Chapter 1
Future Power Systems

1.1 Introduction

Fossil or nuclear primary energy sources (PES) have been widely used in energy systems worldwide. The PES are finite and are forecasted to last only for the next 60 (natural gas) or 200 (hard coal) years at today's level of consumption. However, the consumption of energy has been increasing worldwide for many years. Furthermore, an increase of CO_2 emissions has been observed as a negative result of the increase in consumption, which has become evident from the global warming effect. It has become necessary to define global countermeasures to stabilize the increase in the Earth's temperature.

These countermeasures were first proposed in the so-called Kyoto Protocol in 1995 and concretized in the climate agreement in Paris in 2015 [1]. This agreement was ratified in October 2016 by the European Union (EU) [2], China, the USA, Japan and other countries, and mandates that members reduce their CO_2 emissions by 40 % (corresponding to 1990 levels) by 2035.

The first result of those countermeasures is that the growth of energy consumption in the industrial countries [3] and, consequently, the growth of CO_2 emission, have been decoupled from the gross domestic product (GDP).[1] Unfortunately, despite this decoupling, the energy consumption in the developing countries has continued to grow proportionally to the GDP. These processes are illustrated in Fig. 1.1: the increase of energy consumption is given in Fig. 1.1a and the consumption growth in % per annum is presented in Fig. 1.1b.

As can be seen, the consumption growth in OECD[2] countries has been close to zero for many years (see Fig. 1.1a, black space, and Fig. 1.1b, black line). This

[1] Gross domestic product (GDP) is a monetary measure of the market value of all final goods and services produced in a period (quarterly or yearly). Source Wikipedia.

[2] OECD—Organization for Economic Co-operation and Development.

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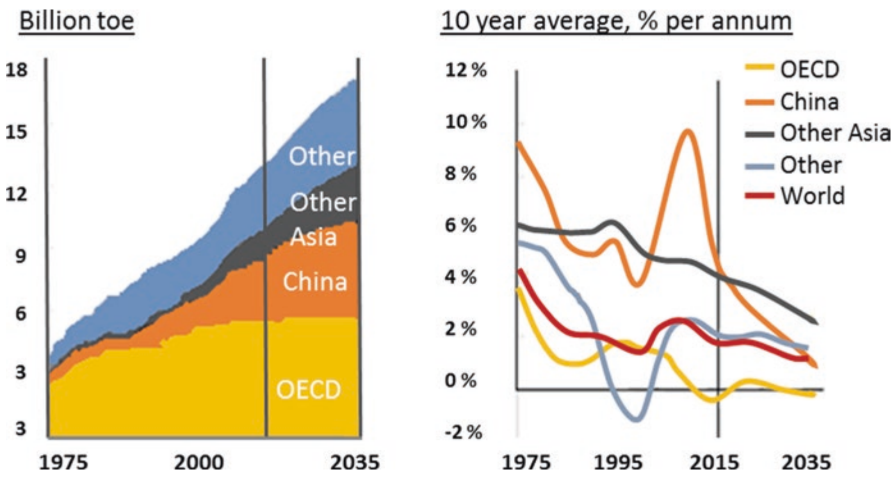

Fig. 1.1 Consumption in toe (The ton of oil equivalent (toe) is a *unit of energy* defined as the amount of energy released by burning one ton of crude oil. One toe is approximately 42 gigajoules.) (**a**) and consumption growth in % by region (**b**). Source BP 2016 Energy Outlook (www.bp.com/energyoutlook)

results from the conversion to more economic production and the installation of money-saving equipment in households in these countries. In other countries, consumption growth is still between 2 and 5 % per year, which is a consequence of accumulated needs over many years. The current per- capita energy consumption in some developing countries, especially those with high populations (e.g., China and India), is still less than 50 % of the per-capita energy consumption in industrial countries.

The shares of primary energy consumption changes globally every year for two main reasons: the shortage of PES and the necessary reduction of CO_2 emissions (see Fig. 1.2). Independent of the current low price for oil, this type of PES has been systematically experiencing a decrease in its dominating role in the energy mix, and likewise, coal and nuclear energy consumption have also decreased (Fig. 1.2a). At the same time, there has been an especially dynamic increase in the use of renewable energy, and this trend is forecast to continue over the next 20 years (see Fig. 1.2b). Natural gas will also be used in the future in more flexible power stations, resulting in lower CO_2 emissions than that produced by combusting other fossil fuels.

Considering these trends in the changing energy mix, one can consider that this is a global effect. Not only the nations of Europe, and especially Germany with the national energy strategy called "Energiewende", but all other countries worldwide are working intensively to develop new, levelled-cost renewable technologies (Fig. 1.3a). Wind and especially solar photovoltaic (PV) energy have become two to four times cheaper, considering energy-production costs, over the last 20 years. The installed power using those technologies has been growing consistently and exponentially. Wind power equipment, with energy production costs at 50 $/MWh,

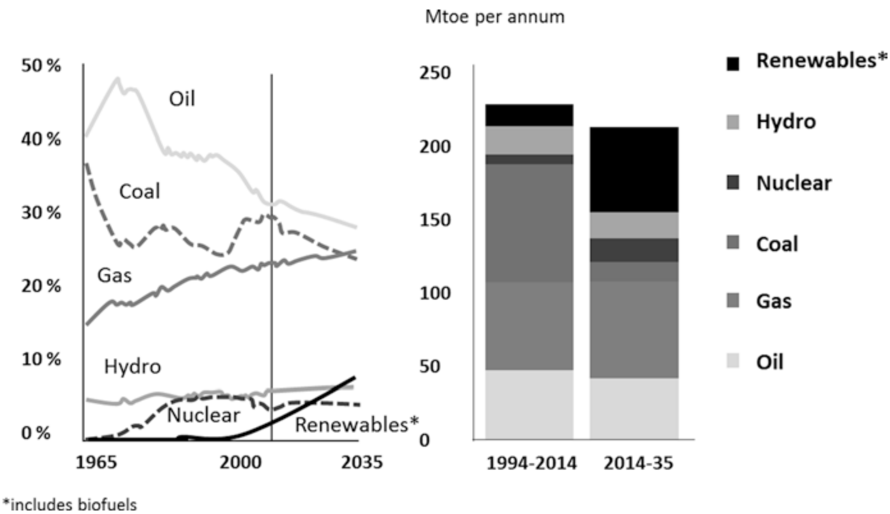

Fig. 1.2 Share of primary energy (**a**) and annual demand growth by fuel (**b**). Source BP 2016 Energy Outlook

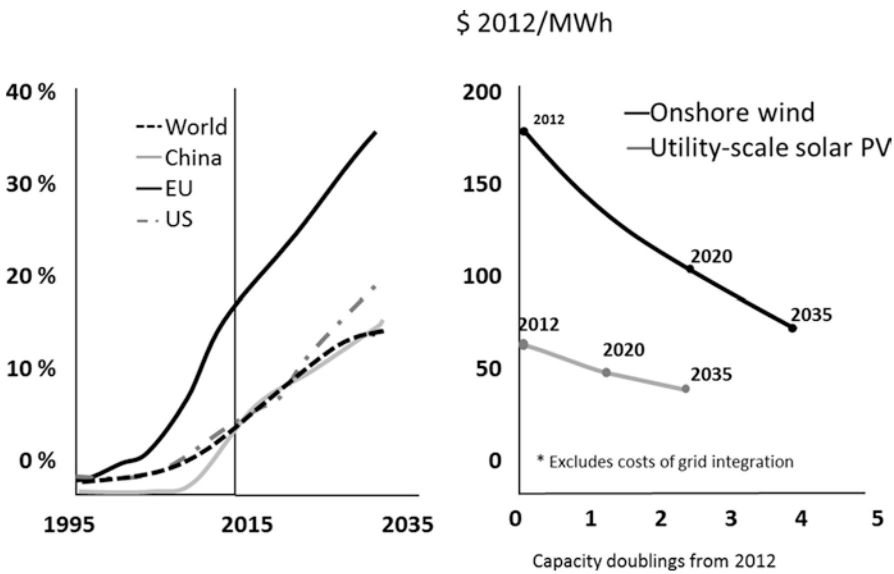

Fig. 1.3 Renewables share of power generation (**a**) and levelled cost of electricity in North America (**b**)

is currently a strong competitor to the traditional technologies (Fig. 1.3b for North American costs), and also a driver for a wider use of renewable energy.

A global market for wind and PV solar power is already established. The prices for energy production using these technologies are comparable per MWh worldwide (Table 1.1).

Table 1.1 Comparison of prices for onshore wind and PV solar in 2015. Source IEA

Country	Onshore wind, US$/MWh	Solar PV, US$/ MWh
United States	47	65–70
Canada	66	–
Germany	67–100	95
Brazil	49	81
Chile	–	85–89
Uruguay	–	90
South Africa	51	65
India	–	88–116
China	80–91	–
Turkey	73	–
Egypt	41–50	–
Australia	69	–

Two positive global effects, from the environmental point of view, have been observed more generally over the recent few years:

- Uncoupling of primary energy use from GDP beginning in the 1990s—as already discussed previously in this chapter (Fig. 1.4),
- Uncoupling of CO_2 emission in the power sector from demand, for the recent few years (Fig. 1.5).

