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Preface

Power systems are among the **most complex technical systems built by humans**. Hundreds of generators, which are located at great distances from each other, are working synchronously day and night. They supply hundreds of millions of people with continuous, high-quality electrical energy. This is the result of more than 140 years of power-system technology development.

Nowadays, **power systems** are undergoing far-reaching **transformations.** The imperative to contain the rate of climate change has put into question the generation of power in large **coal-burning power plants. Nuclear power plants**, although emission-free and efficient, **have also lost societal acceptance** after the catastrophes of Chernobyl and Fukushima. Other forms of **renewable energy**, today mainly from wind and solar generators, are **replacing** the large “dirty” **power plants.** This **conversion process** has been taking place for over 20 years in developed countries and has already **resulted** in a **high share of renewable generation** in today’s energy mix worldwide. The member states of the European Union and the USA, China, and many other countries are increasing their respective share of clean generation in the overall mix at varying speeds. In the European Union, renewable generation already makes up about 20 % of overall generation and is scheduled to grow to 80 % by 2050. However, in some European countries, e.g., Denmark, Germany and Spain, the power generated by renewable technologies is already at a higher level than the maximal demand. In those countries, hours or days—e.g., sunny and windy Sundays—can be observed where 100 % of the local demand is covered by electric energy produced by renewables. In **China**, renewables have reached 17 % of the energy mix, and the country became the **number one producer of wind energy** in **2015**.

Renewable generation depends strongly on the **weather conditions**. Solar generation is possible only during daytime and can fluctuate greatly. Volatility is also a factor in wind-energy generation. The wind does not blow constantly, neither on- nor off-shore. The **strict quality requirements** concerning the delivery of energy (i.e., voltage and frequency) to customers—especially to modern industrial customers—**must be fulfilled** despite the challenging conditions. Consequently, there is a

strong need to find new or activate known **flexibility options** in power systems that would enable a **smoothing of the fluctuations of RES** generation. One of the **best natural options** to smooth the volatility of renewable generation is buffering the energy production with **electric energy storage (EES).**

The **EES** is a **well-known technology,** which has been used successfully from the beginning of power systems. Generally, the self-stabilizing functionality of large generators resulting from the torque of inertia did not need the smoothing function of EES in the past. Today, and even more so in the future, the **use of storage for stabilizing the power system,** or for the development of local power systems based on renewable energy sources (RES), will be increasingly necessary.

This **book** gives **new insight** into the **use of EES** in the power systems of today and the future. It **concentrates** on the **systematic description of storage use**, taking into account the technical and regulatory requirements. In this book, **storage** is considered to be an **essential part of a power system,** which plays various roles, depending on localization or technical and economic conditions. Only an integrated storage consideration will lead to a correct and complete placement of the EES in future power systems.

The **book is designed** as follows: Chap. 1 gives an overview of the technical and regulatory boundaries of the **technological evolution of** the **power system towards smart grids** and demonstrates the obvious **need** for more **flexibility**. Chap. 2 systematically describes the general role of EES in power systems. Furthermore, the power system and **electric storage devices** are represented in one system using a joint **formal description.** This enables a deeper understanding of the systematic use of storage based on defined **business cases**. A **generic model of EES** is also developed in this chapter, and some **basic algorithms** are presented to illustrate how planned processes (e.g., computing of optimal storage or storage module unification) can be realized with use of complementary EES. Chap. 2 focuses on the **distribution system**, where most of the EES are already located to contribute to the local smoothing of RES fluctuations.

Based on those general remarks, the need for storage is discussed extensively in Chaps. 3 and 4. The **results of a study undertaken by the CIGRE** working group C6.15 (electric energy-storage systems) are the basis for the results presented here. This recent study (completed in 2011) was carried out under the leadership of the authors of this book. Chap. 5 **deals with EES technologies**. It covers standard solutions and trends in storage technologies. The use of **battery storage in e-vehicles** for power-system issues is a very recent technology which is discussed in detail in Chap. 6. The **monetary aspects of storage use** are analyzed in Chap. 7. Finally, the influence of storage on **power-system reliability** is the subject of Chap. 8.

This book is the result of more than **20 years of work by the authors** in the research and application of EES. Since their contribution to the DFG[1] German National Program "Information Technologies and Storages in Power Systems" at

[1] DFG: German Research Foundation (Deutsche Forschungsgemeinschaft)

the beginning of the 1990s, the **authors** have been **involved in numerous** other **projects and activities**, such as:

- EU Project "Intelligent Computation and Simulation in Planning and Operation of Power Systems Taking into Account Energy Storages" and Smart Grid Platforms
- German National Projects addressed to storage—ESPEN and Adele-Ing,
- German National Project—Harz.EE-mobility,
- Russian National Project—Resolution 220—Project Baikal,
- Project of the German Academies of Sciences—"Flexibility options",
- Working groups of the EU, CIGRE and IEEE.

The **authors** are **grateful** to all the members of the **research groups of IBN, CIGRE, and EU**. In particular, we want to thank the following people for their intensive cooperation:

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Last but not least, the authors express their gratitude to Springer, particularly Eva Hestermann-Beyerle, Senior Editor, for strong support in the preparation of the concept of this book and for the many discussions and fruitful suggestions.

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[2] IBN: German syndicate: Big Batteries in Power System (Interessengemeinschaft Großbatterien im Netz).

[3] EU: Smart Grid Coordination Group in the work of EU Commission Mandat M490.

[4] CIGRE: International Council of Large Electric System, Paris.

To the **Fraunhofer Institute IFF in Magdeburg** and **Company 50 Hertz Transmission GmbH Berlin** we express our gratitude for strong technical and financial support.

We wish that readers gain interesting insights into this evolving and important topic, and we welcome feedback about our book.

The book **is meant** for students in **master-level courses**, as well as **planning engineers** who are engaged in the electric-energy storage topic and are interested in the optimal design of future power systems (smart grids) incorporating EES.

Contents

Abbreviations

A-CAES	Adiabatic Compressed Air Energy Storage
AC	Alternating Current
bbl	Barrel of Oil
BES	Battery Energy Storage
boe	Barrel of Oil Equivalent
BP	British Petrol
CAES	Compressed Air Energy Storage
CCGT	Combined Cycle Gas Turbine
CCS	Combined Charging System
CHP	Combined Heat and Power
CIGRE	International Council of Large Electric Systems
CIM	Common Information Model
CIS	Geographical Information System
CO_2	Carbon Dioxide
COE	Cost of Electricity
CRF	Capital Recovery Factor
DC	Direct Current
DER	Decentralized Energy Resources
DER	Distributed Energy Resources
DSM	Demand-Side Management
DSO	Distribution-System Operator
D&RES	Distributed and Renewable Energy Sources
EEC lux	European Commodity Clearing Luxembourg
EEG	Erneuerbare- Energie- Gesetz (Renewable-Energy-Law)
EES	Electric Energy Storage
EHV	Extra High Voltage
EIA	U.S. Energy Information Administration
EMS	Energy Management System
ENTSO-E	European Network of Transmission System Operators for Electricity
EPS	Electric Power System

EU	European Union
GDP	Gross Domestic Product
GEF	Global Environment Facility
GTO	Gate-Turn On Thyristor
HEV	Hybrid Electric Vehicle
HF	High Frequency
HV	High Voltage
IC	Investment Costs
ICT	Information and Communication Technologies
IEA	International Energy Agency
IEC	International Electrical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated-Gate Bipolar Transistor
IM	Induction Motor
IOS	Internal Operation Surface
IP	Internet Protocol
IPS	Isolated Power System
LCC	Life Cycle Costs
LCOE	Levelized Cost of Electricity
LV	Low Voltage
MTBF	Mean Time between Failure
MTTF	Mean Time of Failure
MTTR	Mean Time to Repair
MV	Medium Voltage
NASA	National Aeronautics and Space Administration
NCS	Network Coupling Surface
NREL	U.S. National Renewable Energy Laboratory
OECD	Organization for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
ORER	Office of Renewable Energy Regulator
OSI	Open System Interconnection
P2G	Power-to-Gas
PCS	Power Conversion System
PES	Primary Energy Source
PHES	Pump Hydro Energy Storage
PhS	Physical Surface
PLC	Power Line Communication
PTC	Production Tax Credit
PV	Photovoltaic
PWM	Pulse-Width Modulation
RES	Renewable Energy Sources
RFID	Radio-Frequency Identification
SCADA	Supervisory Control and Data Acquisition
SET Plan	Strategic Energy Technology Plan of EU
SM	Synchronous Motor

SMES	Superconducting Magnetic Energy Storage
SOC	State of Charge
TCC	Total Capital Costs
TES	Thermal-Energy Storage
TSO	Transmission-System Operator
T&D	Transmission and Distribution
UCTE	Union for the Co-ordination of Transmission of Electricity
UHV	Ultra-High Voltage
VPP	Virtual Power Plant

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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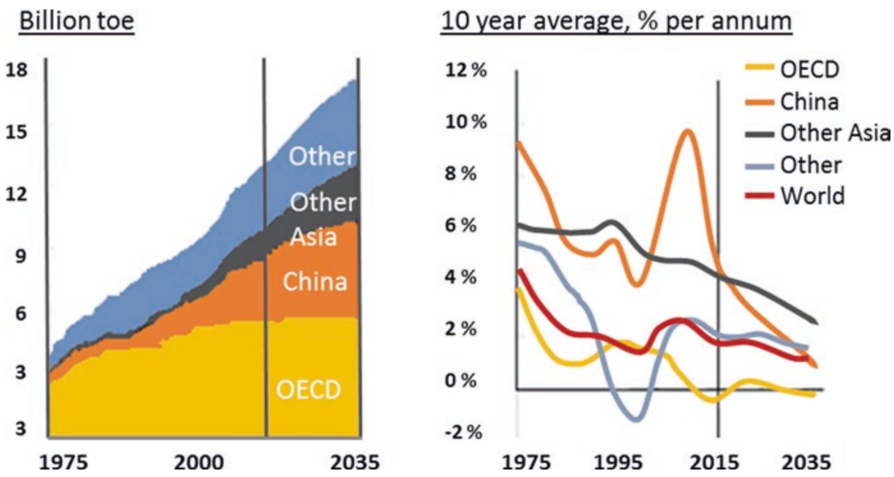

Fig. 1.1 Consumption in toe (The ton of oil equivalent (toe) is a *unit of energy* defined as the amount of energy released by burning one ton of crude oil. One toe is approximately 42 gigajoules.) (**a**) and consumption growth in % by region (**b**). Source BP 2016 Energy Outlook (www.bp.com/energyoutlook)

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,

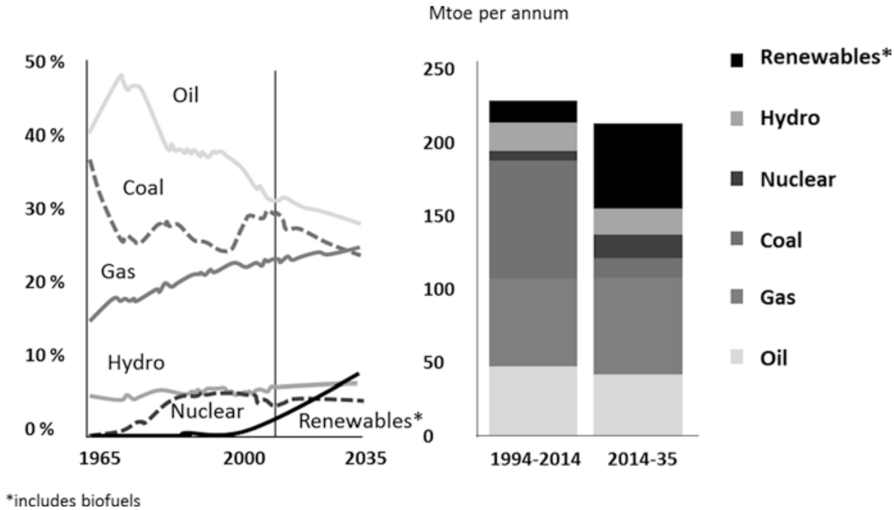

Fig. 1.2 Share of primary energy (**a**) and annual demand growth by fuel (**b**). Source BP 2016 Energy Outlook

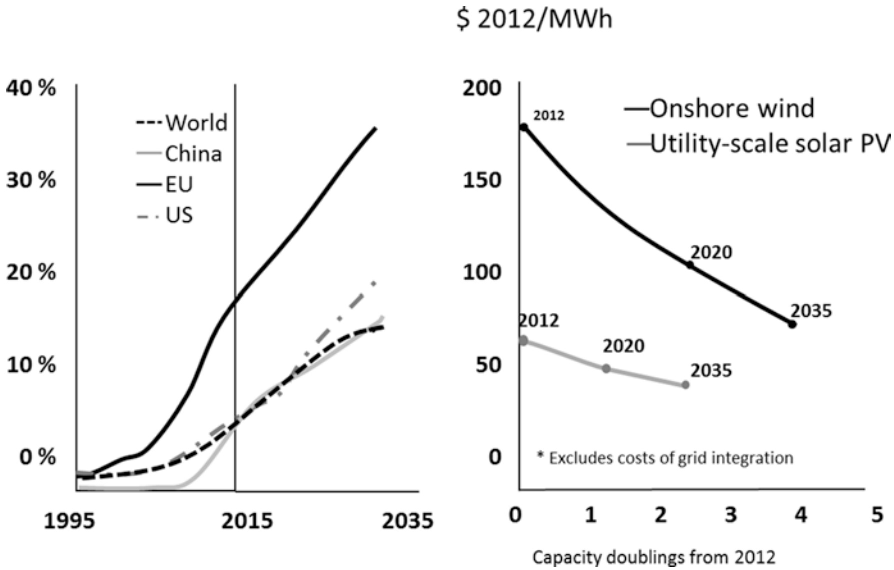

Fig. 1.3 Renewables share of power generation (**a**) and levelled cost of electricity in North America (**b**)

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).

