systems differs worldwide, not only in terms of their technical structure but also in terms of their economic role and organization. Various factors must be taken into account in the structure of the electricity system. Geography, regulation, economy, and technology play a role in the structure of the electricity system. For example, a carbon-neutral energy system has more decentralized generation plants and other distributed resources, and thus also requires more intelligent control due to decentralisation.

From the perspective of the electricity grid, the requirements typically differ for differing population densities: Rural regions typically have a low population density. This means that long lines are necessary to connect buildings. Depending on the terrain, the grid connection can be complex if, for example, mountains or water bodies have to be overcome. In urban areas, the settlement density is greater. As

[1] In economics, one speaks of natural monopolies when sub-additive costs exist, i.e., the costs of a monopolist are smaller than the sum of the costs of all competitors.

[2] Storing electrical energy is only possible by transforming it into another form of energy, such as kinetic, chemical, or gravitational energy, and is therefore very expensive.

the number of buildings and appliances increases per square meter, so does energy demand, which must be covered by the capacity of the grid. Of course, the level of economic development and the type of buildings is also important—industrial or commercial areas have greater energy demand than residential areas. This results in heterogeneous requirements for the electricity grid, especially against the background of growing decentralized generation capacity. For example, isolated solutions are becoming attractive for sparsely populated regions, while in densely populated regions, intelligent coordination of generation and consumption may be a more viable option.

If we look at the geographical situation in Europe and compare it with other continents, we can see clear differences. A good indicator is population density. The lower the population density, the less demand there is, i.e., with increasing decentralization in generation, intelligent grids, i.e., the possibility of grid control measures, are more appropriate in more densely populated areas. Due to its importance for the national economy, the energy sector has always enjoyed special attention. In the twentieth century, both in the USA and in Europe, the energy supply was secured by governmental organizations. In the 1980s, the discussion about the liberalization of the sector began and, in the 1990s, it was pushed forward in different forms on both continents. Due to high investment costs and low marginal costs, energy networks are natural monopolies that remain under state regulation even after market liberalization. Generation, however, has been privatized and is mainly competitive. However, the approaches in the USA and EU differ. While the USA focuses on locational marginal pricing, the EU has implemented a stock exchange-oriented market. Both models have advantages and disadvantages which we do not want to discuss here any further, however, but instead want to refer the reader to the standard energy economics textbooks.

2 Drivers, Barriers, and Challenges of the Ongoing Energy Systems Transition

The future of energy supply is green, i.e., electricity is more and more produced from renewable production technologies such as PV, wind, water, and biogas (synthetic natural gas (SNG), respectively) instead of using fossil generation plants. This trend has several reasons, one is the rapid decline in renewable energy costs and another is the aim to reduce carbon dioxide emissions. In the Paris Agreement, the international community agreed to reduce GHG (especially CO_2) emissions in order to slow down climate change. Many countries are discussing or taking measures to decarbonize their economies, i.e., replace fossil fuels with renewable energies. This means not only that conventional power plants (coal-fired power plants, nuclear power plants) must be substituted for electricity production but also that other sectors such as transport or industry must be converted from fossil fuels like oil and gas to electricity. As a result, the overall demand for electricity is rising, which makes a massive