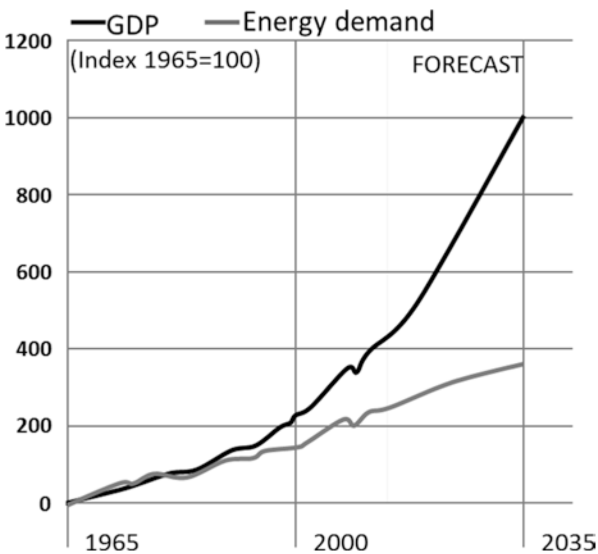

Fig. 1.4 Uncoupling the growth of global GDP and demand. Source BP 2016 Energy outlook [4]

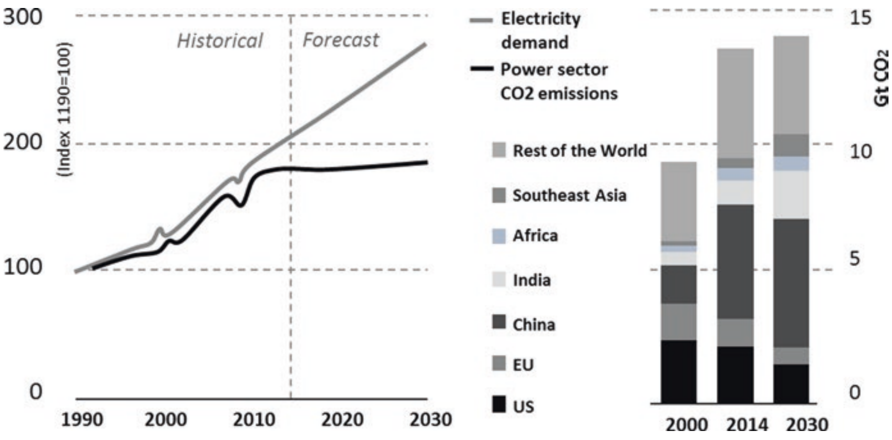

Fig. 1.5 Uncoupling of CO_2 power sector emission from electricity demand: electricity demand versus power sector CO_2 emission (**a**), CO_2 emission by countries (**b**) Source IEA

This second effect is very promising and could result from different countermeasures started by many countries with regard to increasing the energy efficiency, the economic production of industrial goods and the use of no-emission renewable generation.

Electrical demand in places such as China, India and Southeast Asia (see Fig. 1.5) is forecast to increase, as has been mentioned already, balancing out the disparities in per-capita energy use as compensation for the standard of living. But the emissions in these areas will increase at slower rates than in earlier decades. The CO_2 emission in the USA and the EU will decrease as the result of a constant electricity demand. Both of these processes will result globally in the levelling of CO_2 emission (see Fig. 1.5a). In order to support and cover this effect, according to the Paris agreement, industrial countries have agreed to transfer US$ 90 billion to the developing countries over the next 5 years.

To summarize, not only the growth of renewable generation but also, and maybe even more importantly, the clear trend in the decrease of energy intensity is very promising and could result from fulfilling the goals formulated in the Kyoto Protocol. Some countries have reduced (Fig. 1.6) their energy intensity by more than a factor of two (e.g., China), but Europe is still leading with the lowest value.

1.2 Towards a Smart Grid

1.2.1 More Renewable Generation in the Future

Renewable energy and modern economic production are increasingly predominating, but the current power system was planned 30–50 years ago for other conditions. Furthermore, the mix of energy predicted by the Energy Information Administration

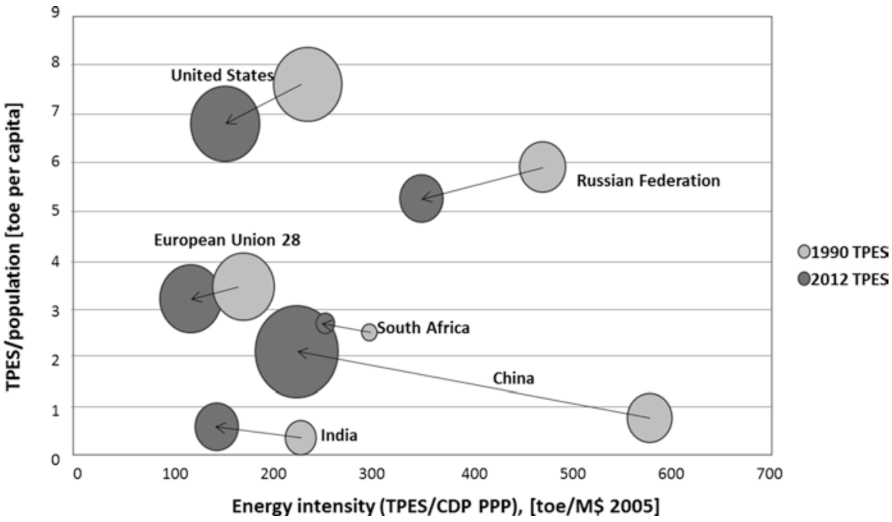

Fig. 1.6 Regional decrease of the energy intensity. Source IEA [5]

(EIA) for 2030 (given in Fig. 1.7) designates a share of 14.6 % for renewables, which will result primarily from the reduction of coal use.

The EU in toto and some European countries individually have more concrete plans for the power system in the future.

Consequently, the EU has set ambitious objectives for the year 2020 in order to:

- lower energy consumption by 20 % by enhanced efficiency of energy use,
- reduce CO_2 emissions by 20 % and,

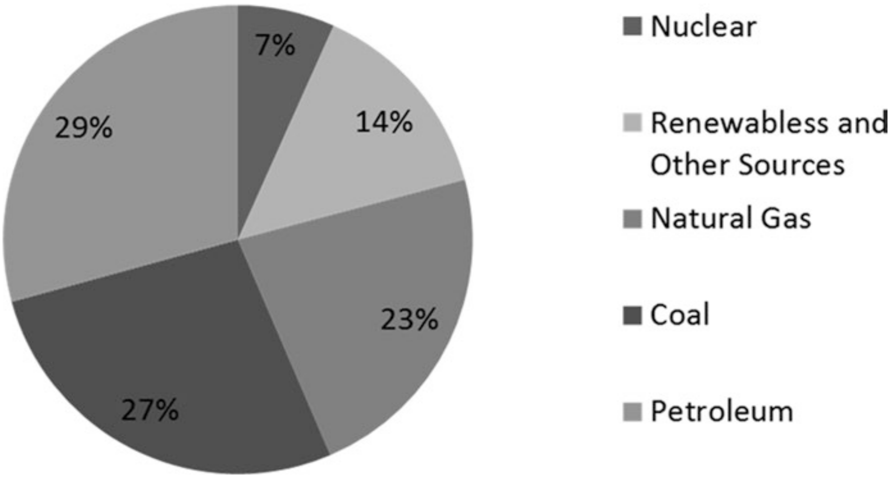

Fig. 1.7 Word energy mix 2030. Source EIA

- ensure that 20 % of the primary energy is generated by renewable energy resources (RES).

In the EU, about 40 % of PES that are used is currently applied for the generation of electricity (the other 60 % is used for transportation, heating, etc.). Electric energy offers the best opportunity for production by RES, such as wind power, solar energy (PV), biofuel and hydro power. Consequently, electric energy has to carry the main part of the renewable-energy production by achieving an annual share of 30 % in 2020. All of the member states of the EU have set their individual targets in support of the common strategy for 2020. In 2006, the European Commission published the "Strategic Energy Technology Plan" (SET Plan) [6], underlining the potential of the various categories of RES and of cogeneration of heat and power plants (CHP), which are also favored to increase energy efficiency. The data of the SET Plan is summarized in Table 1.2.

This plan also contains figures regarding the importation of energy from solar thermal- power stations in Northern Africa, which corresponds with the Desertec vision [8]. The RES and CHP power installed in 2020 will exceed the currently installed power capacity of the Continental European, interconnected transmission system (former Union for the Co-ordination of Transmission of Electricity: UCTE).

Table 1.2 Potential of RES and CHP for Europe [7]

SET PLAN	2020		2030	
Plant type	Energy,%[a]	Power, GW[b]	Energy,%	Power, GW
Wind	11	80	18	300
Photovoltaic	3	25	44	665
Concentrating solar thermal power	1.6[c]	0.8	5.5[c]	4.6
Hydro (large plants)	8.7	08	8.3	112
Hydro (small plants)	1.6	8	1.6	19
Waves	0.8	0	1.1	16
Biofuel	4.7	0	5.3	190
Cogeneration heat and power	18	85	21	235
Sum	59.4	657.8	75.8	1542

[a]Related to the annual consumption. [b]Installed power. [c]Partly imported from Northern Africa.

The rate of dependency of the power production from RES on the weather is considered in the ratio of energy (E) and installed power (P), and is the worst for PV and the best for biofuel and CHP plants. The need to modernize the European electricity networks is based, firstly, on the integration of more sustainable generation resources, especially the partially volatile renewable sources, and secondly, on the growing electricity demand and the establishment of trans-European electricity markets. The context of all these aspects presents major challenges, highlighting the essential need for innovations in this area.

The vision for electricity networks of the future was developed by a European group of experts within the framework of the technology platform "Smart Grids" [9] between 2005 and 2008, and three fundamental documents were published as a result. The Smart Grid definition is presented in the strategic deployment document [9] as follows:

> A Smart Grid is an electricity network that can intelligently integrate the actions of all users connected to it—generators, consumers and those that do both—in order to efficiently deliver sustainable, economic and secure electricity supplies.

A smart grid employs innovative products and services together with intelligent monitoring, control, communication and self-healing technologies in order to:

- enable the network to integrate users with new requirements;
- better facilitate the connection and operation of generators of all sizes and technologies;
- enhance the efficiency in grid operations;
- allow electricity consumers to play a part in optimizing the operation of the system;
- provide consumers with more information and choice in the way they obtain their electricity supplies;
- improve the market functioning and consumer services;
- significantly reduce the environmental impact of the total electricity supply system; and
- deliver enhanced levels of reliability, quality and security of supply.

Consequently, a smart grid supports the introduction of new applications with far-reaching impacts: providing the capabilities for safe and controllable integration of more renewable- especially volatile (i.e., weather dependent) energy sources, and of new categories of network users, such as electric vehicles and heat pumps, into the network; delivering power more securely, cost-efficiently and reliably through advanced control automation and monitoring functions providing self-healing capabilities after faults; and finally, enabling consumers to be better informed about their electricity demand and to participate actively in the electricity market by demand-side response on dynamic tariffs. All this makes smart grids a milestone in support of the European strategy for achieving the largest knowledge-based economy in the world.