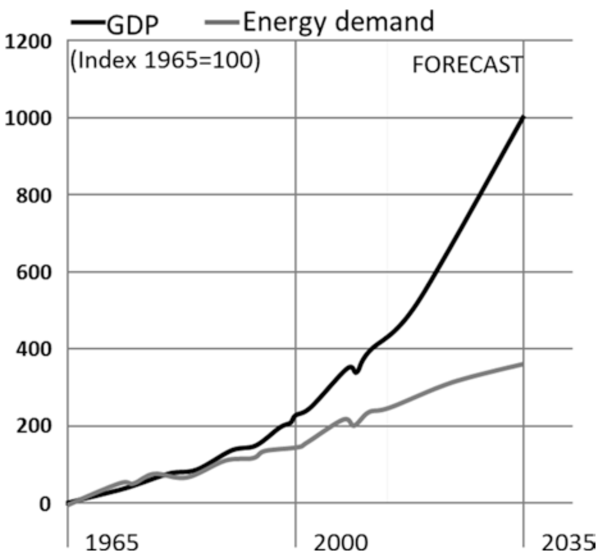

Fig. 1.4 Uncoupling the growth of global GDP and demand. Source BP 2016 Energy outlook [4]

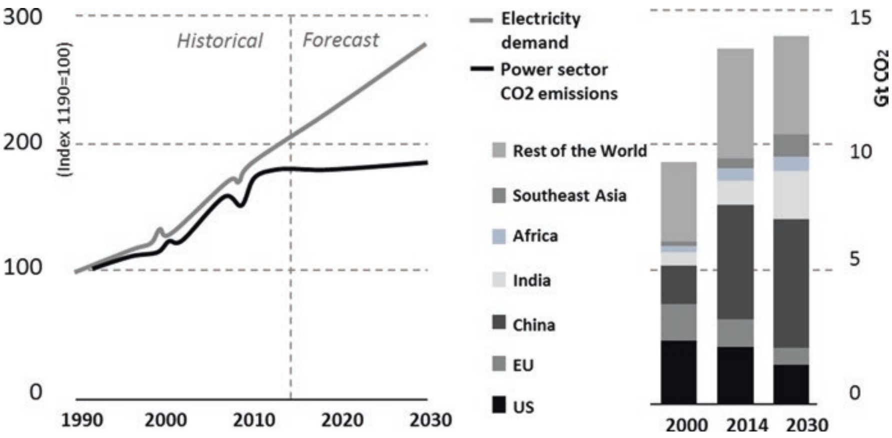

Fig. 1.5 Uncoupling of CO_2 power sector emission from electricity demand: electricity demand versus power sector CO_2 emission (**a**), CO_2 emission by countries (**b**) Source IEA

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

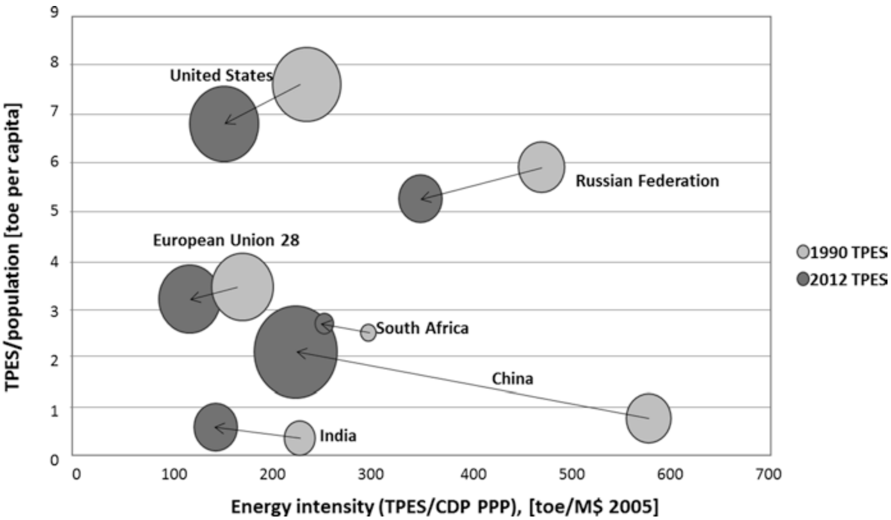

Fig. 1.6 Regional decrease of the energy intensity. Source IEA [5]

(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,

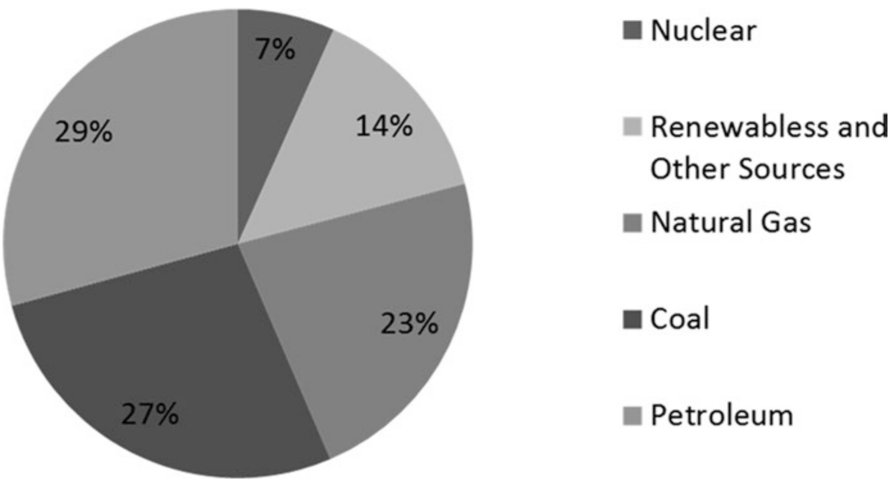

Fig. 1.7 Word energy mix 2030. Source EIA

- 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.

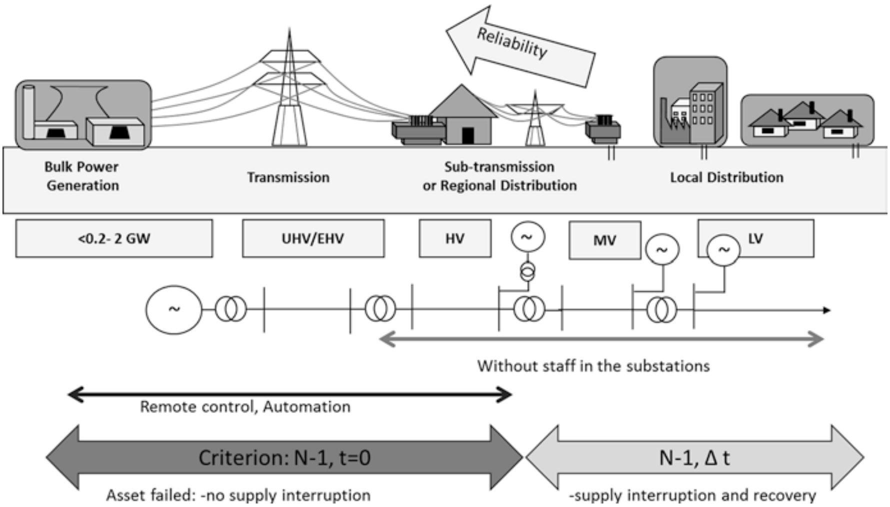

Fig. 1.9 The power system and the operational conditions

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

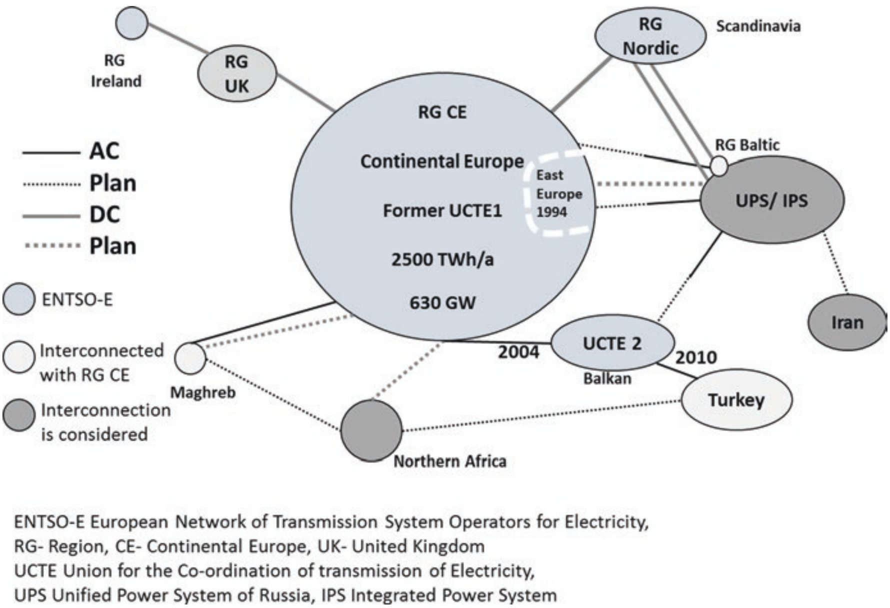

Fig. 1.10 European power systems and their interconnections

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:

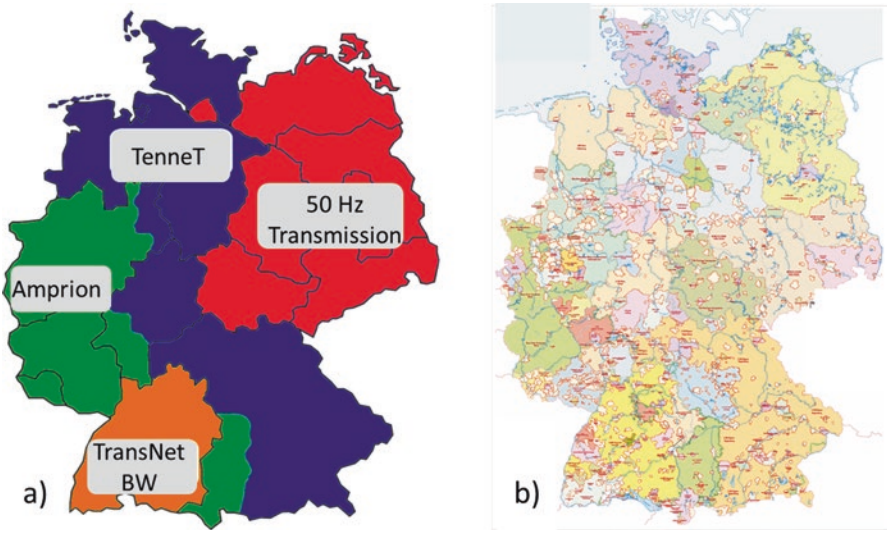

Fig. 1.11 (**a**) Transmission grid operators. (**b**) 850 distribution networks in Germany

- 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.