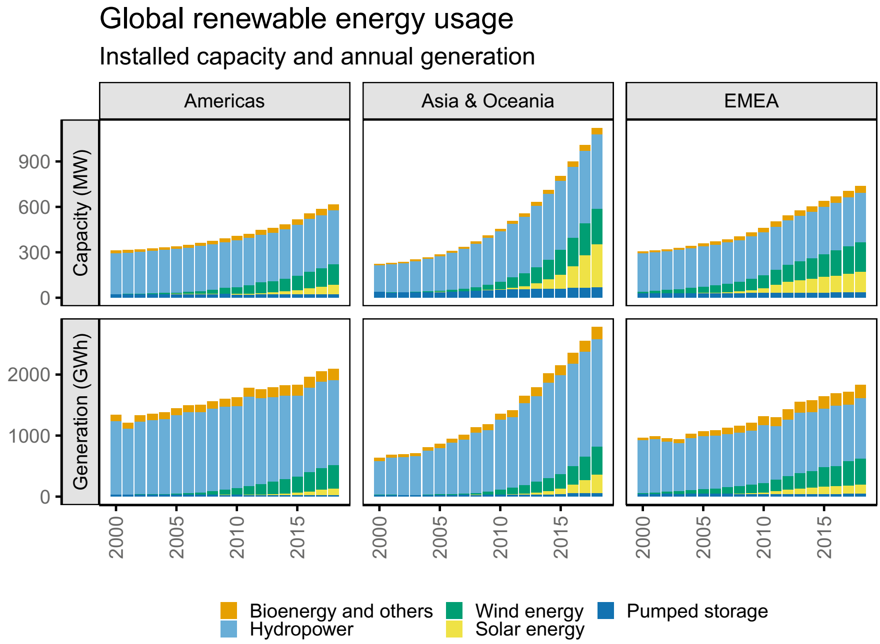

Fig. 1 Global installed renewable generation capacity

expansion of renewable power generation plants and transmission grids necessary. The worldwide installed capacity of PV has grown enormously in the last 20 years. In the period from 2008 to 2018, we see a tenfold increase in worldwide installed capacity. Figure 1 shows the development from 2000 to 2017. We are observing strong growth for Asia (especially China), Europe, and North America. PV yield is dependent on solar irradiation. Due to the geographical location, the largest yields are in the south of North America, Central and South America, Africa, and Oceania. With regard to these areas with high solar irradiation, it is interesting to note that the growth of solar PV in these regions has been relatively low over the period considered. However, the use of solar energy in these regions would be reasonable and is also being discussed, for example, for the production of regeneratively produced hydrogen.

Given the technological advances which also result in cost reduction a growth of installed capacity is expected. According to IRENA (2020), a study undertaken by the International Renewable Energy Agency (IRENA), the PV capacity could rise up to 8,500 GW by 2050 (Fig. 3).

Technological advances have led to considerable cost reductions in solar PV-electricity. Figure 2 shows average total installed costs, capacity factors, and LCoE for the period from 2012 to 2018. In 2010, the cost were still at 37 Cts/kWh, whereas in 2018, the kWh is produced at 9 Cts. This is a decrease by 75%. This could have been achieved through an increase in efficiency. Dependent on the location of the

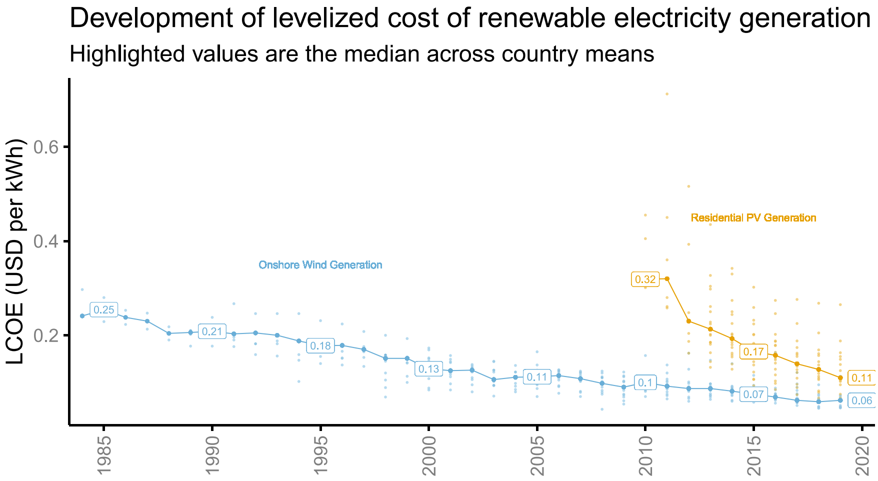

Fig. 2 Global weighted average LCoE for onshore wind and residential solar PV

Solar PV generation plant the LCoE could be lower at approx. 5 Cts/kWh, which makes it competitive with other conventional power generation technologies.

What we observe for solar PV is also true for wind turbines which have developed well in the past decades with respect to installed capacity, cost, and efficiency. Worldwide installed capacity has increased from 16 GW in 2000 up to 622 GW in 2019. As for solar PV, we see the largest increase in Asia (mainly China), Europe, and North America. Figure 3 shows the development. The large increase in installed capacity has also to do with the technological advances. Walker (2020, p. 410) analyzes the trend in turbine capacity. He remarks that the average turbine in the USA in 1990 was 0.218 MW; in 2005, it has risen up to 1.5 MW and increased further to 2.56 MW in 2019. In 2016, the largest turbine has a capacity of 6 MW. Wind blows more reliably with increasing distance from the ground. This is why the towers for wind turbines are getting higher and higher. General Electric, for example, is planning a 12-MW turbine with 260 m hub height above the earth's surface as an off-shore plant. With a rotor blade of 107 m length the turbine even towers above the Empire State Building in New York (which is 319 m of height). The first turbine of this type was produced in 2019 in France.