1.2.2 The Core Elements of the European Smart-Grid Vision

The electricity supply of the future will be shared by central power stations and distributed energy resources (DER). Both concepts may contain RES, some of which may be volatile or intermittent in their output (e.g., wind power plants, which may exist as DER or may be built as their own central power stations, as well). The DER tend to have a much smaller output than the traditional forms of generation, but large-scale deployment will counterbalance this. In addition, placing sources of generation closer to the residential users will reduce the energy transport losses to these customers. Figure 1.8 presents a picture of how the power supply of the future might be imagined [10].

The smart grids will ultimately combine existing technologies—improved and updated—with innovative solutions. The future grids will be based on the existing grids, but will also enable the implementation of new system concepts, such as "Wide/Area Monitoring and Protection," "Microgrids" and "Virtual Power Plants" (VPPs). Centralized generation will still play an important role, but many more actors will be involved in the generation, transmission, distribution and operation of the system, including the end consumers.

Based on these considerations, the core elements of the vision are defined as follows:

1. Create a toolbox of proven technical solutions that can be deployed rapidly and cost-effectively, enabling existing grids to accept power injections from DER without contravening critical operational limits (such as voltage control, switching/equipment capability and power-flow capacity).

pp – power plant, 1 – large hydro pp, 2 – wind farm on-shore, 3 – small hydro pp, 4 – concentrated solar thermal pp, 5 – biofuel pp, 6- wind farm off-shore, 7 – low emission fossil pp, 8 – high voltage DC transmission, 9 – Control center, 10 – micro- grid, 11 – wave pp, 12 – photovoltaic plants, 13 – underground power transmission, 14 – solar heating, 15 – hydrogen filling station, 16 – small electric batteries, 17 – thermal storage, 18 – electricity storage, 19 – cogeneration of heat and power, 20 – fuel cells

Fig. 1.8 Power supply of the future—the vision

2. Establish interfacing capabilities that will make possible new designs of grid equipment and new automation/control arrangements to be successfully interfaced with existing, traditional grid equipment.
3. Ensure harmonization of regulatory and commercial frameworks in Europe to facilitate cross-border trading of both power and grid services (such as reserve power, e.g., Nordic hydropower), ensuring that they will accommodate a wide range of operating situations.
4. Establish shared technical standards and protocols that will ensure open access, permitting the deployment of equipment from any chosen manufacturer without fear of being locked into proprietary specifications. This applies to grid equipment, metering systems and control/automation architectures.
5. Develop information, computing and telecommunication systems that enable businesses to utilize innovative service arrangements to improve their efficiency and enhance their services to consumers.
6. The creation of the first core element, namely the "toolbox," is possible only in conjunction with the other four core elements. The toolbox presents the overview of the innovative solutions which make up the top priority of the smart-grid concept.

Two major trends in the development of the power system can be observed:

1. More transmission: Increasing transmission demands in liberalized markets caused by free energy-trading activities, and by an unlimited feed-in of volatile wind power in some countries, are stressing the power systems and causing frequent congestion of the transmission capacity. The existing transmission lines need to be loaded at higher voltages than in the past.
2. Active distribution: A growing share of electricity will be generated on the distribution level. Distribution networks will become active and need to accommodate bi-directional power flows. These aspects will lead partially to a lower utilization of the transmission grids. However, both trends will lead to extremely volatile-load flows on all levels of the power system.

The toolbox has to provide means that allow a response to the related challenges in an economic and flexible way, and two different toolboxes have to be established, one for transmission and one for distribution, respectively [for details, see smart grid].

On the transmission level, advanced technologies are sought to enhance the transfer capability of the network and to ensure a flexible and smart operation management in the case of congestion. A congestion situation exists if the N-1 criterion (see subsequent details) cannot be satisfied according to the load flows observed through the network.

The majority of changes will take place on the distribution level. The significant growth of the distributed energy generation will impact the network loading and the power quality parameters significantly. In accordance with the smart-grid definition, the interaction between network operations and market activities will become necessary to optimize the enhancement of the distribution network. Consequently, a communication infrastructure has to penetrate entire networks, down to the low-voltage consumer level, to make this kind of interaction possible. Advanced information and communication technologies (ICT) will be the key for:

- advanced distribution automation to enhance the quality of supply,
- a coordinated energy management covering generation, storage and demand in the framework of VPPs,
- provision of new metering services to the consumers, including motivational methods for the efficient use of electricity
  - by dynamic tariffs,
  - by the real-time communication of information to the end consumers, and
  - to visualize the current tariffs, their demand and the related costs.

The other two aspects—the VPP and the smart metering—are means to generate flexibility for:

- the adaptation of the demand to the available low-cost energy, and
- the adaptation of the load flow to the network capacity available.

These aspects are market-related, but they may support the network operations.

In the smart-grid context, the market and grid operations will influence each other mutually. In the environment of large-scale volatile power production, it will become mandatory to coordinate the network and market operations in a smart way.

The main goal of these solutions is to integrate the volatile RES into the network operation without any loss of voltage quality, reliability (N-1 criterion) and security of supply.

The current approaches for fulfilling the N-1 criterion presented in Fig. 1.9 also have to be ensured under the prospective changing operational conditions of the networks. The N-1 criterion is defined as follows: A network always meets the requirements of the (N-1) criterion if it survives the failure of an operating device with no inadmissible restriction to its function for an accidental, technically possible and operationally reasonable initial situation.

Figure 1.9 depicts the overall power system from left to right with indications of the voltage levels at various points. However, the high-voltage (HV) and extra high-voltage (EHV) are defined differently in different regions of the world. In most countries, the HV is defined as the interval between 100 and 220 kV. However, in Japan, the 66 kV level is defined as HV. Voltage levels from 230 up to 765 kV belong to the EHV level.

On the other hand, the rated voltages of the transmission system used in Continental Europe are 220 and 400 kV (or 380 kV), which are both defined as EHV. The ultra-high-voltage (UHV) level is declared as ±800 kV DC and 1000–1200 kV AC. The voltage levels identified in Table 1.3 are used in the considerations of this book.

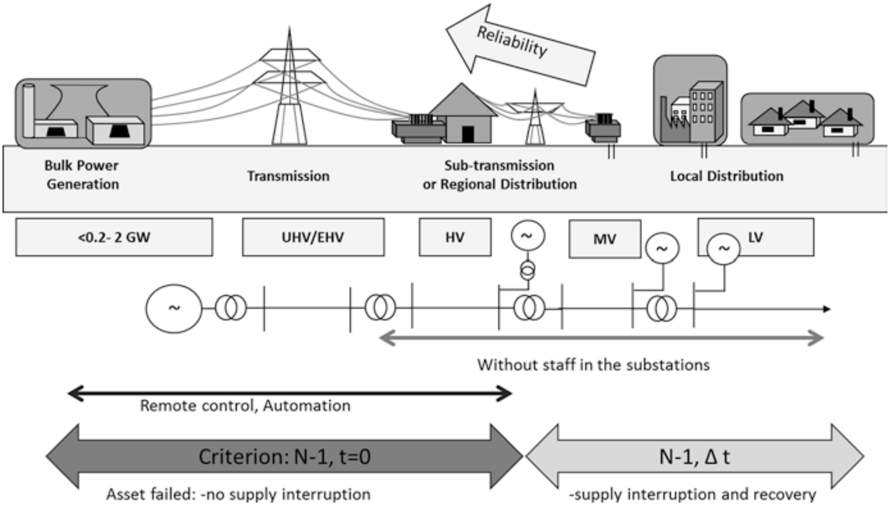

Fig. 1.9 The power system and the operational conditions

Table 1.3 Voltage-level specifications

Ultra-high UHV	Extra-high EHV	High HV	Medium MV	Low LV
>800 kV	>220 to <800 kV	>65 to <220 kV	>1 to <65 kV	0.01 to <1 kV

According to Fig. 1.9, the power flow is described as follows:

- The bulk power plants feed into the transmission network, which operates normally on
  - the EHV level, for example, 220 and 400 (380) kV in Continental Europe, (also 275 kV in UK), 220, 330, 500 and 750 kV in the Unified Power System of Russia/Integrated Power System (UPS/IPS), and 230, 345, 500 and 765 kV in the USA.
  - the UHV level with ±800 kV DC and 1000–1200 kV AC are new technologies which have been developed and are ready for the global markets.
- The transmission network transports the energy to the regional distribution or sub-transmission networks operating on the HV level (66–110–150 kV). Large industrial networks may be connected to the transmission networks directly. Continental Europe uses the rated HV of 110 kV.
- The HV network substations perform three tasks:
  - transforming the HV into Medium Voltage (MV: 6, 10, 20, 30 and 35 kV) for local energy distribution,
  - feeding industrial networks and
  - connecting regional power plants in the range of *20–200 MW.

- The MV networks perform similar tasks, but here, the range of the power plants is lower, from tens of kW up to ten to 20 MW.
- The MV/LV transformer terminals feed directly into the low-voltage (LV) networks, whereby the worldwide standard for the rated LV is 400 V, although 200 V is still in use in a small number of regions. The LV networks supply households, small enterprises, administration, trade and other business buildings in rural and urban areas. Furthermore, the LV networks are obliged to connect small power producers. These producers are often also consumers and, in this sense, the new term “prosumer” has been introduced.

As shown in Fig. 1.9, the network reliability has to grow as the level of the power system increases.

The HV, EHV and UHV networks are completely remote-controlled and supervised, and their protection schemes contain the main and the reserve protection.

At the level of the UHV, EHV and HV substations, the N-1 criterion has to be fully ensured. This means that the secure network operation must continue without any time delay after a failure causes any single component of the power system to switch off, whether it be a generator of a power station, a line, a transformer, a busbar, etc. The local distribution networks at the MV and LV levels are designed to ensure the N-1 criterion with latency. The supply is interrupted for a certain duration (*1 h) which is required for locating the faulty network component and separating it from the network. After these operations are completed, the supply needs to be recovered without restrictions. Finally, all of the smart-grid approaches mentioned previously can be developed and introduced successfully if the electric network operators, the users of the networks and other stakeholders of the electricity markets are motivated to additionally invest in such a way that economic benefits may be generated for all. Consequently, a deep paradigm shift in the existing legal, regulatory and commercial frameworks is required in order to make smart grids economically feasible. Furthermore, standards defining the interfaces between the system components will play an important role. In addition to the electric power and network automation technologies, this text book will also consider the accompanying aspects of smart grids in detail.