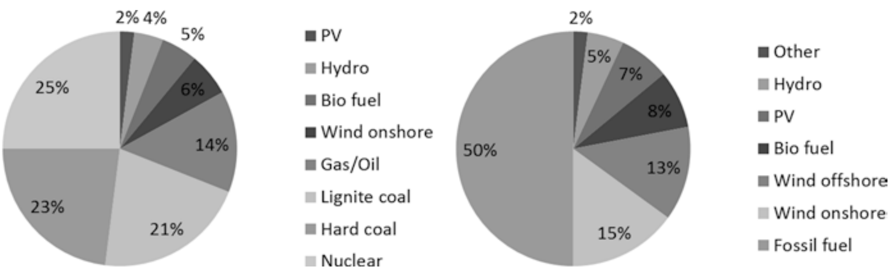

Fig. 1.12 (*left*) Energy mix in 2010 and (*right*) the development targets for 2030 in Germany [12]

- 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.

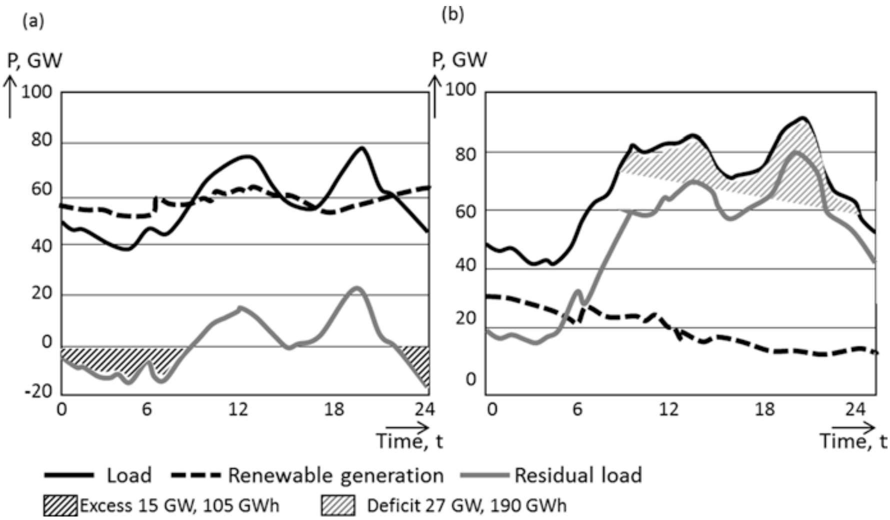

Fig. 1.13 Extreme weather conditions with (**a**) maximum and (**b**) minimum of RES

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.

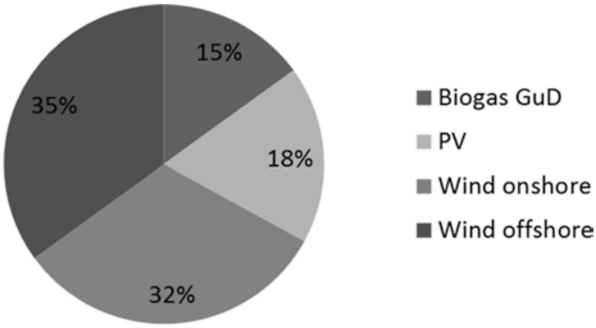

Fig. 1.14 Example of a planned energy mix in Germany in 2050—a normalized diagram

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,

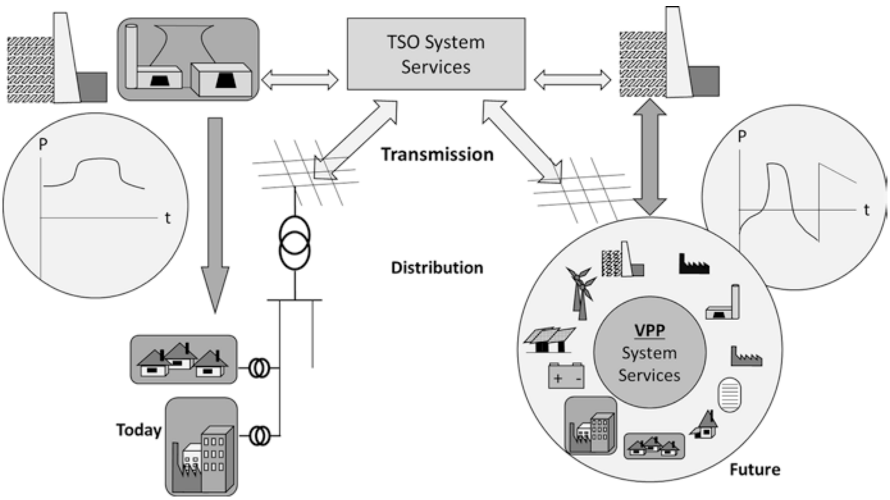

Fig. 1.15 Power system operations today (*left*) and in the future (*right*) [17]

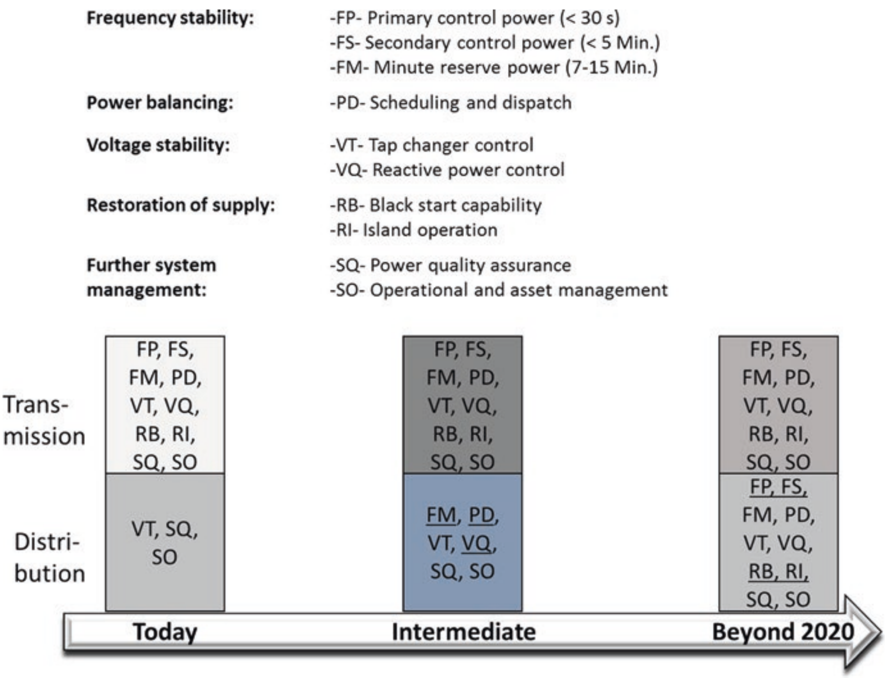

Fig. 1.16 System services: provision today and in the future [7]

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

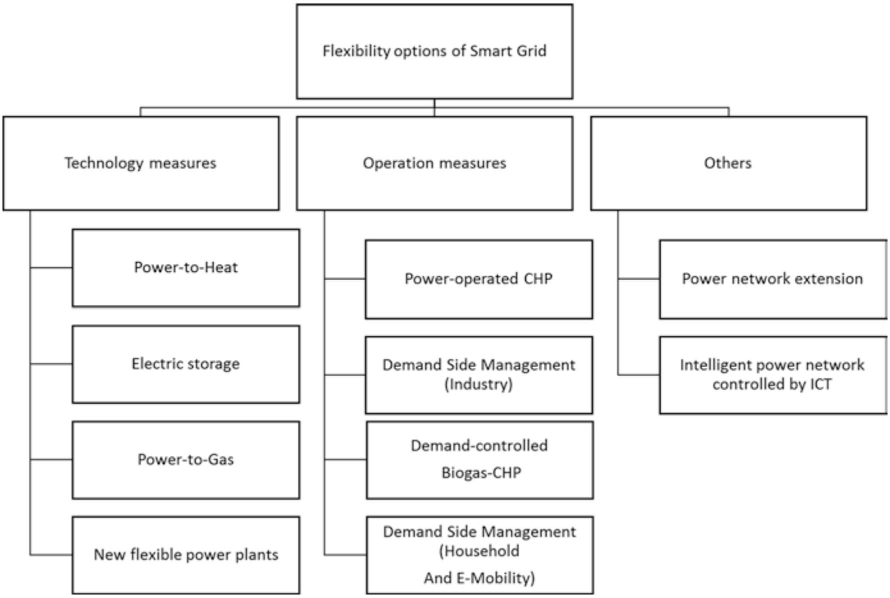

Fig. 1.17 Flexibility options for the smart grid

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].

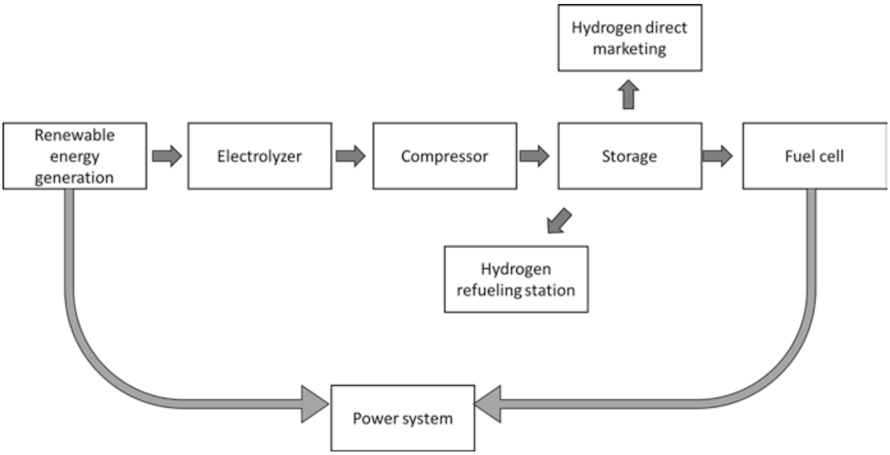

Fig. 1.18 Scheme of a renewable hydrogen-storage system

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.

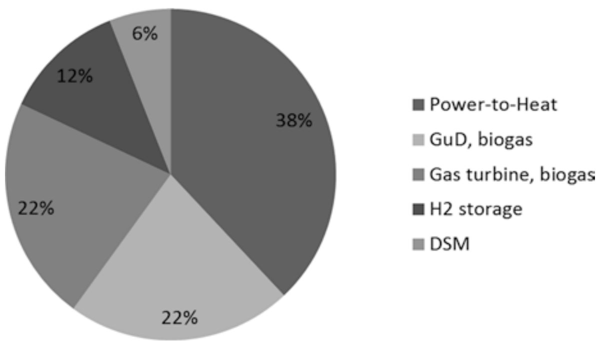

Fig. 1.19 Flexibility options necessery for a no-emission system in Germany in 2050. Results of the Acatech investigation for scenario P3S4. Normalized diagram

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.

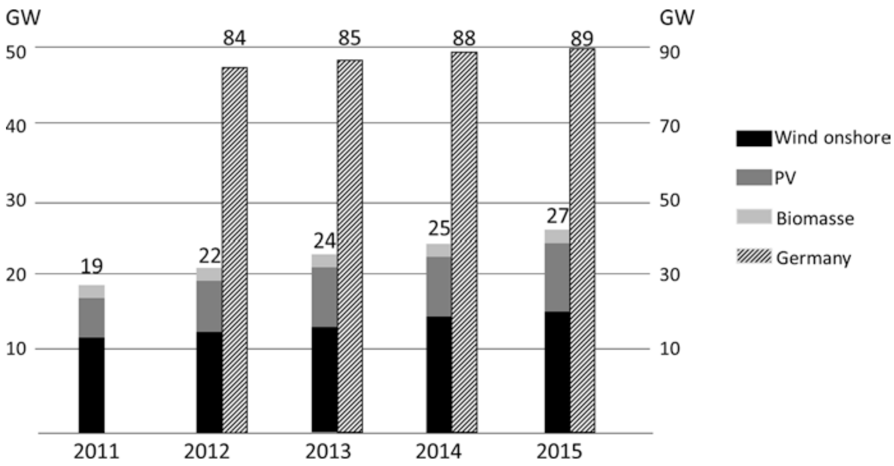

Fig. 1.20 Development of the installed capacity by EEG generating plants in Germany and in the 50Hertz control area. Source Almanac 2015 of 50Hertz Transmission GmbH

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.