According to the efficiency increases of wind turbines, we also observe a significant drop in turbine prices and project cost which result in overall declining LCoE. Figure 2 gives an overview on the weighted average cost development during the 2010s. According to IRENA (2019, p. 19), the cost span of the 5–95% percentile in 2010 was between 5.6 and 11.4 Ct/kWh and declined to 4.3–9.9 Ct/kWh in 2018. Costs differ by region, and are dependent on production and implementation facilities. Costs for off-shore plants are still higher and span between 10.2 and 19.7 Ct/kWh.

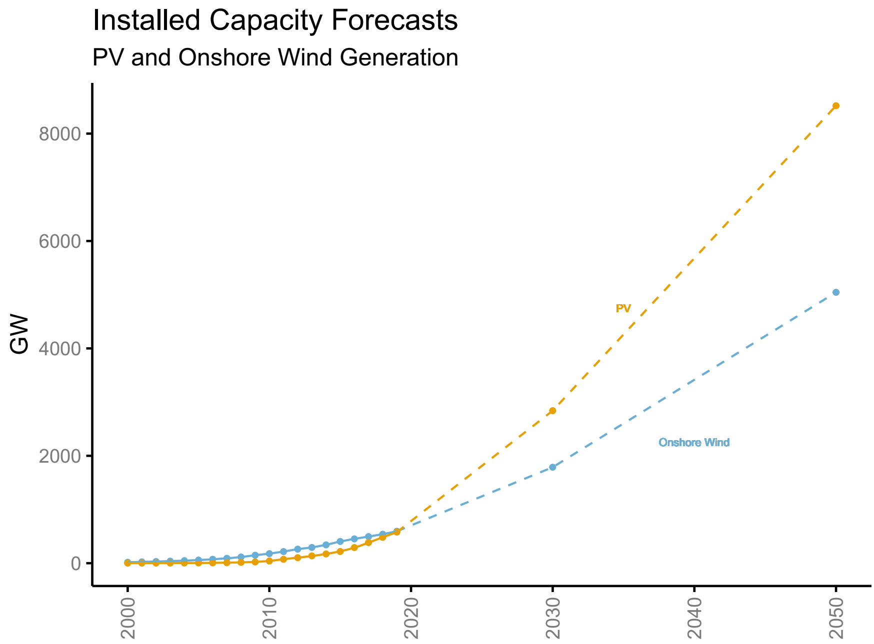

Fig. 3 Projected growth of PV and onshore wind power generation capacity

How does this development relate to Smart Grid developments? The increase in renewable capacity requires a different power grid from the historically established one. In the past, electricity was generated in large power plants by converting fossil primary energy sources such as coal or uranium with the aid of steam turbines. These large power plants were typically built near centers of consumption and were supplemented by run-of-river power plants on rivers, pumped storage power plants and gas-fired power plants. The energy needs to be transported via extra-high (380 k/220 kV) and high-voltage (110 kV) power lines and distributed to the consumers via medium-voltage (10/20 kV) and low-voltage grids (400 V). For this reason, the extra-high and high-voltage networks are referred to as transmission networks, while the medium- and low-voltage networks are referred to as distribution networks. On the transmission grid level in Europe, we typically find redundant system layouts following the n–1 criterion, meaning that security of supply is still guaranteed even if one critical component fails. On the medium-voltage grid, we observe both, redundant and non-redundant system layouts, whereas on the low-voltage level, typically a non-redundant layout is implemented. As described, great progress has been made in terms of technological efficiency and production costs of renewable energy generation plants (wind turbines and PV) over the last 20 years. Compared to coal-fired power plants, renewable energy plants are smaller and often installed on a decentralized basis. Solar PV systems, for example, are installed on rooftops of houses (and in recent years also in large PV parks on the ground), and thus, feed into the low-voltage grid. Wind turbines are usually installed at a certain distance from towns and villages or in large wind farms at sea. Onshore wind energy is typically fed into the low-voltage or medium-voltage grid. Both, the low-voltage and the medium-voltage grids, were not planned and installed taking feed-in electricity into account. In former times, these grid levels were exclusively demand sinks. Now, electricity is generated and fed into the grid on these levels. Unlike in the past, distribution grids are not pure energy sinks, but generation also takes place there which requires new technical solutions. The original network structures are not prepared for this, as load flow reversal can now occur, for example, i.e., electricity from the distribution network can flow into the higher voltage levels. This can be observed especially in distribution grids with a lot of installed PV and few consumers, which is the case, for example, in less densely populated rural regions where large roof areas (e.g., on barns) are available. Wind sites, on the other hand, are not necessarily located near the centers of consumption.