1.2.3 Changes of the Energy Policy in Europe and the Consequences for Smart Grids

The European Commission was the initiator of the smart-grid vision and the related concepts, as already demonstrated. Some countries in the EU have established extremely ambitious targets in accord with extensive changes in their energy policies. However, these changes have consequences regarding the operation of the power system in general and the electricity networks at all levels. The establishment of smart grids will be accompanied by technological and legislative challenges that will need to be met within the interconnected power systems of Europe.

The Western and Central European transmission-system operators have established the European Network of Transmission System Operators for Electricity (ENTSO-E) which consists of five synchronous transmission systems interconnected by DC links:

- the Continental European transmission network (RG CE—Region Continental Europe, former UCTE),
- the transmission network of the United Kingdom (RG UK),
- the Scandinavian transmission network (RG Nordic),
- the network of the Baltic countries (RG Baltic, synchronous with UPS/IPS), and
- the network of Ireland (RG Ireland).

Being the body of transmission-system operators of electricity at the European level, ENTSO-E's mission is to promote important aspects of energy policy in the face of significant challenges, such as:

- Security—it pursues coordinated, reliable and secure operations of the electricity- transmission network.
- Adequacy—it promotes the development of the interconnected European grid and investments for a sustainable power system.
- Market—it provides a platform for the market by proposing and implementing standardized market integration and transparency frameworks that facilitate competitive and truly integrated continental-scale wholesale and retail markets.
- Sustainability—it facilitates the secure integration of new generation sources, particularly the growing amounts of renewable energy and, thus, the achievement of the EU's greenhouse-gases reduction goals.

The transmission network of Continental Europe (RG CE) is the largest synchronously interconnected transmission system in the world, serving 450 million people with an annual electricity consumption of 2500 TW h. It contains an installed power-plant capacity of about 630 GW and 230,000 km of transmission overhead lines (400/220 kV). The transmission network was extended by incorporating the former East German and the CENTRAL transmission networks of some Eastern European countries in 1994 and by the re-connection of the Balkan countries in 2004 (after the war in the former Yugoslavia). The network is synchronously interconnected with the power systems of the Maghreb countries (Northern Africa) and, since 2010, with Turkey. The largest synchronous interconnected transmission system which adjoins ENTSO-E is the UPS/IPS.

The UPS/IPS is still not interconnected with the ENTSO-E grids (except for a weak HV-DC link to Nordel). Strong 750 kV AC-lines terminate in Poland, Hungary and Bulgaria, but they are not used for a synchronous interconnection. Only one 750 kV line from Western Ukraine (Zapadno Ukrainskaja) to Hungary (Albertirsa) is in operation. Some Ukrainian power plants are synchronously disconnected from

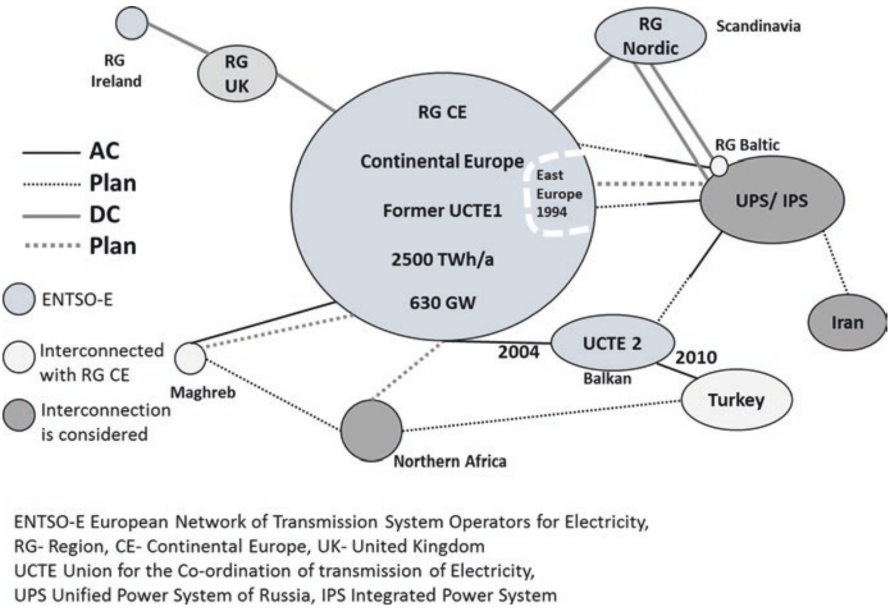

Fig. 1.10 European power systems and their interconnections

UPS/IPS, and so this line is used to transmit electric power from "Burstyn Island" in the Ukraine to and from Hungary.

Figure 1.10 shows the relationships between the European power systems, where the size of the circular areas is related to the installed power capacity of the systems. The closing of the Northern African (NA) loop from the Maghreb countries to Turkey has been planned for many years. However, dynamic stability problems have prevented the interconnection with the system of Central Europe up to now.

The German power system comprises the largest part of the RG CE and is embedded in the middle of the interconnected transmission network. Interconnections to all neighboring systems are in operation. Furthermore, Germany achieved the highest level of reliability of supply worldwide.

The German government has set the most ambitious targets regarding fundamental changes in their energy policy, known as "Energiewende." In this context, the German example is selected to demonstrate the special consequences of the smart-grid philosophy and the appropriate technical solutions enabling the maintenance of the high level of power quality under the new conditions.

The German transmission system is operated by four transmission system operators (TSOs) performing in four control areas, as shown in Fig. 1.11a. The voltage levels of the underlying networks are 110, 30, 20, 10 and 0.4 kV. About 850 network operators are active in this area (Fig. 1.11b).

The special role of Germany in the global world of electric power systems can be characterized by three specific aspects:

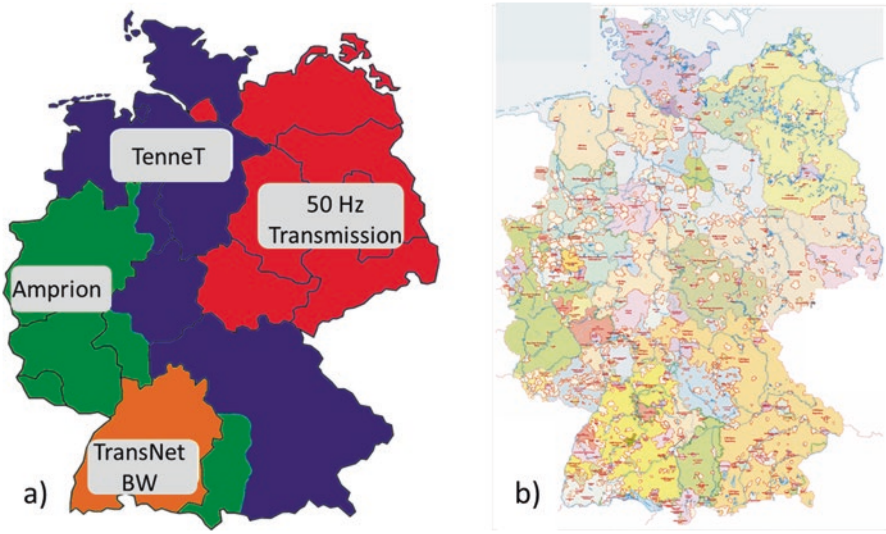

Fig. 1.11 (**a**) Transmission grid operators. (**b**) 850 distribution networks in Germany

- Firstly, Germany has set the most challenging targets for the development of the energy mix. Figure 1.12 shows the primary energy mix of the electric power production in Germany for 2010 and one of the expected energy-mix scenarios, scenario 2B, for 2030 [11].
- Secondly, Germany has planned the shutdown of all nuclear power stations by 2022. Nuclear power covered approximately 25 % of the annual electricity consumption in 2010. The nuclear power stations are well distributed throughout Germany and located near the load centers. As a consequence, a significant dislocation of power production and load centers has and will occur which requires a strong enhancement of the transmission grid, on the one hand, and the growth of regional generation within the distribution networks, on the other hand.

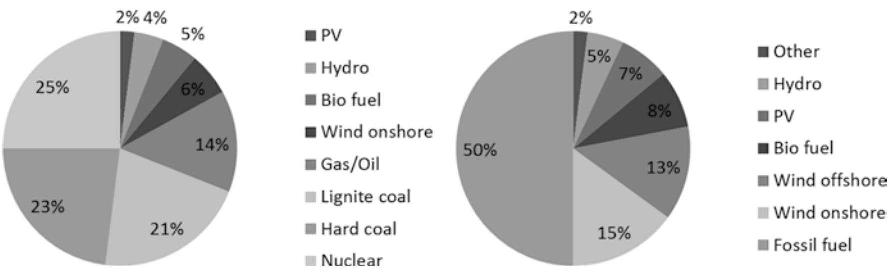

Fig. 1.12 (*left*) Energy mix in 2010 and (*right*) the development targets for 2030 in Germany [12]

- Thirdly, a significant reduction of the annual demand is foreseen, caused by improved efficiency of energy usage. At the same time, however, a significant growth regarding the connection of new types of consumers, such as electric vehicles (six million are planned for 2030), heat pumps and other devices, is foreseen. The main challenges of such a development strategy lie in the volatility of a significant share of the energy production and in the geographic allocation of load centers, which are located mostly in Central/Southern Germany, while the large-scale growth of wind power generation is in the North.

The distribution of load and generation in Germany was more or less harmonized in 2010. As a rule, the large generation plants were located near the load centers.

About 10 % of the peak load of 80 GW could be covered by nuclear power stations located in the South of Germany. When they have been shut down, however, the territorial ratio of generation and load will change significantly. The growing territorial imbalances of load and generation can be solved in two ways:

1. Enhancement of the transmission grid for bulk power transmission from North to South, and/or
2. Growth of dispersed generation connected to the distribution networks.