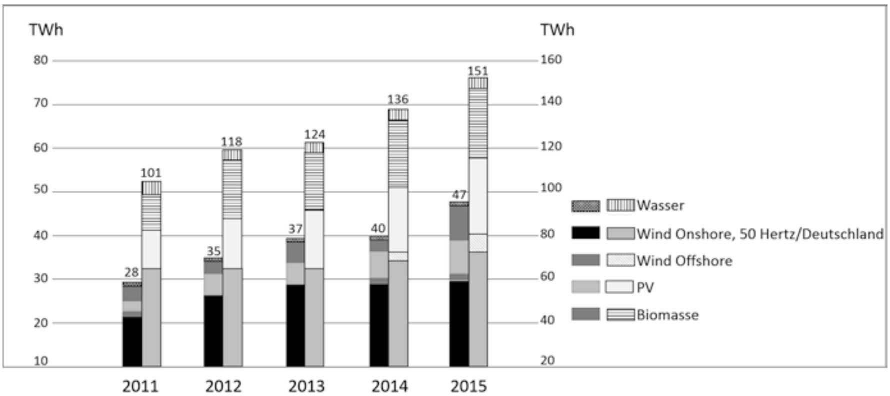

Fig. 1.21 Development of feed-in from renewable energy in Germany (*right column* in each year) and in the grid area of the TSO 50Hertz (*left column* in each year). Source Almanac 2015 of 50Hertz Transmission GmbH

[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.

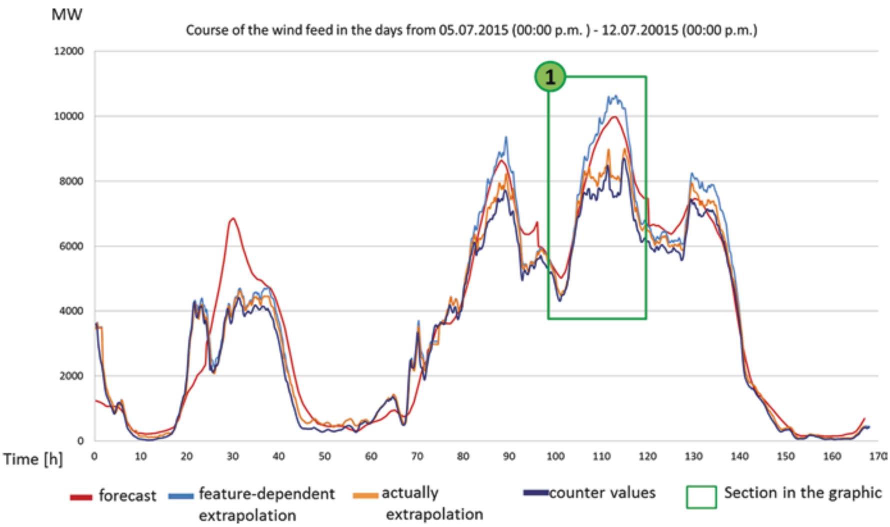

Fig. 1.22 Wind-energy generation in the TSO 50Hertz grid area on July 5–12, 2015. Source Almanac 2015 of 50Hertz Transmission GmbH

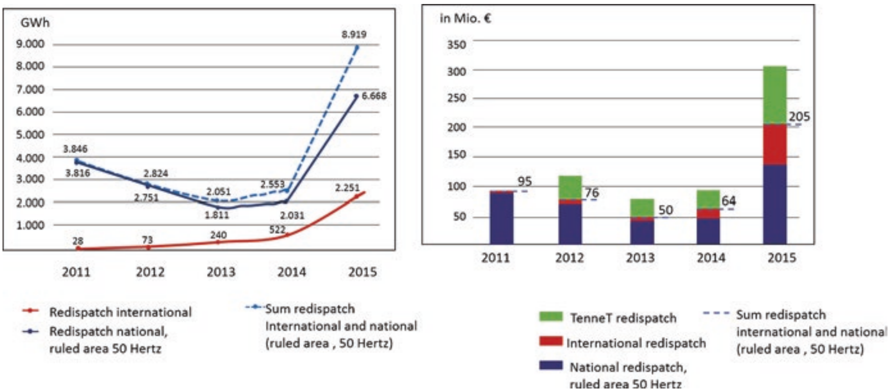

Fig. 1.23 Re-dispatch caused by renewable generation: re-dispatched energy (**a**) and re-dispatched costs (**b**). Source Almanac 2015 of 50Hertz Transmission GmbH

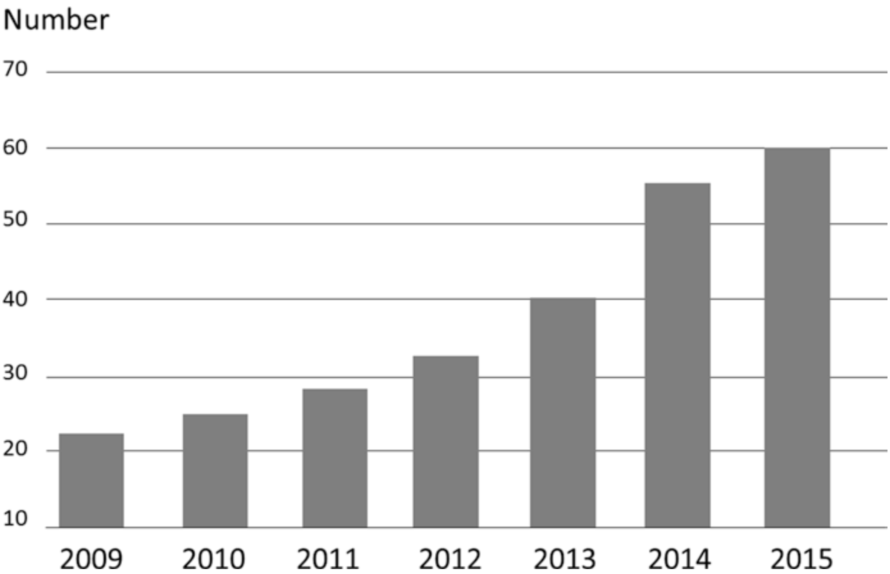

Fig. 1.24 Number of primary-control power providers in Germany. Source Almanac 2015 of 50Hertz Transmission GmbH

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}	$P_{\mathrm{min}} = \pm 1$ MW
Dimensioning power P_{N}	$P_{\mathrm{N}} > 100$ MW → obligatory delivery $P_{\mathrm{N}} < 100$ 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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Chapter 2
Electric Energy Storage System

2.1 Requirements for an EES System

2.1.1 Development of the EES Use in the Power System

Electrical energy storage has been used in powers system since the beginning.

The first power systems were constructed as DC systems and are generally associated with the name Thomas Edison, who founded the General Electric Edison Company in the United States in the late 1880s. The first electric city light was supplied by electricity from a DC generator combined with battery storage. The first large power station used the energy of falling water and converted it into AC electricity [1]. The energy storages (batteries) at that time were a necessary part of the power system and extended the limited supply of power from generators in the night, operating those generators in parallel with batteries that had been charged during the day.

Many local energy storages (batteries) were also used later (e.g., in Germany in the 1930, see also Table 2.1) to stabilize and support the power system, especially during the night. Energy storage comprised about 2 % of the installed power (7 GW) at that time.

The tasks of energy storages in the advance power systems of the twentieth century have changed. The construction of large power stations and reliable meshed high-voltage power systems led to the decrease of energy production costs (also see Fig. 2.1). Therefore, local energy storages have lost their economic advantage and have been decommissioned. Nevertheless, electric storage systems, in this case hydroelectric power storages, continue to be used in the power systems for two main reasons: their very fast power reserve and peak-power supply units.

Other grid services are covered in the modern power system directly by generation power units (e.g., spinning reserve) and local operation issues (e.g., voltage control).

A revival of local storage, particularly batteries, occurred at the end of the twentieth century as a result of the regulatory boundaries of the time. Several special applications of local storages were constructed and operated with economic benefits (see Table 2.2). But, the changes in the supply structure due to the visible growth of

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Table 2.1 BES systems in German cities (1930) [2, 3]

Location	Battery power in MW	
	2 h discharge	20 min discharge
Berlin	66.5	186.0
Hamburg	17.3	49.0
München	11.0	31.0
Leipzig	10.2	29.0
Stuttgart	6.4	18.0
Bremen	4.9	13.9

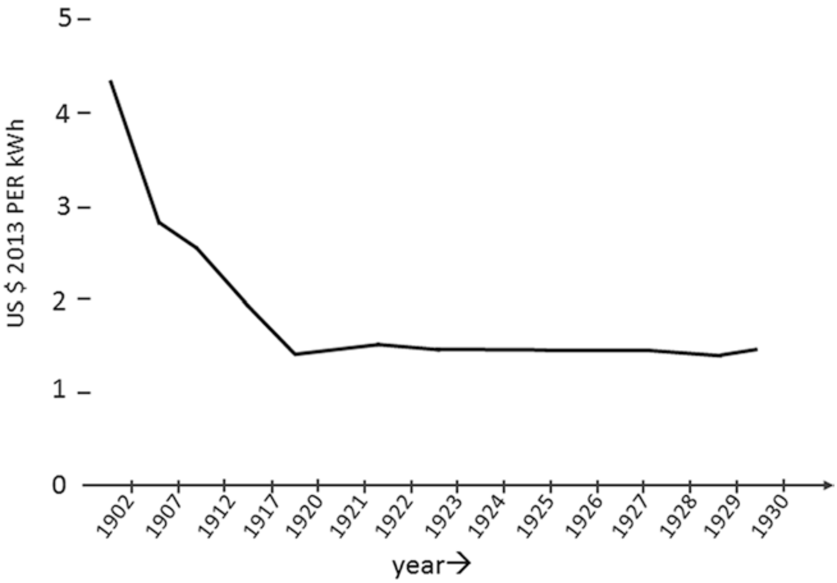

Fig. 2.1 Average price for electric energy 1902–1930 (in US$ 2013) [4, 5]

renewable generation in the twenty-first century made it necessary to revise the role of EES in the power system.

Considering the structure of the generation mix today in counties like Denmark or Germany, a portion of the renewable energy produced is often wasted, normally due to forecasting errors.[1] The transmission system operator 50 Hz Transmission in the northeast of Germany spent more than 1 billion Euros in 2015 on rescheduling measures [6] resulting from the forecast error. This tendency will continue if 80 % renewable generation is reached in the 50 Hz operating area. Today, the renewable generation in this zone makes up about 40 %. Collecting this wasted renewable energy for later use as reserve power is a new option for EES. Also, delivery of other system services, especially at the distribution level (see also the next chapters), make EES one of the most important flexibility options for smart grids throughout the world today.

[1] The mean value of the forecasting error of renewable generation is estimated at about 2.5 % over for 24 h. The real error could be much higher.

Table 2.2 Battery energy storage systems in operation at the end of the twentieth century (planned and in operation) [3, 4][2]

Company/Location	Power/Capacity	Battery: producer and type	Converter: producer and type	Primary applications	Secondary applications	Date
Elektrizitätswerk Hammermuhle Selters, Germany	400 kW 400 kWh	Dr. Jungfer (Austria): flooded lead-acid	Benning: line commutated	Load Leveling		1980–2000
Southern California Edison Chino, CA/USA	10 MW 40 MWh	Exide: flooded lead-acid	GE: self- commutated GTO	Utility Energy Storage Demonstration, Load Leveling, Spinning Reserve	T&D Deferral, Frequency Regulation, Voltage Regulation	1988
Crescent Electric Member Coop. Statesville, NC/USA	500 kW 500 kWh	GNB: flooded lead-acid	-: line-commutated	Peak Shaving	Voltage Regulation	1987
Johnson Controls; Humbolt Foundry Milwaukee, WI/USA	300 kW 600 kWh	-: maintenance-free, gelled, lead-acid	-: dual-bridge, six-pulse, line-commutated	Peak Shaving		1989
Delco Remy, General Motors Muncie, IN	300 kW 600 kWh	-: heavy-duty, low-maintenance, lead-acid automotive batteries.	Omnion: six-pulse, line-commutated	Peak Shaving, Battery testing	Alternative automotive battery uses.	1987
BEWAG—AG Berlin, Federal Republic of Germany	17 MW 14 MWh	Hagen: flooded lead-acid (CSM technology)	AEG: 12-pulse, line-commutated	Frequency Regulation, Spinning Reserve		1986

Table 2.2 (continued)