Controlling the grid on the low-voltage and on the medium-voltage level becomes necessary. For this reason, sensors and controllable network components are installed and turn the distribution network into what we call the Smart Grid. With an intelligent low-voltage grid, it becomes possible to manage supply and demand directly at this level. It is necessary to balance the distribution grid within the technical constraints (e.g., voltage band or frequency).

From an economic point of view, renewable energy plants should be installed where the highest yield can be achieved. This typically results in a regional distribution of wind turbines and solar PV depending on wind power and solar irradiation. Looking at the German situation, for example, we observe wind sites at the coast (North of Germany), whereas the centers of consumption are in the South which means that the solution lies not only in the Smart Grid but that transmission lines are also necessary.

In this book, we want to deal with this transition of the energy system and consider both technical and economic challenges and their solutions.

3 Smart Grids

The distribution network is not intelligent per se. Distribution networks provide the electric connection of end consumers to the power grid at the low-voltage electricity supply level. The low-voltage grid is connected to the medium-voltage network. At the transfer point, the local network stations, electricity is transformed from medium voltage to low voltage and then distributed to the end customers' network connection points. This results in a unidirectional flow of electricity.

With the increase of renewable power generation and additional electric load from new devices like electric vehicles (charging points) or heat pumps, the need to control the low-voltage distribution network increases: In order to feed electricity into the grid, the source must increase the voltage slightly above the grid voltage. If there is a lot of distributed generation connected to the distribution network, this can cause overvoltages or reversal of the electricity flow. Ideally, the decentrally generated energy is also used directly in the distribution grid to avoid transmission losses. Since the power generation of renewable energy sources depends on favorable conditions, a high degree of utilization is possible when the consumption side reacts to the power supply and, for example, cars are charged when excess power production exists. This required an intelligent energy management system that measures the status of both generation plants and consumers as well as the distribution network and intervenes with control technology. The control technology must therefore master the complexity resulting from the monitoring of the grid situation and the control of the plants on both the consumption and generation side. The aim is to maintain the technical grid conditions and to deal efficiently with load and generation peaks. In this way, the use of expensive reserve power can be avoided.

A prerequisite for this is that the network condition information can be recorded and processed. This also includes the status data of the generation plants and, in particular, of the consumers. Smart meters, i.e., electricity meters that record the power consumption up to the minute, are used to measure consumption at precise times. Time-based metering of generation and consumption not only creates the transparency required for control but also the possibility for further functions such as dynamic tariffs, fault monitoring, or the switching on and off of devices. Information and communication technology enables an intelligent and automated interaction of generation and consumption devices. This intelligent infrastructure is a fundamental prerequisite for new business models. Thus, the distribution network is developing into a smart grid. The term smart grid first appeared in the literature in the 2000s and has become more common since 2004 (Bollen 2011). However, there is no general agreed upon definition and worldwide different interpretations exist.

European Union

According to Jiménez (2011), the EU Smart Specialisation Platform[3] provides the following definition: "*A Smart Grid is an electricity network that can cost efficiently integrate the behaviour and actions of all users connected to it—generators, consumers and those that do both—in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety.*"

United Kingdom

The UK Department of Energy and Climate Change provides the following definition (The Smart Grid Forum 2014): "*A smart electricity grid that develops to support an*

[3] https://s3platform.jrc.ec.europa.eu/smart-grids.

efficient, timely transition to a low carbon economy to help the UK meet its carbon reduction targets, ensure energy security and wider energy goals while minimising costs to consumers. In modernising our energy system, the smart grid will underpin flexible, efficient networks and create jobs, innovation and growth to 2020 and beyond. It will empower and incentivize consumers to manage their demand, adopt new technologies and minimise costs to their benefit and that of the electricity system as a whole."