In this way, Germany, with its ambitious targets, has to play the role of progressive mover regarding the evolution of the transmission and distribution networks into smart grids. Furthermore, the volatility problems have to be solved. The planning of the energy mix as depicted in the diagrams, see Fig. 1.12, is an approach which needs to be supported by generation and load-profile analysis for the year considered (here 2030). This analysis was performed in the scope of EU project W2E [13], with the assumption that by 2030, the annual net consumption will consist of 44.8 % industrial demand, 24 % business/trade services, 23.4 % households and 7.8 % traffic (including electromobility and hydrogen production). Each load group follows specific profiles that are different for weekends, working days and the seasons. The sum of all the various load profiles has to be covered by the energy production every second of the year. The typical 1/4 h profiles of the load groups and the generation categories of the RES, based on multiple year-long analyses by the Fraunhofer Institute for Wind Energy Systems in Kassel, were adopted into [13] the German targets for 2030 according to plan (for details, see Fig. 1.12).

The total load profile was filled with the possible amount of renewable generation for each 1/4 h of the year. In this way, the load and renewable power ratios were defined for 35,040 1/4 h values, in accordance with the energy mix planned for the year 2030. Figure 1.13 shows two extreme days of the annual load—renewable power diagram—one with a maximum and the other with a minimum of renewable-energy generation. The maximum of RES is presented on the left-hand side: the renewable sources may cover up to 90 % of the daily load profile in this situation. Furthermore, a surplus up to 15 GW power with an amount of 105 GW h energy occurs over 9 h in the weak-load period.

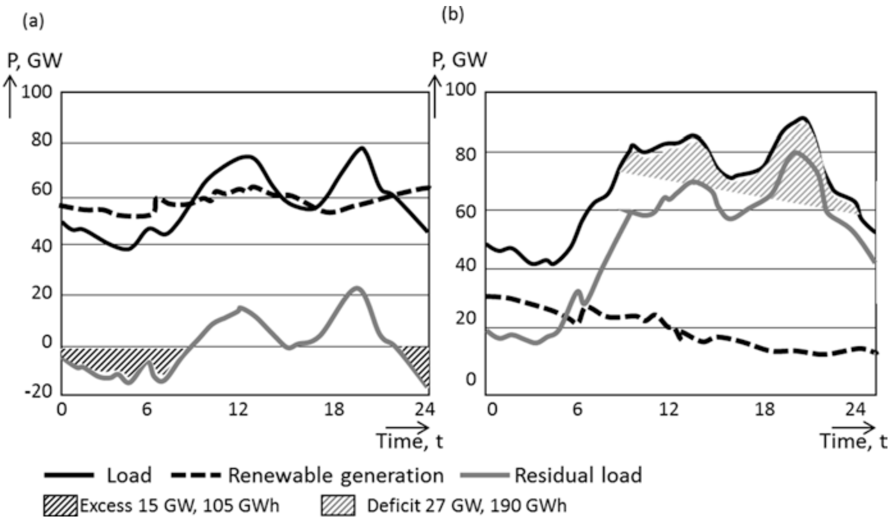

Fig. 1.13 Extreme weather conditions with (**a**) maximum and (**b**) minimum of RES

On the right-hand side of the diagram, the minimum coverage of the load profile by renewable energy can go down to 16 %. This means that during the peak-load period, up to 77 GW have to be covered by traditional sources when the maximum available power of fossil sources is limited to 50 GW [11] (65 GW installed generation capacity reduced by 15 GW to consider network losses, reserve power and the capacities disconnected for maintenance). Consequently, there is a 27 GW deficit of peak power and 190 GW h of energy lacking during 14 h that have to be covered by installing more fossil power or by using other sources, such as storage units, adaptive reduction of the demand and/or the importation of electric energy.

Extensive investigation concerning the energy mix in Germany between 2015 and 2050 has been carried out. This project, developed by the Academy of Science [14] (Acatech, Leopoldina and Academia Union) used the European target of an 80 % reduction in CO_2 production in the generation mix in 2050. The results also show the necessary energy mix including a reduction of 100 % CO_2, in a kind of no-emission power system. Realization of a no-emission power system is possible, if at first just theoretically, and various scenarios lead to fulfilling the boundary conditions for such a system [15].

One representative composition of future generation (with the code P1aS4) is shown in Fig. 1.14.

Wind and PV power dominate the energy mix in this scenario. This mix also needs two additional supporting technologies which could attain the following capacities in this scenario:

- Power-to-Heat (P2H)—15–20 TWh

and

- Generation management—40 TWh.

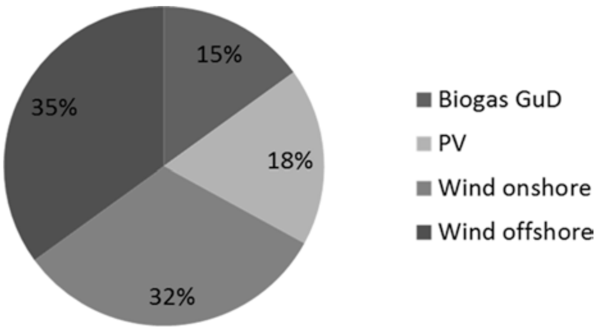

Fig. 1.14 Example of a planned energy mix in Germany in 2050—a normalized diagram

It is clear from this study and other investigations that a new kind of power system is necessary to manage the challenges of the future. This smart grid needs more flexibility in generation, consumption and energy transmission [7].

The smart-grid strategy of the future consists of an intelligent coordination of the users connected to the power system, in the sense that load and generation may be balanced, also in extreme situations, by a limited volume of available fossil-based power production. The ambitious German policy for energy development necessitates that it become a country where smart grids have to be introduced as a top priority. But first, a number of new technological solutions need to be created to meet the related challenges.

1.2.4 Power System Operation in the Future. The Need for More Flexibility in the Smart Grid

The operation of the current power system consists of large, centralized power plants, a hierarchical network and a huge number of dispersed consumers, all of which have to be controlled by central control centers. The future system will be characterized by a large number of small D&RESs, many of them with intermittent power output. All these D&RESs have to be operated in parallel with conventional power plants. Furthermore, on the consumer side, there will be possibilities to influence the consumption by means of flexible tariffs and other mechanisms [16]. Demand-side management will play a growing role for power balancing in the future. Coordinated energy generation, load management and an integrated planning process for the power system will be necessary.

One possible solution for this problem is to transfer a part of the control intelligence close to the D&RES units and controllable loads by using "agents." Such an agent receives instructions from the higher-level control structure and has a certain range within which it can control its unit or group of units.

An example illustrates the concept: A household agent receives information about tariffs, electricity demand, etc. from the superior control mechanism and information about heat demand, status of storage units, etc. in the household. Additionally, the agent receives predictions for these parameters, based on weather forecasts, load profiles, etc. With the help of this information, the agent can optimize the deployment of the household devices, for example, whether to start or stop a fuel cell, the refrigerators or compressors.

The clustering of many such small controllable loads, generation and storage units into pools with a manageable power import/export from/to the outer grid provides the function of a VPP that can contribute to the system services. This principle is shown in Fig. 1.15. Such a system can only be based on a powerful and reliable communication structure.

The communication tasks of the future distribution networks include:

- The contribution to the active power balancing with dispatch of power generation, storage and controllable loads creating a VPP. The VPP of the future will be able to deal with islanded operation by means of generation and demand-side management.
- The transfer of metered values as a support for widespread energy management and for billing.
- The provision of further system services, such as congestion management, reactive power and voltage control, fault location, supply restoration after faults, islanded operation and black-start capability.

System services are currently provided mainly by TSOs. In the future, the TSOs will also be responsible for the load, but more and more aspects will be provided on the distribution level. Figure 1.16 shows the system services and the changes of their provision.

Responsibility for the system services will be shifted (Fig. 1.16) from the TSO to the distribution-system operator during the next 15 years. It is planned that, in 2020,

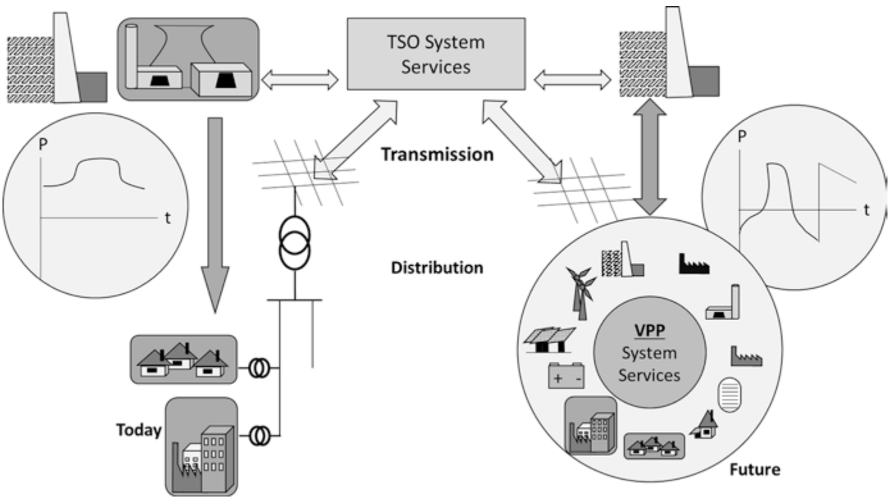

Fig. 1.15 Power system operations today (*left*) and in the future (*right*) [17]

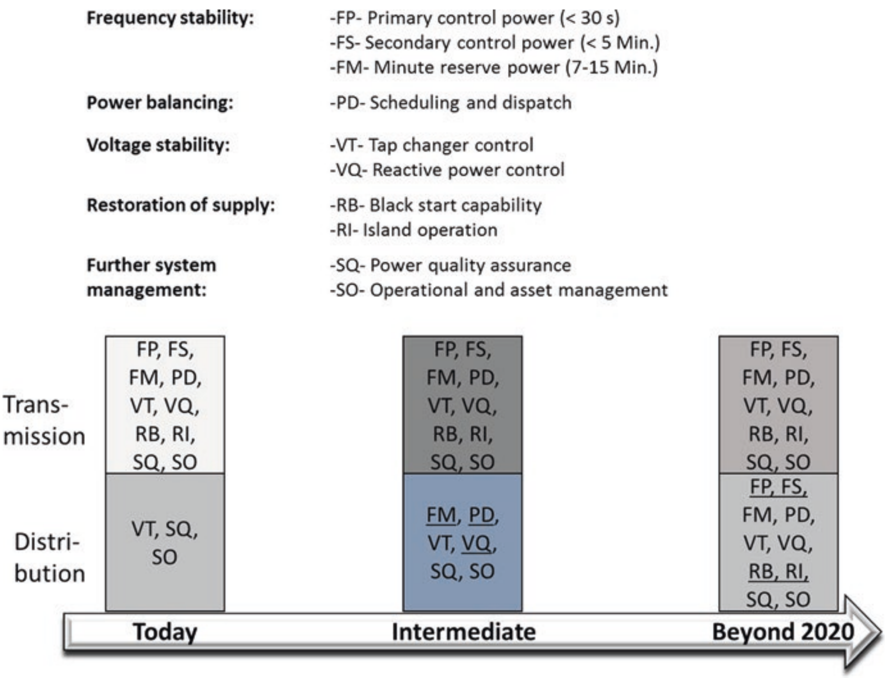

Fig. 1.16 System services: provision today and in the future [7]

all system services, for example, primary control power or reactive power control, will also be provided on the distribution level. This situation will make it possible to operate the power system in island mode.