Company/Location	Power/Capacity	Battery: producer and type	Converter: producer and type	Primary applications	Secondary applications	Date
Kansai Electric Power Company Tatsumi, Japan	1 MW 4 MWh	Japan Storage Battery: flooded lead-acid	Toshiba: 12-pulse, self-commutated, GTO	Multi-Purpose Demonstration, Load Leveling, Utility Application Testing	Frequency and Voltage Regulation, Active and Reactive Power Control, Spinning Reserve	1986
Hagen Batterie—AG Soest, Federal Republic of Germany	500 kW 7 MWh	Hagen: flooded lead-acid		Load Leveling		1986
Vaal Reefs Exploration and Mining Co. South Africa	4 MW 7.4 MWh	Hagen: flooded lead-acid (CSM technology)	AEG: six-pulse line-commutated	Peak Shaving/Emergency Power		1989
San Diego Gas and Electric San Diego, California	200 kW 400 kWh	Exide: valve-regulated lead-acid (VRLA) with gelled electrolyte.	Omnion: transistor-based, self-commutated	Customer Peak Shaving, Transit Peak Shaving, Load Leveling, Load following, Start-up, Spinning Reserve, T&D Deferral	Spinning Reserve, Voltage / Reactive Power Control, T&D Deferral	1992
Puerto Rico Electric Power Authority San Juan, Puerto Rico	20 MW 14 MWh	C&D: flooded lead-calcium grid	GE: 18-pulse, self-commutated, GTO	Frequency Control, Spinning Reserve, Frequency Regulation	Voltage Control	1993
Pacific Gas and Electric San Ramon, California	250 kW 167 kWh	Delco-Remy: maintenance-free, lead-acid batteries	Omnion: transistor-based, self-commutated	Distributed Peak Shaving		1993

Table 2.2 (continued)

Company/Location	Power/Capacity	Battery: producer and type	Converter: producer and type	Primary applications	Secondary applications	Date
Stadtwerke Herne AG, Herme, Germany	1200 kW 1200 kWh	HAGEN Batterie AG: flooded lead-acid batteries with negative copper grids,	Piller: self-commutated IGBT	Peak Load Shaving	Power Quality	1997
Bocholter Energie- und Wasserver-sorgung, Bocholt, Germany	1600 kW 1000 kWh	3 strings of 272 flooded lead-acid batteries with negative copper grids, OCSM type by HAGEN Batterie AG	Piller: self-commutated IGBT	Peak Load Shaving	Power Quality	1998
Pacific Gas and Electric Various Sites in Ca	500 kW 1 MWh	None specified	None specified	Distributed Peak Shaving, T&D Deferral		1994
Hawaii Electric Light Company Island of Hawaii (Big Island)	10 MW 15 MWh	GNB: valve-regulated lead-acid battery	GE: 18-pulse, self-commutated	Frequency Regulation, Spinning Reserve	Peak Shaving, Generation Deferral, Voltage Support, Load Leveling, Load Following	1994
Chugach Electric Association Anchorage, Alaska	20 MW 10 MWh	None specified	None specified	Load Leveling, Load Following, Start-Up, Reduced Load Shedding, T&D Deferral, Frequency Regulation, Spinning Reserve		1995

Table 2.2 (continued)

Company/Location	Power/Capacity	Battery: producer and type	Converter: producer and type	Primary applications	Secondary applications	Date
Golden Valley Electric Association Fairbanks, Alaska	70 MW 17 MWh			Frequency Regulation, Spinning Reserve		1995
Oglethorpe Power Corporation Atlanta, Georgia	2 MW 10 sec	-: valve-regulated lead-acid.	Six-pulse, self-commutated	Power Quality, Load Leveling, Generation Capacity, T&D Deferral, Value of Service or Cost of Outage	Generation Deferral, Spinning Reserve, Voltage Regulation, T&D Deferral, Power Factor Correction, Frequency Regulation, Emergency Power Supply, Load Following,	1995
Stadtwerke Karlsruhe GmbH	100 kW 100 kWh	EXIDE: flooded lead-acid cells	Gustav-Klein GmbH: self-commutated IGBT	Peak Load Shaving	Power Quality	2003
Stadtwerke Karlsruhe GmbH	100 kW 100 kWh	EXIDE: valve-regulated lead-acid	Gustav-Klein GmbH: self-commutated IGBT	Peak Load Shaving	Power Quality	2003

Current forecasts estimate that the global energy-storage market will have an annual installation of 6 GW in 2017 and over 40 GW by 2022 [7]— from an initial base of only 0.34 GW installed in 2012 and 2013. The battery market alone will increase up to about 73 % by 2020 [8]. Furthermore, Li-ion batteries are projected to occupy more than 67 % of the total market share by 2020. Li-ion batteries are used extensively in BES for the smart grid as they can be produced with high capacities. This battery type offers high operating voltages in comparison to other batteries, such as lead-acid batteries and sodium-sulfur batteries. Other benefits of Li-ion batteries include their light weight and compact size, which will augment their adoption into the energy storage system. All regions of the global market are forecast to increase Li-ion battery storage over the next 4 years. There will be a general increase of US$1.7 billion in the smart grid, battery and storage, and efficiency sectors. The Americas dominated the battery-storage market for the smart grid and accounted in 2013 for around 60 % of the total market share.

2.1.2 Requirements for EES and Extension of Storage Usability in the Smart Grid

Some new business cases for EES use can be beneficial when the generation mix is dominated by weather-dependent renewable generation.

The "white paper[2] of IEC [9]" summarizes these business cases for three groups, utilities, consumers and generators of renewable energy, as follows:

- from the point of view of utilities:
  - Time shifting: Reducing the generation costs by storing in the off-peak time (mainly at night) and discharging at peak time (mainly in the daytime or noon peak hours).
  - Power quality: EES can provide frequency control functionalities and, when located at the end of heavily loaded lines (especially in the distribution), may improve voltage drops by controlled charge/discharge operation.
  - Making more efficient use of the network: Time-limited congestions in a power network may occur when the transmission/distribution line cannot be reinforced. Large-scale EES (especially large-scale batteries) located in strategic places can mitigate the congestion and help to postpone and suspend reinforcement of the network.
  - In isolated grids: The operation of small, isolated power grids (e.g., islands or regions located far away) powered by diesel or renewable generation can be stabilized by EES.
  - Emergency power supply for protection and control equipment: Batteries can be used for this important emergency activity in case of outage.

[2] White paper – report which summarizes the advantages and disadvantages, costs, etc., of concrete solutions or technology.

- from the point of view of consumers:
  - Time-shifting/cost-saving aspect: Incentives for flattening the electricity load for consumers are given in the form of time-varying electricity prices. Reduction of peak power by using EES can also decrease the customers' connection costs.
  - Emergency power supply: EES can be used for the consumers' emergency power supply.
  - Electric vehicle and mobile applications: V2H (vehicle to home) or V2G (vehicle to grid) can also be used locally (charged with local PV generators) or globally (charge- and/or discharge-supporting network services).
- from the point of view of generators of renewable energy:
  - Time-shifting: Storing surplus electricity in EES and using it when necessary for ancillary services or selling to the network operator.
  - Effective connection to grid: EES can absorb fluctuations more effectively than other mitigation measures, e.g., a phase shifter.

One can see from this classification that some of the EES services can be used by various users for both similar and differing business cases—so a multiple usage is possible (e.g., time-shifting).

Furthermore, taking into account the grid services, the EES can provide the following kinds of mentioned services [10]:

- Bulk-energy services:
  - Electric energy time-shifting (arbitrage)
  - Electric-supply capacity
- Ancillary services:
  - Regulation
  - Spinning, not-spinning and supplemental reserves
  - Voltage support
  - Black start
- Transmission infrastructure services:
  - Transmission-upgrade deferral
  - Transmission-congestion relief
- Distribution infrastructure services:
  - Distribution-upgrade deferral
  - Voltage support
- Customer energy management services:
  - Power quality
  - Power reliability
  - Retail electric-energy time-shift
  - Demand-charge management

The EES can be generally characterized for planning and operating purposes by some specific parameters independent of the technologies used. The list of these parameters and short descriptions are given in Table 2.3.

The mean parameters requested from the EES are now given in Table 2.4, taking into account the various EES applications mentioned previously.

Table 2.3 Specific parameters of EES. General requirements

Parameters	Dimensions	Typical values	Description
Output power or power capacity	kW, MW	Distribution 10–100 kW Transmission Up to GW	The nominal power of the output way (e.g., transformer).
Storage capacity	h, also in kWh or MWh	Short-term Seconds to minutes Long-term hours to weeks	The length of time the nominal power could provide up to the limit of the charge depth. After this, it is still possible to extract the energy from the storage, but some damage is possible.
Depth of charge	% of capacity	Batteries 40 %—up to min 10 % Other EES 10 %	The minimal level of capacity which could be achieved without damage of storage by nominal charge/discharge process.
Charging ratio	% of the nominal power	Depends on technology, 10–100 %	The power rate at which the storage can be charged without damages. This generally depends on charge unit construction and technology. Most battery types are not linear and can be given as a voltage-dependent curve.
Discharge power ratio	% of the nominal power	Depends on technology, 100% and more	The amount of power which the storage can discharge without damages. This generally depends on discharge unit construction and technology. Most battery types are not linear and can be given as a voltage-dependent curve.
AC voltage requirements	V or kV	Depends on technology and power	Depends on power; the AC voltage must be complementary with connection requirements.
Duty cycle requirements	Cycle per life time	Depends on technology 1000 up to 10,000 cycles per lifetime	Depends on application; a different cycle number is necessary to reach economic benefits from EES, e.g., for 10 years' pay back and one day's full cycle, about 5000 cycles of storage is necessary.
Portability requirements	Optimal module size	Depends on technology 100 % and more	Especially for mobile or local storages; an optimal storage size should be standardized.

Table 2.3 (continued)

Parameters	Dimensions	Typical values	Description
State of charge (SOC)	In % of capacity	Depends on technology and time	Especially important for operation issued. The SOC can also be forecast and used for optimal storage operation.
Depth of discharge (DoD)	In % of capacity	Depends on technology	It is the ratio of the maximum amount of energy that could be discharged from an energy storage system to the maximum storable energy.
Self-discharge	Daily loss of energy in % of capacity	Depends on technology	Represents the losses of energy from such internal processes as endothermic reactions (in batteries), flow resistance in pumps (in flow batteries) or water evaporation (in pumped storage plants).
Energy density	kW/m³ or kW/liter	Depends on technology	It is the ratio of energy discharged to the energy storage system's total capacity.
Start-up time	s	Few second to minutes	It is the time required to deliver the power requested to a consumer.
Ramp-up time	s	Few second to minutes	It is the time needed to deliver the maximum power.
Specific costs	€/kW (power-specific costs) €/kWh (energy-specific costs)	Depends on technology: €/kW 300–2000 €/kWh 50–1000	Most reasonable parameter for usage of EES. Very strongly dependent on technology and application.

Table 2.4 Summary of technical requirements for applications [3]

Application	Storage (in min)	Power	AC voltage in kV	Duty cycle requirements	Floor space (importance)	Portability (importance)
Spinning reserve	10^1–10^2	10^1–10^2 MW, LC	10^1–10^2	10^1/year, random, discharge only	Medium	Low
Area control & Frequency responsive reserve	Charge/ discharge Cycles of <10^1	10^1–10^2 MW, LC	10^1–10^2	Random, continuous charge/dis-charge cycle clustered in 2-h blocks daily	Low	Low
Load levelling	10^2–$0.5*10^3$	10°–10^2 MW, LC	10^1–$0.5*10^3$	10^2/year, regular, periodic, weekday block discharge, increased use in shoulder months	Medium	Negligible
Transmission system stability	10^{-3}–10^{-1}	10^1–10^2 MVA, SC	10^1–$0.5*10^3$	10^3/year, random, charge & discharge cycles	Medium	Low
Transmission voltage regulation	10^1–10^2	10°–10^1 MVAR, SC	10^1–10^2	10^2/year, random charge & discharge cycles typically weekdays, seasonal by region—at least 6–7 months	Medium	High
Transmission facility deferral	10^2	10^{-1}–10^1 MVA, LC	10^0–10^1	10^2/year, most likely during weekday peak, charge & discharge	Medium	Medium
Distribution facility deferral	10^2	10^{-1}–10^0 MW, LC	10^0–10^1	10^2/year, most likely during weekday peak, charge & discharge	Medium	Medium
Customer energy management	10^1–10^2	10^{-2}–10^1 MVA, LC	10^{-1}–10^1	10^2–10^3/year, regular periods	High	Varies
Power quality & Reliability	10^{-3}–10^0	10^{-2}–10^1 MVA, SC	10^{-1}–10^1	10^2–10^3/year, irregular periods, charge & discharge	High	Varies
Renewable energy management	10^0–10^3	10^{-2}–10^2 MVA, LC	10^{-1}–10^1	10^2–10^3/year, regular periods, dis-charge only, unpredictable source	Varies	Varies

2.2 Generic Model of EES

2.2.1 Standardizing Generic Model of EES

The calculation and planning for power systems is divided into two types [11]:

- static calculation and planning, and
- dynamic calculation and planning.