United States of America

The U.S. Departement of Energy provides the following definition[4]: "*[...], the digital technology that allows for two-way communication between the utility and its customers, and the sensing along the transmission lines is what makes the grid smart. Like the Internet, the Smart Grid will consist of controls, computers, automation, and new technologies and equipment working together, but in this case, these technologies will work with the electrical grid to respond digitally to our quickly changing electric demand.*"

China

According to Brunekreeft et al. (2015, p. 29) and Yu et al. (2012) the Chinese government has published a definition of smart grids: "*Smart grid technologies have the purpose to integrate new energy, materials and equipment as well as advanced technologies in information, automatic control and energy storage for realizing digital management, intelligent decision-making and interactive transaction in power generation, transmission, distribution, consumption and storage. Furthermore, smart grid assets optimize the resource allocation and satisfy diverse needs of customers as well as ensure the safety, reliability and cost-efficiency of power supply. Finally, the new technology [in the sense of smart technology] bridges the constraint of environmental protection and the development of the power market.*" The Chinese view includes an integration of provincial and regional grids with a strong (ultra) high voltage backbone.

International Energy Agency

A general definition, which is often used, was published by the International Energy Agency (IEA) (2011): "*An electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users. Smart grids co-ordinate*

[4] https://www.smartgrid.gov/the_smart_grid/smart_grid.html.

the needs and capabilities of all generators, grid operators, end users and electricity market stakeholders to operate all parts of the system as efficiently as possible, minimizing costs and environmental impacts while maximizing system reliability, resilience and stability."

In summary, all definitions have some aspects in common. Smart grids emerge as the union of different technologies: the physical energy network on the low voltage level, bidirectional communication capabilities for network participants, ICT and sensor technology to optimize and control bidirectional energy flows, and to enable new business models and services. The US definition explicitly points out the similarity to the Internet but underlines its application to the electrical grid. The Chinese definition differs from the others as it explicitly includes higher voltage level grids in its definition, while all other definitions make no specification in this respect. Typically, several goals are associated with the smart grid (Ekanayake et al. 2012, p. 6):

1. Ensure reliability and security of supply;
2. Optimize economically efficient grid monitoring and control, grid operation, and operation of assets (e.g., generation, controllable load, storage, grid technology);
3. Enable consumers to contribute to grid management;
4. Improve physical capacity and flexibility of the network;
5. Enable demand-side management and demand response;
6. Facilitate the integration of renewable energy generation into the grid;
7. Integrate communication, sensing, and measuring;
8. Resist attacks;
9. Enable and grant open access to markets and services.

In order to achieve these goals, a suitable technical architecture is required that enables interoperability between the various technical systems. In principle, a distinction can be made between different technical levels, which are structured hierarchically. Figure 4 shows the structure of the Smart Grid Architecture Model, which was developed by the Smart Grid Coordination Group as a standardization framework. The lowest level is the *component layer*, in which all physical components (system actors, applications, power system equipment, protection and tele-control devices, network infrastructure, computers) in the smart grid context are described. In the *communication layer* above, protocols and all mechanisms for inter-operational information exchange are defined based on the use case, function, or service and associated information objects or data models. This establishes syntactic interoperability and network interoperability. The communication layer enables the exchange of information objects that are exchanged between the functions, services or components. These information objects are defined in the *information layer*. One level higher, the *function layer* represents the functions and services derived from the business cases and their relationship. This creates the technical prerequisite for forming the *business layer* as the top layer, in which the regulatory and economic market structures, business models, products and services, and market participants are described. With the division into these levels, the previously described properties and objectives of the smart grid are technically structured and new business models are thus