The performance of the smart rid mentioned previously requires some new measures to fulfil the requirements for safe and secure energy delivery. These measures are called the flexibility options for the smart grid.

The flexibility options listed in Fig. 1.17 are necessary to perform the transition from the power system today to the smart grid of the future. The flexibility options should support, either separately or in combination, or even sometimes replace, the current providers of system services cited in Fig. 1.16. Table 1.4 gives a systematic overview of which flexibility options are applicable for specific system services.

Power-to-Heat

Power-to-Heat (P2H) is an alternative technology which is having a renaissance in areas where highly-renewable generation is present in the power system. Conversion of electrical energy from heat is not normally economic, but, if there is a surplus of electric power from renewable energy, e.g., wind or PV generators, this cheap electric energy can be converted into heat. Furthermore, if the P2H technology is in use, it is not necessary to restrict (derate) the renewable generation and

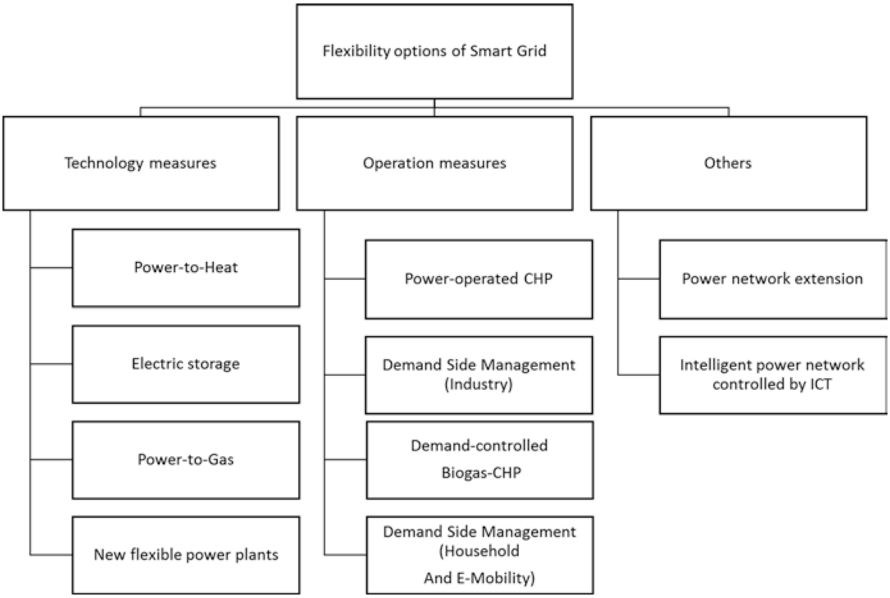

Fig. 1.17 Flexibility options for the smart grid

waste the potential produced energy. The second smart-grid-specific application of P2H involves the control of the negative power range. In this case, it is possible to transfer this system service functionality from the power station to the P2H facility. Taking this into account, some power stations in the power system, which are used for must-run power, can be shut down at times of high renewable generation. The advantages of P2H technologies are additionally:

- low investment costs, for example, 100 US$/kW,
- simple, reliable technology, and
- very short turn-on, turn-off time.

Currently, one observes a great deal of interest in this technology, which is illustrated by the many new projects.

Electric Energy Storage
Electric energy storage is also a very well-known technology which offers a great deal of flexibility options depending on the power and capacity of the storage. Further information about this can be found in the next chapters.

Power-to-Gas (P2G)
This technology requires a technically complicated conversion process involving gas production. Power-to-Hydrogen is one of the P2G technologies, jointly with Power-to-Synthetic Methane, Power-to-Liquid, Power-to-Chemicals and

Table 1.4 Applicability of various flexibility options for system services

	FP Primary control	FS Secondary control	FM Minute reserve	PD Scheduling & re-dispatch	VT Tap chang-er control	VQ Reactive power control	RB Black start cap.	RI Island ope-ration	SQ Power qual. ass.	SO Asset manag.
Power-to-Heat		X (negative)	X (negative)	X			X			X
EES	X	X	X	X		X	X	X	X	X
Power-to-Gas	X	X	X	X		X	X	X	X	X
Flexible power plant	X	X	X	X		X	X	X	X	X
Power-operated CHP	X	X	X	X		X	X	X	X	X
DSM—industry		X	X	X				X		X
Demand-controlled biogas CHP	X	X	X	X		X	X	X	X	X
DSM household & e-mobility			X		X	X	X	X	X	X
Power network expansion				X	X	X			X	X
ICT[a]	X	X	X	X		X	X	X	X	X

[a]The ICT cannot contribute directly to system services, but is necessary for optimal operation and coordination of all services in a smart grid [18].

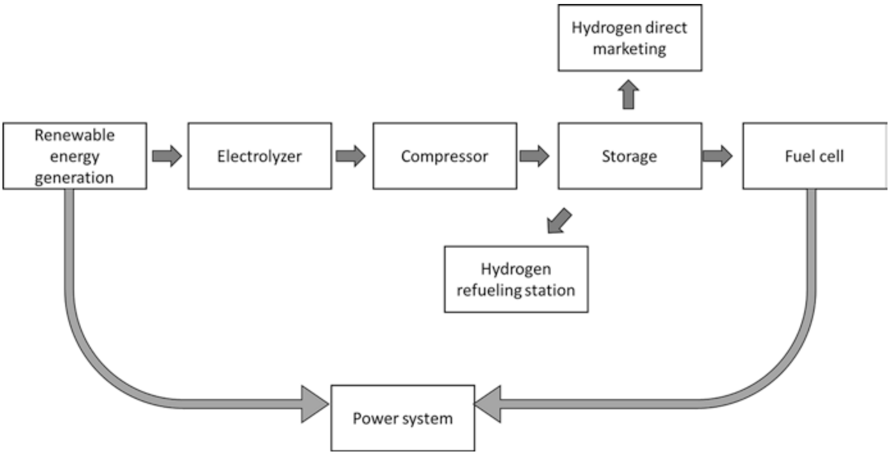

Fig. 1.18 Scheme of a renewable hydrogen-storage system

Power-to-Materials. Electrolysis is normally used, and hydrogen is obtained as the primary gas (see Fig. 1.18). The hydrogen can be stored in compressed form under various pressures [19] (at 350 or 700 bar) and is used not only used in reverse for power production, but also as a fuel for vehicles. The hydrogen vehicles can use pure hydrogen if they are equipped with fuel cells, which can produce electric energy using the reverse process. The fuel-cell car uses electric motors.

The hydrogen does not necessarily have high energy density [20], so the CO in a chemical process can be fed into a so-called methanizing process. Finally, methane gas is produced, and this synthetic gas can be used as a fuel in the gas turbine. Green hydrogen can commonly replace fossil fuels in the future. Currently, neither the amount of renewable generation, nor the state of the technology (very high investment costs of more about 5000 US$/kW) allows wide utilization of this method.

Flexible Power Plant

The efficiency of power-plant operation depends strongly on the output power. Consequently, the power plants are operated close to the nominal power. If the power plant is operating on partial load, the efficiency is worse. The partial load is generally also limited to, for example, 40 % of nominal load. When very high renewable generation occurs, many power plants must run on a partial-load mode and maintain a must-run operation. Such an operation is very uneconomic and increases the energy costs to the customers drastically. The power plant manufacturers are already working on new power plant designs where the smallest units, for example, 100 or 200 MW, will not have the disadvantages mentioned above and will operate with a full-scale load with almost the same efficiency.

Power-Operated CHP

Normally, CHP are operated in a head-output-controlled mode. The electric power was, basically, useful waste from the heat production. The balancing of power fluctuation in the smart grid is one of the most important issues, and the CHP can help with fluctuation compensation by using the output power-controlled operation mode. This only requires a small change in the control panel of the CHP and can contribute many advantages to the smart-grid operation.

DSM—Industry

Depending on the country, industry constitutes a high, or even the highest, demand on the total energy consumption. The power required by technological processes is delivered on time by the traditional power plants. However, the output of weather-dependent RES cannot be controlled in the same manner as the traditional power plant. Therefore, a paradigm shift is necessary. Instead of demand-dependent energy delivery to industry, in the future, the control of industrial processes will be dependent on the level of renewable generation. The driver for this paradigm shift could be tariffs, which can be varied depending on available renewable generation. If the renewable generation is very high, the price for the energy will be low, which will be preferential for the high demand. If the paradigm shift mentioned above occurs, industry will have, thanks to the new flexibility, the possibility to deliver additional system services (see also Table 1.3).

Demand-Controlled Biogas CHP

The general operation mode of a biogas CHP delivers constant maximal power. In the smart grid, with large amounts of volatile renewable generation, this operation mode must be modified. The biogas CHP will play the role of an almost-peak-load generation unit, which should sensitively reacts to maintain the power balance in the system. The economic use of the biogas will also be necessary, because the biogas CHP must establish the base load in a time of renewable-energy deficit.