A time scale is not used for the static calculations. Here only the maximal demand is used for dimensioning the electrical equipment and energy in order to balance the energy production during 1 h or one day (24 h).

EES models with different accuracy are necessary to provide calculations in the planning process of the power system. The chosen EES models for this calculation should match the accuracy and details corresponding to the mean models of the power system equipment, for example, generators and transformers.

Dynamic models of electric equipment are necessary for dynamic calculation; these models mostly described the features of objects by partial differential equations [12]. More adequate EES models based on, e.g., equivalent networks [13, 14], are sometimes required for the detailed planning of EES (e.g., dimensioning the inverter). The EES models for dynamic calculations will be not discussed in this book because they have been presented in more detail in other publications (also see Table 2.4). Depending on the calculation timescale, the models can also be simplified, and, if the calculation incorporates a very short time (e.g., less than a second), constant behavior of the equipment model of the EES model can be assumed in a critical situation.

Measurement data and physical characteristics of the devices are used for parameterization of models described mathematically. The accuracy of the models should be further adapted in order to provide extensive simulations of large networks in such a way that the main parameters and characteristics of single devices (here also EES) are considered without needlessly increasing the computing time.

Concerning the general requirements of the modeling, the EES can be integrated into the calculation in the power system as a combined generation/load device. The generation devices (generators) must be fully considered in such a model if the storage system is equipped with one such unit. This is the case if the pump hydro-energy storages (PHES), flywheels or CAES storages are used. In the case of electrochemical storages—when no rotating mass is in use during the conversion—only the performances of electrochemical processes and inverter properties must be considered in the model.

The generic structure of an EES model should have at least three surfaces to fulfill the requirements previously mentioned (see the following Fig. 2.2). The first, the main surface, consists of the physical model that is mainly described by the mathematical description and comprises the central point of the EES model. This *Ph*ysical *S*urface (PhS) of the model is then merged into its particular surrounding

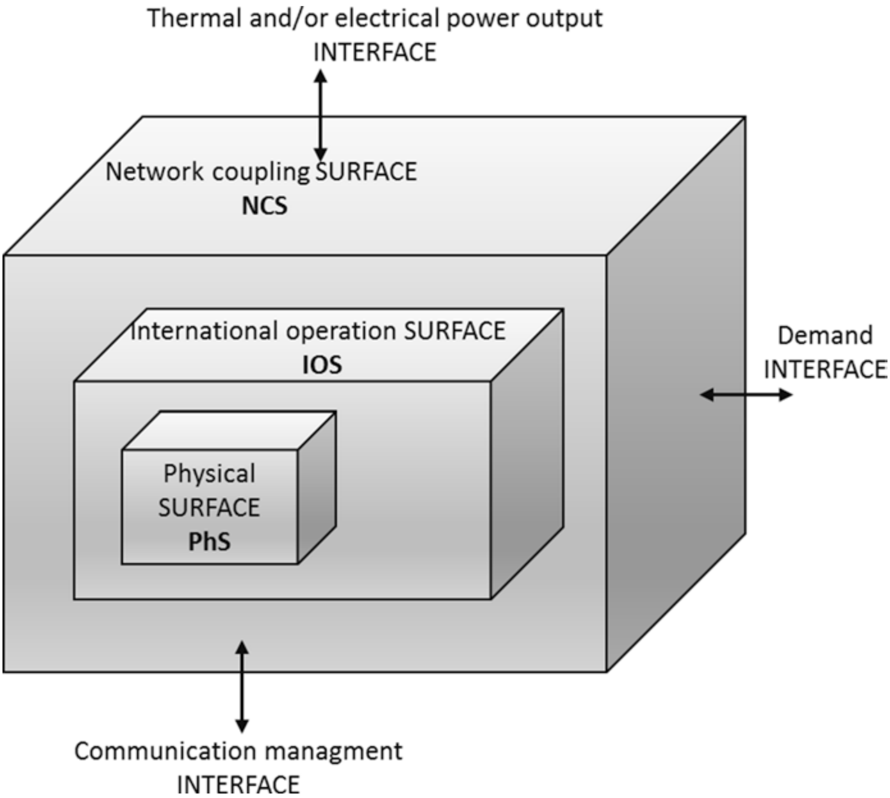

Fig. 2.2 Generalized surface and interface structure (SIS) of the EES units modeled

conditions, such as the thermal and electrical demand of the load, and new interfaces and demands on the model structure are introduced, particularly considering the emulation of the control systems. Table 2.5 summarizes the modeling requirements for the PhS of EES considering various types of storages and kinds of model implementation.

Table 2.5 Modeling the physical surface of EES for power-network planning

Model specification	Storage type	Model used
Static models for planning issues/long-term simulation	Common generic model independent of storage type	Reservoir model Parameterized depending on storage type
Dynamic models for simulation issues/short-term simulation in time domain	PHS, CAES, flywheels Batteries Storage medium H_2	Advance AC generator model [x1], e.g., equivalent networks or torsion model [x2] Equivalent networks model or inverter model [x3] Inverter advance model [x4]

The PhS together with the emulated surrounding systems create the second platform—the *I*nternal *O*peration *S*urface (IOS) of the EES unit. The third model surface, the *N*etwork *C*oupling *S*urface (NCS) of the unit, realized mainly as a simplified inverter model together with the linking transformer, completes the structure of the EES unit model for the long-term interval simulations. The NCS surface has thee interfaces:

- thermal and electrical output,
- demand and
- communication management.

The energy supply of the EES and exchange between the EES and the power system is realized using the thermal and electrical output. This interface must also be rated respective to PhS parameters (e.g., nominal power).

The demand interface determines the output power requested and the communication management interface makes possible optimal control of the EES operation.

The model mentioned above corresponds well with the more general architecture of the power system given in the common information model (CIM) standard (also see Fig. 2.3). Using the CIM, the same kind of standard description can be used for different devices (e.g., storage, transmission and distribution devices) and also for various areas of implementation (e.g., market, optimal system operation). Thanks to standardizing the CIM description, it is easy to build the whole

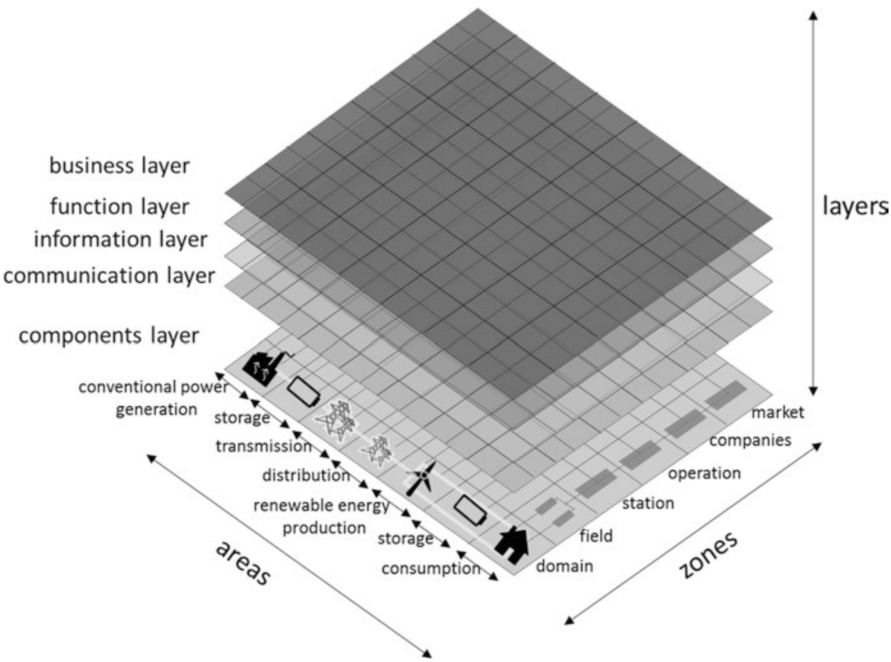

Fig. 2.3 The architectural structure of power system elements in comparison with standards [15]

model of the particular power system from the physical, as well from the ICT, point of view.

There are five surfaces (levels) in the CIM model presented here. The base level is the Component Level (surface). In addition to the general 3-SiS model of storage, the functionality and business levels are present in the CIM general model.

The consideration of different applications of EES is possible—in a systematic way—in the form of use cases. A use case describes the actors, relationships between them and information flow within each particular application. Use case blocks are identified and presented for storage tree usage in Fig. 2.4.

The use cases mentioned in Fig. 2.4 can be described as follows:

Economic Use of EES

Description

The EES supports the integration of RES into the power system. Using EES, the RES integration can be optimized and made profitable for all market participants. The market players here are the RES, EES, owners of EES and RES, direct sellers, energy market, power system operators and the local power system.

Own Consumption Operation Mode

Description

Stationary EES can buffer the electric energy produced by the RES. The dedicated use of EES close to small RES generation (e.g., PV on the roof of buildings) minimizes the transported power and increases the rate of self-supply, which is connected with economic benefits. The market players here are the EES, owners of the EES, consumers, power system operators, the local power system and local energy management systems (EMS).

Network Serviceable Operation

Description

Stationary EES can react to different events during the power system operation. Thus, EES can buffer the energy and, at other times, inject energy into the system.

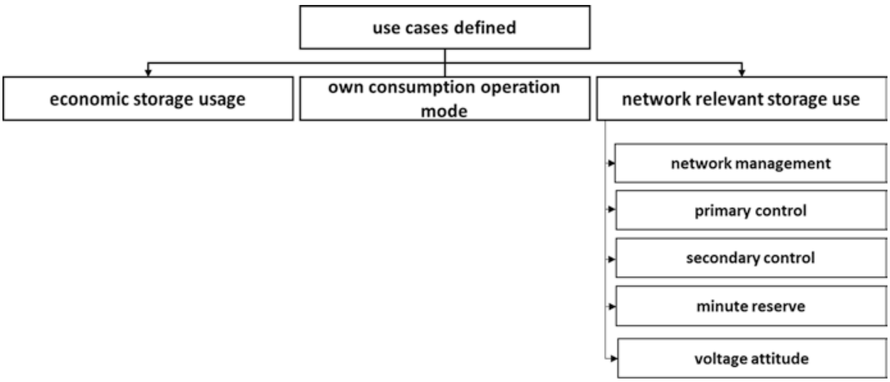

Fig. 2.4 Use cases defined for EES

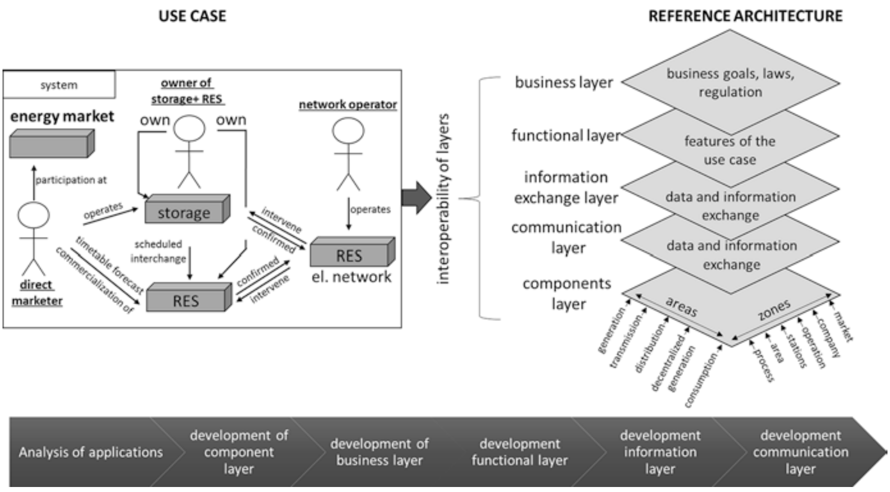

Fig. 2.5 Use case—own use of EES—description in CIM

The use of EES in this use case is possible in the critical areas, improving the supply security of the system and delivery of power system services.

The market players here are the EES, operators of the VPP (virtual power plant), power system operators, power system network, EMS and the consumers. Considering the EES in the context of the whole power system is important, and observing the system from the point of view of its components is very useful (also see Fig. 2.6)

A presentation in CIM enables one to describe the use cases concerning the EES and other elements of the power system in a standardized way. This is given as an example in Fig. 2.5.