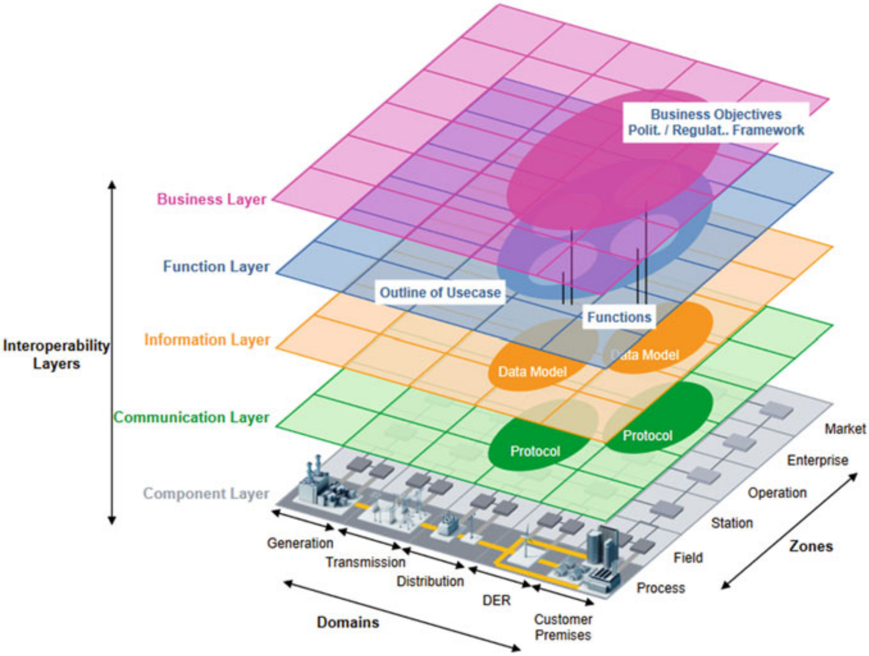

Fig. 4 SGAM framework (CEN-CENELEC-ETSI Smart Grid Coordination Group 2012, p. 30)

made possible. Accordingly, with the smart grid, not only technical challenges (e.g., efficient use of electricity in the distribution network, prevention of voltage band violations, control of load flow reversal, fluctuations in network frequency) become solvable, but new business models and services can emerge through the communication and information layer. For example, smart charging of electric vehicles can lead to capacity relief of the distribution grids or to better use of renewably generated electricity. Through appropriate control, renewable-generated electricity can be used directly in the neighborhood, e.g., through switchable loads such as heat pumps or stationary batteries. This gives rise to various economic and technical issues, which we will discuss in more detail in the further chapters of this book.

The transformation of the energy system to a carbon-free system requires major efforts and investments. This can only succeed if, in addition to the technical possibilities and what is economically feasible, there is also social acceptance. Therefore, the following guidelines for the transformation have been proposed by the Internet of Energy Working Group (Weidlich et al. 2013):

1. Subsidiarity: The distribution networks have local characteristics, which is why a generally applicable approach does not appear to make sense; instead, specific measures are necessary depending on the local framework conditions. Subsidiarity follows the idea of solving network problems first at the level where they arise and delegating them to higher levels for solution only if no solution is possible locally.

2. Flexibility as an economic good: as electrical energy requires permanent balance between generation and consumption, flexibility in generation, transmission, storage, and consumption becomes more important. Flexibility has an economic value. Thus, it can also be understood as a tradable economic good whose price adjusts to the respective situations.
3. Adequacy in infrastructure development and transformation: the distribution of costs, risks, and rewards in the course of the transition of the energy system should be appropriately distributed. Proportionality should be maintained and the interests of individuals and the general public should be balanced. This applies to all levels of the smart grid, from the infrastructure to the communication and information level to the market level.
4. Cost fairness: The costs of grid expansion and generation capacity expansions should include both external effects and take into account both pay-as-you-go components and benefit ratios. An undifferentiated apportionment to all consumers does not seem fair.
5. Incentives for Innovation and Investment: Since progress and efficiency result from innovation and investment, the necessary regulatory and technical conditions should be created so that, for example, grid operators have a choice between innovative solutions through smart grid technology and investments in grid capacity, rather than relying only on grid capacity expansion by default.

Even though great progress has been made in the field of the smart grid in recent years, the transition of the energy system is far from over. The smart grid is not yet the standard in distribution grids, although the technical need for widespread implementation is increasing. In the wake of the Paris Climate Agreement, the majority of countries are aiming for a zero- or low-carbon power supply. This means that the share of renewable generation units will continue to grow. At the same time, the transport sector is also undergoing a transition toward more electric vehicles, meaning that the number of charging stations will grow worldwide. In the next section, we will therefore look at the speed of the transition.