DSM Household and E-mobility

The control of household demand can effectively help the energy balancing in the smart grid. Some studies [21] have shown that the demand-side potential in households is high, e.g., about 5–10 GW in Germany, but, unfortunately, this potential is normally available immediately for less than one hour, but sometimes repeatedly, in the course of one day. Nevertheless, the DSM in households, because of small investment costs, can be activated quite simply. The driver for this flexibility option could be the adaptation of tariffs in the same way as for the DSM in industry mentioned previously.

In the future, when millions of electrical cars, mostly driven by the energy stored in the car batteries, exist on the market, each home power connection will be equipped with an electric car charging station [22]. This charging station will allow bi-directional electric energy flow and control. In this case, the potential for providing system services by DMS control in households will be very high.

Power Network Expansion

The natural method for improving power system features is the expansion of the power network. New, stronger overhead lines and cables and more suitable equipment—such as short-circuit breakers or power transformers—make it possible to increase the transport capacities. Furthermore, network expansion results in a higher short-circuit current and the implementation of dynamic features. In the smart grid, these measures must be better coordinated between the distribution and transmission systems for an economic balance of costs.

ICT

The realization of the smart-Grid concept is not possible without the rapid development of ICT. Digital protection and measuring systems trigger a high flow of data between various players (traders, producers, consumers). The data must be transported, evaluated, interpreted and saved. All these processes must be very fast, safe and secure.

How large the requirement is for various flexibility options in a future smart grid has also been investigated within the scope of the ESYS study by the Academies of Science in Germany, mentioned previously.

Figure 1.19 presents the share of needed flexibility options based on investigations for the scenario with 100 % reduction of CO_2.

The total power of these measures was computed at 84 GW for Germany. Power-to-heat, biogas, H_2 Storages and DSM were selected for the secure operation of the future power system investigated in this scenario.

1.3 Regulatory Boundaries for Smart Grid and Electric Energy Storage

The use of flexibility options in the smart grid, and here especially electric energy storage, depends strongly on the market structure and market design in various countries. Likewise, different market structures in the electricity industry require different solutions regarding the question of ownership and operation of electricity storage projects. Normally, a systematic adjustment of existing regulatory frameworks [23] occurs, corresponding to the development of the energy market.

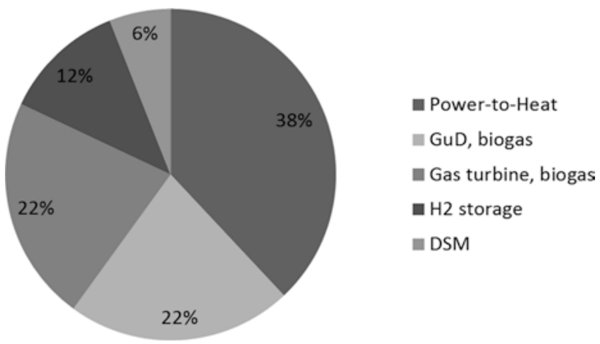

Fig. 1.19 Flexibility options necessery for a no-emission system in Germany in 2050. Results of the Acatech investigation for scenario P3S4. Normalized diagram

Electricity storage is available using a number of various different technologies, such as batteries, flywheels, compressed air and pumped hydro, as well as in various size configurations, ranging from kW to multi MW or even to GW scale. Further dimensions, including the size of the storage in terms of energy capacity, its response characteristics, costs and lifetime issues, will be discussed in the next chapter.

Most deployment of storage appears to be in those areas which can be considered niches, usually island systems or small systems, especially where there is a need for ancillary services, such as frequency regulation, peaking or reserve power, or mitigation of the effects of integrating renewable generation.

In order to clarify these issues, Table 1.5 presents some specifications on various types of electricity market structures and systems, as illustrated by Canada, Germany, Greece and the UK, taking into account the results of the GIGRE study [24].

The data in Table 1.5 illustrates the quantitative need for significant investment in electricity storage, however, there has been a relatively small investment in the actual deployment of electricity storage. Projects have been deployed in places where there are subsidies or grants for storage, but elsewhere, with few exceptions, advanced electricity storage is still in its infancy. Ancillary services, such as frequency regulation and the provision of peaking power or reserve power, where the incumbent technology is diesel or gas-fired reciprocating engines or turbines, are exceptions. Subsidies can be justified where they support the introduction of the technology, effectively supplying an option for the future, or where they provide revenue that current markets do not value. The presence of subsidies should not be taken as evidence that storage is uneconomic. Countries treat storage in various ways, and it is suggested that storage should be considered as a separate asset class and not simply as a proxy for generation and demand. The sample of countries considered here is too small to reveal whether there is a direct correlation between the type of market structure and storage adoption. We have seen that, where niche opportunities exist in the power system, particularly on islands and in small systems, and especially where there is an increasing proportion of renewable generation, storage is not only more likely, but it also becomes more essential and has a high economic, commercial and technical justification.

How the law and, consequently, the opportunities for flexibility options (e.g., electric-energy storage) must be modified depending on the generation mix will be demonstrated through an example—Germany.

Over the past few years in Germany, as a result of the "Energiewende" and the related Renewable Energy Law (EEG), the renewable-energy supply has grown rapidly. At the end of 2015, installed power in renewable energy had increased up to 89 GW and is now higher than the peak power.[3] Figures 1.20 and 1.21 show the growth of renewable generation in Germany, especially in the TSO 50Hertz Transmission[4] operation zone which is characterized by very high renewable generation in conjunction with relatively small demand.

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[3] The peak power in Germany in 2015 was 82 GW.

[4] 50Hertz Transmission GmbH is one of four transmissions operators in Germany (see also Fig. 1.11a). This regulation zone is characterized by very high renewable generation and relatively small demand.

Table 1.5 Opportunities for electric energy storage use in various countries

Country	Market structure	Amendments for energy storage	Applications of storage	Opportunities for storage
Canada	Fully traded electricity market	No favorable tariff	*System Control*: A storage system can be used to smooth the output of a wind facility, thereby, lessening its impact on the utility system, or it can be used to control the voltage at the wind- farm connection directly. *Energy arbitrage*: A storage system can be used to store or release energy based on preset conditions, i.e. time-shifting load or energy.	Demonstration projects, e.g., • 1 MW (2 MWh) lithium batteries and several 500 kW flywheels • 1 MW adiabatic CAES, Liquid-Air "cryogenics" storage
Germany	Vertically separated and regulated	For system stabilization, pumped hydro-storage or adiabatic compressed-air energy storage (A-CAES) Use "Power-to-Gas" (Hydrogen or Methane)	*System stabilization* at the transmission level *Seasonal exchange* and future common energy concept *Local energy markets*	
Greece	Greece comprises a mainland system and a number of island systems	Isolated micro-systems In the scope of electricity markets, energy transactions are made in an organized market or pool. The Day-Ahead Market	*Island operation*	The HPS includes two small hydroelectric plants, both equipped with Pelton turbines, one at the first new reservoir (1.05 MW), and the second at the second new reservoir (2 × 1.55 MW), which also participates in pumped-storage operation. The pumping station comprises 8 × 250 kW constant speed and 4 × 250 kW variable speed pumps (rated electric motor capacities). A 3 × 900 kW wind park is included in these hydroelectric plants

Table 1.5 (continued)

Country	Market structure	Amendments for energy storage	Applications of storage	Opportunities for storage
UK	The UK system is a fully traded market, with gate closure one hour before real time.	Under the nationalized industry structure, a number of pumped hydro-storage plants were built and remain in commercial operation under private ownership. A secondary opportunity exists to see storage deployed in the distribution networks where storage can be used to support the existing network, or to defer or avoid new investment in infrastructure		Demonstration projects
USA [25]	The USA has numerous power- system structures and markets which share some common features but have many variations.			It is expected that that there will be countless opportunities for the deployment of electricity storage, at various scales and locations, in a power system as large as the USA. In the early stages, key applications remain the reinforcement of local networks and provision of ancillary services, especially frequency regulation and reserve or peaking power. In the longer term, energy balancing, especially to avoid curtailment of renewable generation, will become significant. The ability to sum value streams is an important part of the ongoing work to promote the adoption of storage by trade associations and other organizations.

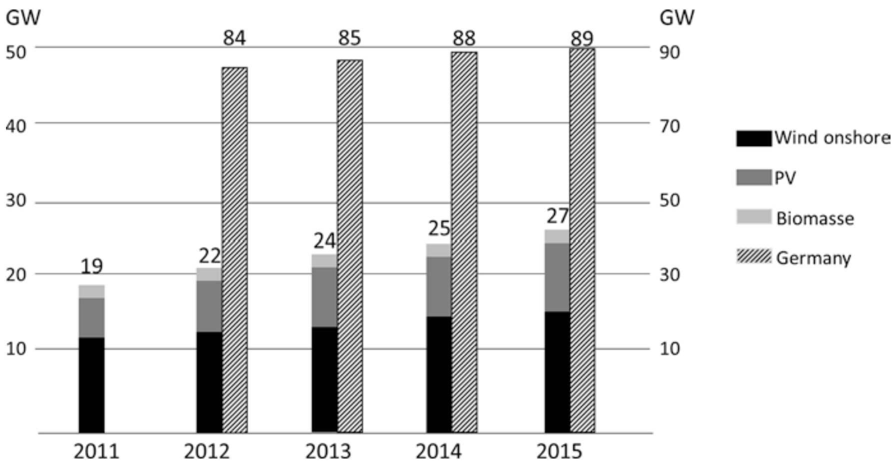

Fig. 1.20 Development of the installed capacity by EEG generating plants in Germany and in the 50Hertz control area. Source Almanac 2015 of 50Hertz Transmission GmbH

Taking into account various renewable technologies, the energy supplied depends on the total generation time of nominal power per year.[5] The growth of this important factor is shown in Fig. 1.21. The 151 TWh energy means that about 23 % of the total electric energy in 2015 was produced in Germany by renewable sources. The TSO 50Hertz grid area used about 49 % of renewable energy in the supply of the demand in its own zone and delivered more than 30 % of all the renewable energy delivered to the German power system.