Three active actors are involved in the process examined in this example, namely: the owner of the storage and RES, the system operator and the market agent. They each have different relationships to the objects (e.g., market, power network) and use storage in specific ways (e.g., hold, share).

Taking this architecture into account, all the use cases can be described structurally and, in this case, also modeled in the same standard manner.

The components interface is the backbone of the reference architecture and includes the equipment, applications, people and organizations involved in use cases. In this way, it is possible that a single component, particularly addressed by the use case, defines the participants and allocation to different domains and zones. Thereby, a single component is assigned to a concrete hierarchical zone and influences that area of the electric energy conversion (also see Fig. 2.6).

Finally, the business level of the model can help to decide the implementation of storage into the power system. This level includes different business processes, services and the organization of the electricity market that are each connected to the specific use case. The organization goals as well as the economic and regulation issues must be strongly considered here.

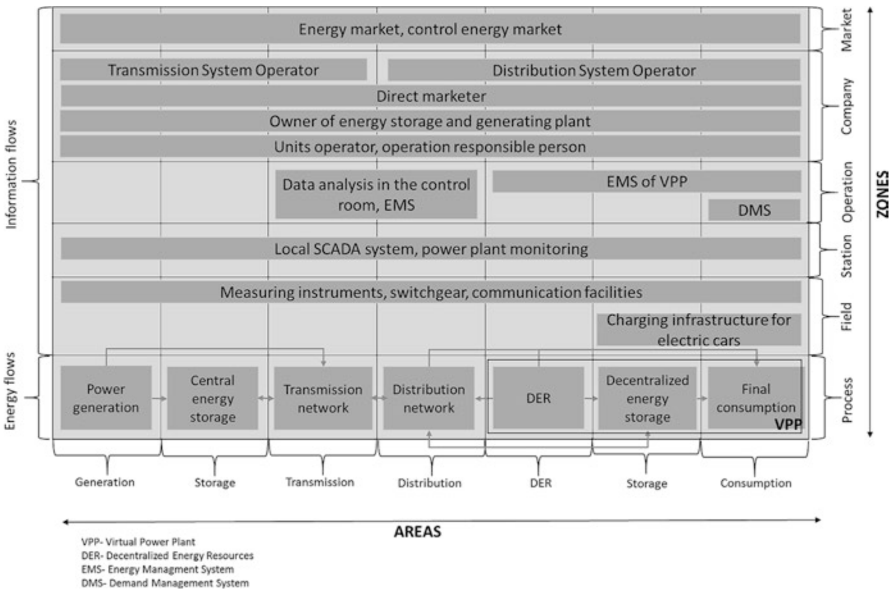

Fig. 2.6 Overview of the components of the power system

The functionality level is comprised of the function of each component and its relationships corresponding to the domain and zone. A particular function can be extracted from functionality. A sub-use case could be constructed from more specific use cases.

The information level consists of data which will be used or extended by various components by the activation of specific functions. The information sets that are exchanged are deducted from use cases in the form of sequence diagrams. The fundamental canonic data models were assigned using the analysis of available standards and show if there are any additional obligations or boundaries in its description.

Figure 2.7 presents the overview of the information level for the use case "economic use of energy storage". This information schema follows the schedule given below:

(1) At the beginning of each month, the EES and RES operator make a decision about the market-oriented energy delivery so that it will not be paid in the form of the feed-in tariff corresponding to the EEG 2014 §20 (1).
(2) In the next step, the RES owner/operator must decide if he prefers his own direct commercialization or the commercialization of the professional group. The latter should be preferred, especially for small RES units.
(3) Finally, the sell/buy order is placed on the spot market.
(4) After evaluation of the trade conditions, the market player is informed about the setting of his order.
(5) The finalized contract is framed (ECC Lux).
(6) After successful framing the scheduled ECC Lux, the resulting energy is planned by the responsible TSO. The TSO confirms, in an ideal case, the schedule with a final confirmation report. Thus, the delivery of the energy can follow.

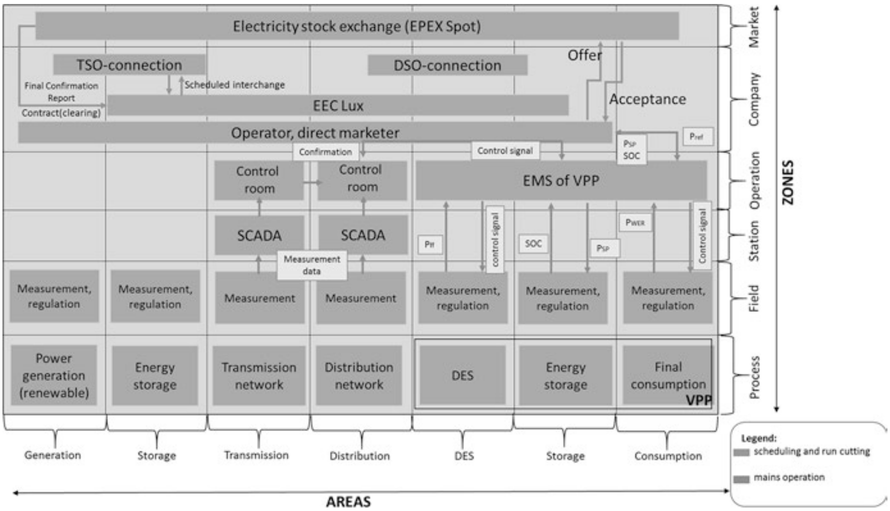

Fig. 2.7 Information level (surface): economic use case of EES

The focus of the communication surface for the practical realization of the contract mentioned above is the descriptions of protocols, interfaces and mechanisms for the interoperable information exchange between players in the defined use case. As mentioned before, the corresponding issues could be identified based on the data and canonic data model and are presented in Fig. 2.8. The VPP, its functionality and the role of EES usage in the future power system are pointed out in both the information and communication. The EES is a fixed part of the VPP concept and, in this case, the use of storages in the power system is indispensable.

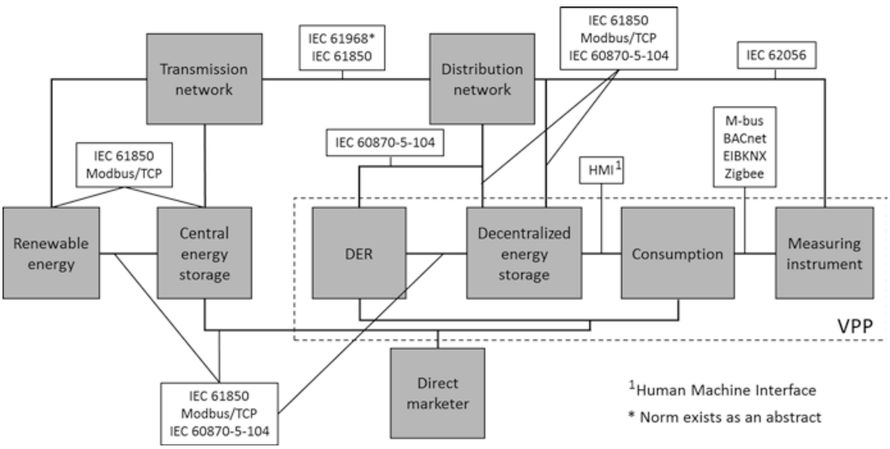

Fig. 2.8 Communication level for the economic use case of EES

The communication protocol used for the ICT connection in the future power system is also increasingly being standardized according to IEC standards. The protocol IEC 61850, which was developed especially for smart grid needs, has become particularly popular [16].

2.2.2 Physical Surface of the EES Model. Mathematical Generic Model

If the storage use is to be explicitly prepared, the EES should be modeled during the power system planning process. Such a standardized model can be based on the fundamental reservoir model, or it can be represented as a set of equations with linear or non-linear elements.

Because a long time scale is required for the planning process, the nominal power and the energy balance should be calculated for a specific time period, for example, 1 h or one day (24 h). These calculations result from the demand and use case as well as the charge and discharge processes in this time period [17]. These processes can cause losses that are connected with the energy conversions from electric energy to storage medium, EES and vice versa ESE, respectively, and also self-discharge if the storage is not in use, Elos. The whole loss of energy El in a time period T is given by Eq. (2.1):

$$E_l = E_{los} + E_{ES} + E_{SE} \tag{2.1}$$

The integral mathematical equation with restriction describes the storage energy E and can be formulated as:

$$E(t) = \int_0^{\Delta T} P_{in}(t)u(t)dt - \int_0^{\Delta T} P_{out}(t)v(t)dt \tag{2.2}$$

where:

$$u(t) = \begin{cases} 0 - \text{no} \quad \text{charging} \quad \text{time} \\ 1 - \qquad \text{charging} \quad \text{time} \end{cases} \tag{2.2a}$$

$$v(t) = \begin{cases} 0 - \text{no} \quad \text{discharging} \quad \text{time} \\ 1 - \qquad \text{discharging} \quad \text{time} \end{cases} \tag{2.2b}$$

The restrictions concerning the storage operation are given by (2.3a) and (2.3b).

$$u(t) \quad \wedge \quad v(t) \neq 1 \tag{2.3a}$$

$$E(t) \geq E_{min} \quad \wedge \quad E(t) \leq E_{max} \tag{2.3b}$$

where Emin and Emax are the possible maximum and minimum energy storage capacity, respectively.

The restrictions in the general storage model are specific for particular storages. The kind of storage is also hidden in the functions f_1 and f_2 which describe the charge/discharge processes [18]:

$$P_{in}(t) = f_1(E(t), E_{max}, E_{min}, z) \tag{2.4}$$

$$P_{out}(t) = f_2(E(t), E_{max}, E_{min}, z) \tag{2.5}$$

where z is the type of energy storage equipment.

Until now, only batteries have been used as local storage on an industrial scale (see Table 2.2). For this reason, the parameterization of the generic model was carried out exemplarily for a battery-energy-storage (BES) system (see also Sect. 2.3.3). The BES consists of three major subsystems: battery cells/stacks, power converters and balance of plant (known also as battery management system). The batteries are connected to the electric utility through a power converter, which rectifies AC to charge the batteries and later converts the DC back to AC to supply the utility load. The battery subsystem is sized to satisfy the energy (kWh) required by the customer for various functionalities, for example, a shaving the peak load to the necessary limitation. By contrast, the power converter subsystem is sized to satisfy the peak-power requirement (kW) of the load, which corresponds to the peak discharge rate of the battery (also see Fig. 2.9).

The parameterization of the models has been done exemplarily using the 30 kW/61 kWh lead-acid test BES installed by the BEWAG power utility in Berlin [18]. Three battery models were investigated in this test: the integrated reservoir model, network voltage model and fourth-order dynamic model. The test results showed that it is possible to determine the parameters for the three battery models using the same extensive test measurements.

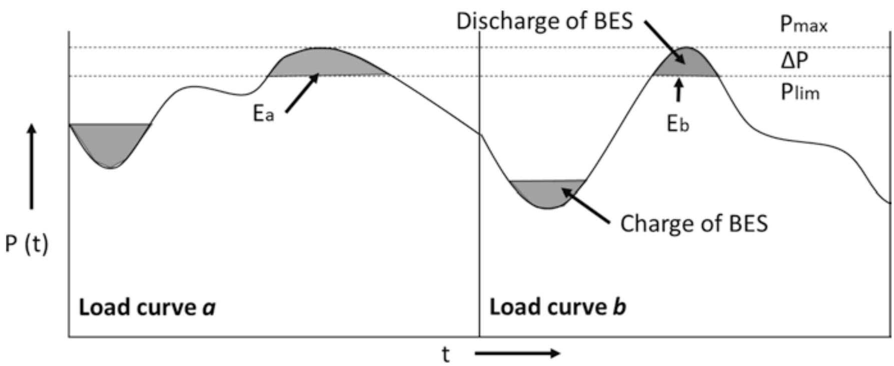

Fig. 2.9 Dependence of storage size upon the load profile E_a and E_b and the storage capacity in kWh by the load curve *a* or *b*, respectively

The integration reservoir model shows satisfactory exactness when the battery is discharged up to about 40 % of its capacity. By discharging the battery beyond this limit, an error of up to 20 % in the energy balance over a 24 h period between model calculations and measurements was observed. This error depends on the dynamics and intensity of charge/discharge cycles. The network-voltage model and dynamic model with partial optimization of parameters show an accuracy of about 98 % for the 24 h energy-exchange period. All of the models can be applied for calculating the optimal BES size, but generally, the integration reservoir model only meets the accuracy requirements for the planning of power-system expansion using slow charge/discharge processes.