4 The Quest for the Social-Welfare-Optimal Speed of Smart Grid Technology Diffusion as an Important Element of a Sustainable Energy Transition

A transition of the electricity supply system toward exploitation of the benefits from smart grid technologies requires directed investments, social acceptance, and regulatory change. Diffusion of innovations, however, often takes a long time, sometimes decades (Rogers 1995). From a social welfare point of view, policy-makers should also take care that the promotion of innovative technologies is neither too fast (e.g., adoption of immature or overly expensive technology) nor too slow (e.g., forfeiting benefits in terms of competitiveness). Numerous important—and often interrelated—barriers exist, such as investment needs and financial resources; market uncertainty;

lack of a regulatory framework; low public awareness and engagement; lack of innovativeness in the industry; lack of infrastructure; technology immaturity; lack of the necessary technical skills and knowledge; integration of the grid with large-scale renewable generation; need for advanced bi-directional communication systems; lack of open standards; and cyber security and data privacy issues (Luthra et al. 2014).

Smart grid technologies are being implemented slowly, often only due to changed regulation (such as the mandatory installation of smart meters, which otherwise may take decades). Companies need to develop business models that create enough value to be worthwhile, for their customers and themselves, in a risky and rapidly changing environment. Today, because of the chicken–egg situation (lacking widespread availability of smart grid technologies versus lack of business models to make money), smart grid technologies are often not accompanied by business models, at a larger scale, that are able to exploit on smart grid functionalities.

The temporal change of a system's footprint is shaped by numerous different driving and other influencing factors. The dynamics and net cost–benefit ratio depend on the co-evolution of technical, societal, economic, and institutional partial systems. There are supply-push and demand-pull forces at work, and chicken–egg problems have to be overcome (e.g., electric vehicle sales are strongly dependent on the spread of the charging stations, design of standards, and financial policy support may be sub-optimally designed and crowd out private investments).

Welfare economics tells us that there is some optimal speed of transformation, determined by the expected costs and benefits which are the more uncertain the more distant one looks into the future. In the light of the enormous complexity of energy systems, and the social, economic, and ecological interrelations, such an analysis is challenging. Nevertheless, it will not be optimal to transform the system as fast as possible.

The power grid has evolved over many years, is a very capital-intensive and path-dependent infrastructure, and for many reasons constitutes a strong lock-in situation. An example is the long tradition of using alternating current technology for power transmission and distribution, and the largely still untapped potentials of direct current technology as an alternative.

Smart grids can have major impacts on consumers through (induced or required) changes in consumer behavior and lifestyles. Bigerna et al. (2016) have proposed a taxonomy of socio-economic aspects in terms of private (direct) costs, social costs arising from consumers' perceptions, privacy, cyber security, and regulation (Bigerna et al. 2016). Welfare gains and optimality—in a dynamically, potentially rapidly evolving system (where disruptive, game-changing 'smart' technologies are at play) with a lot of uncertainty—depends on resource availability, technological diffusion, political, and regulatory decisions but also societal valuation and acceptance.

The increased use of intermittent renewable energy sources, coupled with the increased use of distributed energy resources and the phase-out of conventional power generation, has positive effects in terms of decarbonization but negatively affects security of supply. To deal with the underlying challenges of this massive transformation of the energy system smart grids have to be developed. A range of smart grid technologies, including smart meters and advanced metering infrastructure, are being developed and gradually installed. Due to the rapidly increasing complexity of the system, and the largely unpredictable dynamics of this at the same time revolutionary and evolutionary process, system operators face an enormous challenge. An important question in this respect is how much can be left to the markets and how much needs to be centrally planned and controlled. The more long-term the perspective, and the more investment is needed, the more likely markets need to be directed. As an increasing part of the supply, demand and storage of energy, both temporally and spatially, is left to distributed resources and actors, the more dangerous it is to leave tasks to actors without responsibility for the energy system's overall performance and reliability. On the other hand, system operators cannot be expected to be able to orchestrate the entire system in all detail without being allowed to monitor the entire system in great detail as well, raising privacy and non-acceptance issues. Overall, there is a high potential for disruption, which in the case of more severe, and thus longer-lasting, electricity system outages, may have devastating consequences.

5 Policy Challenges

Decarbonization of the world economy necessitates also fundamental changes in the power system—i.e., a deep transformation of the electrical grid system, and therefore large (public or private) investments. Two major challenges are the integration of DER and electrification of the transportation sector. Both require a much more intelligent electricity network, i.e. smart grids (Cambini et al. 2016).