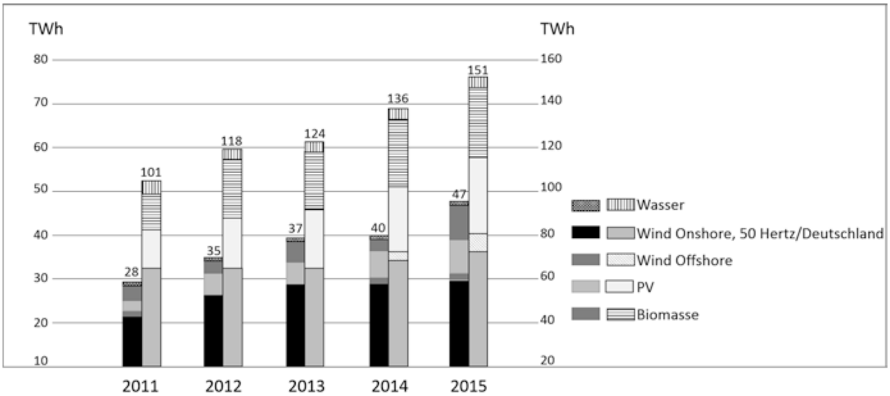

Fig. 1.21 Development of feed-in from renewable energy in Germany (*right column* in each year) and in the grid area of the TSO 50Hertz (*left column* in each year). Source Almanac 2015 of 50Hertz Transmission GmbH

[5] This value depends on renewable technology and the geographical location of the generation devices. This value is medium for Germany: 1100 h for PV; 2100 h for wind onshore and 3500 h for wind offshore.

This realistically high amount of renewable generation causes some difficulties for the secure operation of the power system (mentioned earlier), which will increase in the future and require use of different flexibility options (also previously mentioned). Some emerging problems in the secure operation of power systems with high renewable generation have already been identified.

The first is the uncertainty of renewable generation forecasts. The TSO uses a few computer forecasting tools for renewable generation which use historical data and current measurements to predict the renewable generation, and then use this predicted value for the unit commitment planning for the next few days. The medium forecast error is small (about 3–5 %), but it depends on the weather conditions; the maximal error can be much higher. One example of forecast error, for July 5, 2015, is shown in Fig. 1.22. A very strong wind front was forecast with a maximal wind-generation power in the TSO 50Hertz grid area of about 10 GW; but in reality, a maximal power of about 8 GW was measured. The error was on average about 20 % during an 8 h period. This error must be compensated for by the unplanned run-up of power stations, which requires expensive rescheduling and additional costs.

This cost related to the forecast error increased drastically in Germany in 2015 and was more than a 100 million Euro in the TSO 50Hertz grid area in 2015 (see Fig. 1.23).

The extreme forecasting error could be a driver for more flexibility in the smart grid and lead to a decrease of pre-classified facilities (e.g., industrial loads or electric energy storage) for primary, secondary and minute reserves in the power system. This process can already be observed in Germany. The growth of pre-classified facilities in Germany is shown in Fig. 1.24.

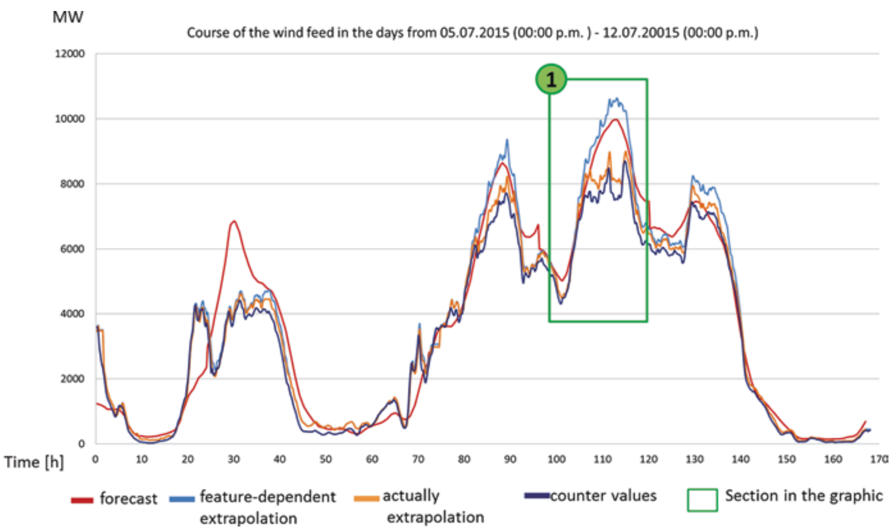

Fig. 1.22 Wind-energy generation in the TSO 50Hertz grid area on July 5–12, 2015. Source Almanac 2015 of 50Hertz Transmission GmbH

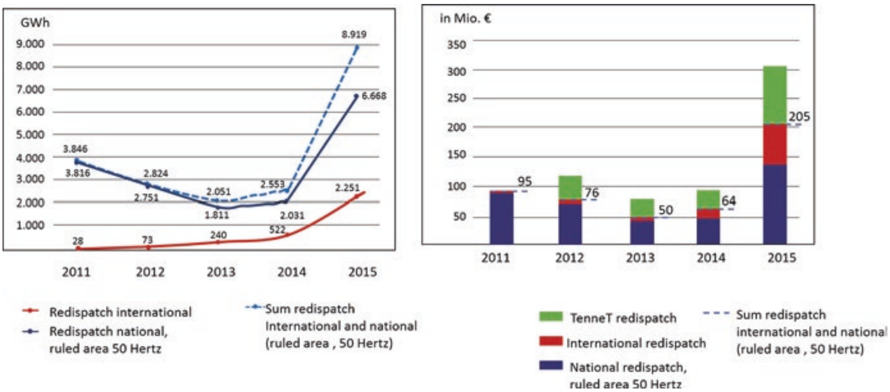

Fig. 1.23 Re-dispatch caused by renewable generation: re-dispatched energy (**a**) and re-dispatched costs (**b**). Source Almanac 2015 of 50Hertz Transmission GmbH

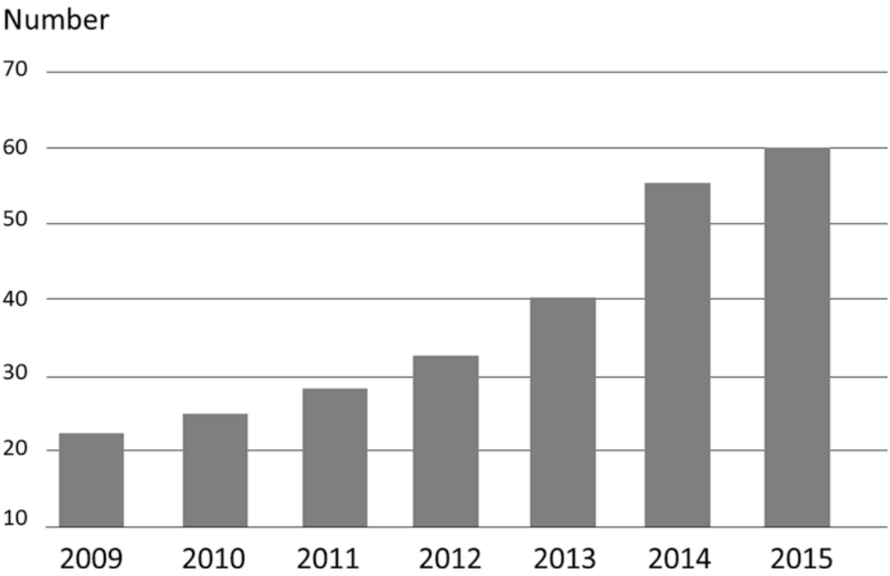

Fig. 1.24 Number of primary-control power providers in Germany. Source Almanac 2015 of 50Hertz Transmission GmbH

The power of pre-classified power providers has grown in the TSO 50Hertz grid area and amounts to 2.2 GW for primary, 4.5 GW for secondary and about 10 GW for minute reserves.[6]

Various laws have also already been adapted to the new grid (generation) situation in Germany. Since the energy market in Germany is organized as a wholesale

[6] The peak power in the TSO 50Hertz Transmission GmbH zone is about 13 GW.

market, there are currently no specific preferences for flexibility options. The relevant laws concerning the energy market in Germany are [26]:

- The energy economic law (*Energiewirtschaftsgesetz*—EnWG)
- The renewable energy law (*Erneuerbare-Energien-Gesetz*—EEG)
- The power-heat-coupling law *(Kraft-Wärme-Kopplung-Gesetz*—KWKG)

and also the guidelines:

- Power access regulation (*Stromnetzzugangsverordnung*—StromNZV),
- Power re-compensation regulation (*Stromnetzentgeltverordnung*—StromNEV)
- Low-voltage connections rules (*Niederspannungsanschlussverordnung*—NAV)

There are a few specific formulations concerning the smart-grid flexibility options in the various laws mentioned above.

Examples are the security-relevant specification in the renewable energy law (Table 1.6) and the pre-classification (Table 1.7) guidelines.

Table 1.6 Security-relevant specifications in the EEG

Paragraph	*Content*
§9	Technical specification for RES and CHP facilities for access by network operators • Facilities > 100 kW: Remote control provision and current status sensor kit required • Photovoltaic 30 … 100 kW: Remote control provision kit required • Photovoltaic < 30 kW: Remote control provision or permanent restriction of active power delivery (on 70 % of installed power) kit required
§14	Authorization of network operator for power-delivery control from RES and CHP facilities for elimination/prevention of network bottleneck (infeed management)
§15	Re-compensation payment for infeed management

Table 1.7 Pre-qualification of the primary regulation providers [27]

Criterion	*Requirements*
Minimum power P_{min}	$P_{min} = \pm 1$ MW
Dimensioning power P_N	$P_N > 100$ MW → obligatory delivery $P_N < 100$ MW → delivery of primary control power possible but not obligatory
Available primary control band	Min. 2 % of dimensioning power of technical unit
Estimation characteristic	Whole pre-classified primary control power for frequency deviations of 200 mHz and before 30 s
Power provision	100 % of the offer period
Service delivery duration	Min. 30 min
Pooling	Pooling of facilities inside accounting grid possible

Test Questions Chap. 1

- What are the correlations between the GDP and use of fossil-based PES in industrial countries?
- What are the European goals with regards to energy politics?
- Towards a Smart Grid. What are the main new features of the future power system as compared to today's power system?
- It is possible to imagine a 100% renewable-energy system? How would it work?
- List the possible flexibility options for a smart grid. Will we need these options in the future?
- Are there any legal frameworks that would make it easier to use flexibility options in the power system?

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