The transition from today's centralized, hierarchical and top-down organization of the electricity supply system towards a smart grid requires huge investments, new regulation and new ways of organizing (i.e., planning, constructing, and operating) the infrastructure. Smart grid investments are related to enhancing the power system infrastructure (e.g., measuring and sensor devices), the ICT infrastructure (hard- and software), and smart end-use devices.

However, in a smart grid framework there will also be totally new relations between the economic actors—not just suppliers and consumers of energy, but also prosumers. Overall, this transition can be expected to create major shifts in consumer behavior, lifestyles, and culture (Bigerna et al. 2016). Furthermore, it requires social acceptability and acceptance, which is affected, among other factors, by the perceived short- and long-term costs and benefits of smart grid investment. On the cost side, this involves not just investment and operating costs, but also costs of maintaining cyber security, costs of privacy loss, and others. It also requires new standards, regulation, and institutions.

The development of the smart grid infrastructure can be viewed as a co-evolutionary process of systems (technologies, institutions, user practices, ecosystems and business strategies) more or less aligned with energy (and climate) policies (Hall and Foxon 2014). For policy-makers it is crucial to better understand the drivers and processes of change, offering better chances to steer the various systems towards the envisaged sustainable energy transition.

The policy and governance challenge is to adequately support the co-evolution of systems, by mitigating non-monetary barriers and providing financial support and regulation to foster the transition. Given that the optimal level (and trajectory) of distributed versus centralized generation (and storage) is unknown, policy-makers should make an effort to define and operationalize the energy policy trilemma in order to find, and keep, a balance between the different trade-offs identified (e.g., social justice, security of supply, environmental sustainability) for the sustainable energy transition aimed for, and system transformation needed.

From a regulatory perspective, a main challenge is to decide how much can be left to the market and how much needs to be left in the hands of regulated entities such as DSOs to follow a predefined path of innovation and development.

6 Regulatory Challenges

Finally, from a regulatory perspective, smart energy systems, increasing energy system integration facilitated by ICT and machine learning (ML), as well as the re-emergence of multi-business utilities, calls for multi-sector regulatory bodies. These need to overlook the activities, define adequate regulatory frameworks (including penalties for non-system-compatible behavior), and to steer the course towards efficiency and system resilience. Efficiency is determined by efficient markets as well as economies of scale and scope (Jamasb and Llorca 2019, Sect. 3.3). In the literature, there is considerable debate on the pros and cons of single-sector versus multi-sector regulation. Needless to say that there is considerable unchartered territory out there with respect to how smart energy systems will evolve and diffuse society and the economy.

In Chap. 2, besides an outline of what distinguishes 'smart energy economics' from the more conventional energy economics, also addresses regulatory issues along the lines of the new paradigm “Energy system integration (ESI)”, aiming at exploiting horizontal synergies and efficiency at all levels, based on sound economic principles and ex-ante and ex-post evaluation, as well as a well-balanced policy framework and a secure and resilient, integrated physical infrastructure, and enabling integration with other infrastructural sectors (e.g., transportation, telecommunication, water). The challenge is to quantify expected net gains of vertical separation (as it has been pursued for the last 30+ years) versus vertical integration (enabling integration of DER also across wider areas). Economies of scale need to be compared to economies of scope and of coordination (of inter-dependent activities, but also of jointly used knowledge—related to planning, policy and regulatory design etc.), the performance of multi-businesses needs to be gauged against the performance of unbundled market activities.

Chapter 5 explores some regulatory and institutional challenges related to smart grids, balancing basics of regulation with the topical developments around smart grid evolution. A fine balance needs to be sought in terms of competition versus coordination between networks (and network operators) and the network users. The three issues addressed are: (1) the adequate governance of (evolving) smart grids at the distribution level in order to enable non-discriminatory access to monopolistic networks; (2) appropriate regulation (cost-, price- or output-based) in the light of new tasks for network operators; and (3) network charging to address (decentralized) network congestion and designing well-functioning markets for flexibility.

Review Question

- What are the main drivers and challenges of the ongoing energy systems transition?
- Explain why electricity and power systems are so special for the sustainable energy transition.
- Describe what energy policy-makers need to take into consideration when implementing sustainable energy policy measures and programs.
- What are the main characteristics of smart grids?
- Describe the term ‘sector coupling’ and provide two examples.
- Name four misconceptions in policy-making related to the energy system transition.
- Summarize the main policy challenges related to the development of smart energy infrastructure viewed as a co-evolutionary process.

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