2.3 EES in the Transmission and Distribution System

2.3.1 Factors Influencing the Value of Storage in Transmission Networks

From the general specifications given in Sect. 2.1.2, many storage application fields and benefits can be applied to the transmission system.

Pump-hydro energy storage (PHES) is characterized by high capacity (up to 10 h) and high installed power (up to 3 GW), and is traditionally used for improving the dynamic behavior of the power system (e.g., primary and secondary reserve [19]) and for providing some additional system services (e.g., black-start capability [20]). Currently, due to the high infeed of renewable energy, some new functionalities of PHES and other high capacity storage, such as CEAS, can be used. The following services may also be provided by energy storage systems in transmission networks:

- Investment deferral: New transmission lines add incremental capacity, whereas storage can be added at smaller ratings. A storage solution can, therefore, be advantageous.
- Loss reduction: The value of the storage systems arises from the reduced costs associated with losses and the improved environmental performance of networks.
- The value of the storage system in congested networks arises from the difference between the prices in the two zones, as well as from the potentially improved utilization of generation capacities.

These "new" storage applications have some limitations:

- Conflicts with "must-run" generation: The optimal operation of storage devices can conflict with the operation of base-load generators. A key point for minimizing this conflict appears to be the flexibility of the rest of the system.
- An excessively high storage capacity, which is required by some transmission implementation (e.g., investments deferral can sometimes require more hours of storage for only a few events per year, especially in winter), reduces its utilization factor.

Furthermore, some specific considerations must be taken into account for the installation of storage systems in transmission networks. Generally, each transmission network has unique characteristics. Before incorporating storage systems into a specific network, analysis of the targeted power system is necessary. Some characteristic issues, depending on the case, encourage the installation of storage systems (e.g., technical advantages), while others (e.g., economic benefits) discourage them. The specific characteristics of transmission networks mentioned before could be of a technical, geographical or economical nature and can be generally summarized as follows:

- Technical: Improving power flow, stabilizing system voltage, improving system stability (e.g., by delivery of reactive power), improving fault current capacity.
- Geographical: Interconnected power system, isolated power system.
- Economical: Comparisons in ratings, size and weight, capital and operating cost, life efficiency, per cycle cost.

Testing a variety of locations and technology types for the storage system installation can help to find the best solution.

It is useful if a storage–system generally satisfies one of following conditions:

- Loading rate of transmission lines is high and can be leveled by the use of storage

or

- system voltage is below standard voltage levels and can be improved by storage.

Additionally, conditions for the expected fault current and system stability before and after installation of the storage need to be checked in detail.

Next, geographical conditions should be considered when installing storage systems in interconnected systems or isolated systems. The installation of storage systems must satisfy the following conditions:

- Interconnected power system: location of the storage in a high-price zone compared to other areas;
- Isolated power system: only one source exists (storage assumes the reserve functionality) or not enough power is available for peak demand.

Finally, comparisons between economic considerations should be performed. These considerations should record ratings, size and weight, capital cost, life efficiency and per cycle cost.

2.3.2 EES in the Distribution System

The distribution system is the part of the power system in which the most changes have occurred in recent years. Clearly, most of those changes were caused by the massive development of renewable and decentralized generation. The distribution system has changed from a passive one, in which the energy flow was only top down, to an active one and, furthermore, has undergone a transformation in character to smart distribution. This means that the ICT are integrated into the coordination of the operation (and also distribution). This step was a big innovation in the power-system operation philosophy, but was necessary because part of the duty of system services must be coordinated increasingly between DSO and TSO and will migrate to smart distribution in the future [16].

The distribution system is fed by very highly distributed generation—for example, in Germany in 2016, there is about 60 GW (theoretically about 80 % of peak demand) generated mostly by wind and PV. These changes in the supply configuration lead to rule changes in the electrical market.

Considering the paradigm shift just mentioned, the use of storage in distribution has a particularly important position today and will continue to be important in the future. Some of the main functions of storage in distribution have already been mentioned, and the market position of EES is briefly described in Sect. 2.1. The most important services of EES in smart distribution can be summarized as follows:

- Distribution infrastructure services:
  - Distribution upgrade deferral
  - Voltage support
- Customer energy-management services:
  - Power quality
  - Power reliability
  - Retail electric energy time-shift
  - Demand charge management

These functionalities can be extended by other means, e.g., local domestic storage, storage integrated in e-cars or storage used in VPP (also see Sect. 2.1.2), the implementation of which will be realized within the next few years. In order to meet the goals of the generation mix for Germany and other countries in 2050, distributed storage (mostly advanced batteries) and long-term storage (mostly using H_2 as the storage medium) will be necessary for both a stable and affordable power system. (See Sect. 1.1 for more details on the future goals for generation mix.)

2.3.3 Example of Modeling and Implementation of the Models in the Planning and Simulation in Distribution

Independent of the fact that some storage technologies are already technically ripe, the use of storage in the power system is still coupled with high or very high expenses. Therefore, it is necessary to combine various functionalities to reach real economic benefit. In this chapter, five methodical examples will be given to illustrate the advanced procedures that can lead to wide storage implementation in distribution.

A: Optimal Storage Dimensioning in Smart Distribution

The most important economic benefit of EES can be shown by the peak-load-shaving operation mode. In this case, the benefits can come from both the price of power in energy tariffs and also from a delay of necessary network investment in the case of overloading equipment, e.g., lines or transformers.

The cost of the storage and corresponding benefits are dependent on the power and energy of optimal storage. In a storage model, load growth changes during the planning period and pricing data are necessary to determine the EES module using the daily load curve in the specific network.

One possibility is the use of an iterative search process for the computation of optimal storage for a particular load profile. The load profile is characterized by a relatively flat curve with one or two maxima. An example of a load profile is introduced in Fig. 2.9. Furthermore, how the use of storage allowed the shaving of the peak demand of ΔP power is also shown in Fig. 2.9. On the one hand (i.e., load curve a), a reasonable energy (time) is necessary for shaving the peak on this load curve. On the other hand, this is not the case in load curve b, when effectively less energy in the storage is required for the same ΔP peak shaving. If ΔP increases, taking into account the specific of the load curve, the necessary storage energy will also increase, but not proportionally.

Shifting energy costs needs to be considered, so it is necessary to know the energy price difference between on and off peak times. The various benefits resulting from those prices must balance the storage costs, which are calculated using the specific cost of power and energy (also see Table 2.4).

The process calculating optimal storage size is illustrated in Fig. 2.10. Increasing the ΔP (nominal power of the storage) also increases the costs of the storage (see also Eq. (2.6)). Finally, when the size of the storage is so big that there is not any more benefit from using it (storage costs line cross the benefit line in Fig. 2.10), then the iterative searching procedure of ΔP increasing stops. The optimal storage size ΔP_{opt} is found in the maximum of the benefits curve.

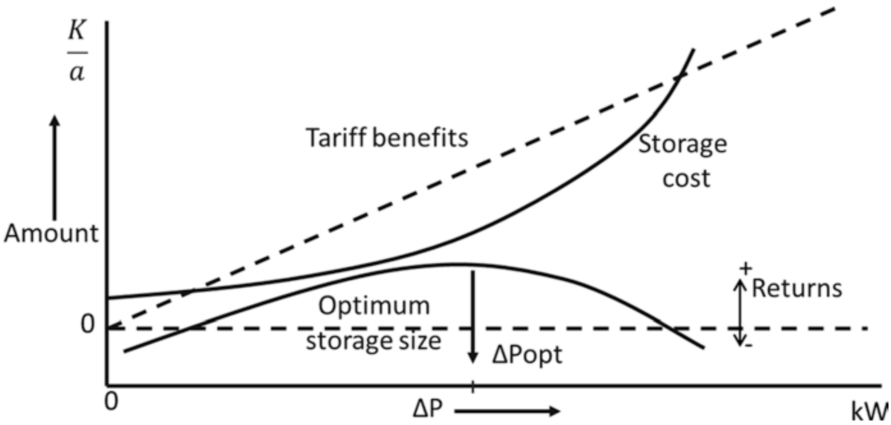

Fig. 2.10 Optimization of storage size for a given load curve. General idea

This approach can be implemented for longer periods of time, for example, 1 year. If a yearly load curve is not available, a yearly-approximated load curve can be composed using 12 daily load curves, which characterize Saturdays, Sundays and working days in all four seasons (spring, summer, autumn and winter). A yearly load curve for a network node in a German distribution system is shown in Fig. 2.11 as an example.

The calculation of the optimal storage mentioned above is based on cost balancing. Both the tariff benefits Z_t that correspond to the tariff power price (energy price and connection-power price C_{CON}—(2.8)) as well as the benefits corresponding to investment delays C_{InvD} (2.9) in various parts of the network must be summarized for planning purposes. On the other hand, the investment C^{I}_{EES} (2.6) and discounted costs C_{EES} (2.7) of a necessary BES should be identified. The economic balance depends strongly on the power P_{EES} and the energy E_{EES} of the optimal BES, and can be calculated by Eq. (2.10).

$$C^{I}_{EES} = \alpha_{EES}\, P_{EES} + \beta_{EES}\, E_{EES} \tag{2.6}$$

$$C_{EES} = C^{I}_{EES}\,(1+b_1)\sum_{k=1}^{T}\frac{1}{(1+i)^k} \tag{2.7}$$

$$C_{CON} = \alpha_{tar}\, P_Z \sum_{k=1}^{T}\frac{1}{(1+i)^k} \tag{2.8}$$

$$C_{InvD} = \sum_{l=1}^{N}\left(K^{I}_{Inv,l}\sum_{k=1}^{D(Inv^l)}\frac{1}{(1+i)^k}\right) \tag{2.9}$$

$$K_{Ben} = K_{CON} + K_{InvD} - K_{EES} \tag{2.10}$$

where: P_{EES}, is the power in kW, E_{EES} is the energy of the BES in kWh; α_{EES} and β_{EES} are specific power (€/kW) and energy (€/kWh) prices of the BES; α_{tar} is the

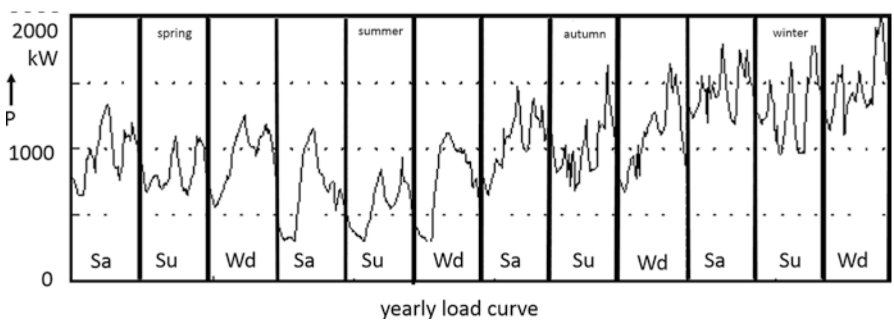

Fig. 2.11 An example of a yearly load curve

coefficient containing the tariff connection cost of power; p is the discount rate; T is the service life; β_{ex} is the coefficient containing the factor of the exploitation in the cost of the storage and C_{Ben} is the total cost benefits.

It is known from practical experience that the service life (T) of BES reflects on the battery life, and this depends on the operation mode of the BES and its technology. If the battery is handled with care, a T value of about seven to 10 years can be expected (a maximum battery storage T of 17 years has been reported[3]). However, this 7–10 year operation is less than one-third the life of other network equipment, e.g., cables, transformers and circuit breakers, and, therefore, the BES is relatively expensive when the discount calculation is taken into account. On the other hand, the discount calculation is necessary when the different scenarios of expansion planning are compared.

Regarding the constant values of the coefficients α_{EES}, $\beta_{EES,}$ α_{tar} and β_{ex}, the power and energy of the optimal storage depend on multiplication of the values service life *SL* and discount rate *p*. The optimization procedure is given by Eq. (2.11):

$$\Lambda\left(BES_{opt} : BES_{opt} => BES_{i} \rightarrow C_{Ben} = \max\right) \tag{2.11}$$

$i \in N$

where: BES_{opt} is the optimal BES, C_{Ben} is the benefit of the optimal BES and N is the number of elements in the set of storage.

The procedure for determining the optimal storage, e.g., corresponding to the yearly load curve given in Fig. 2.11, is shown in Fig. 2.12. The resulting benefits curve is shown in Fig. 2.12a. The tariff-benefit curve and the BES cost curve are

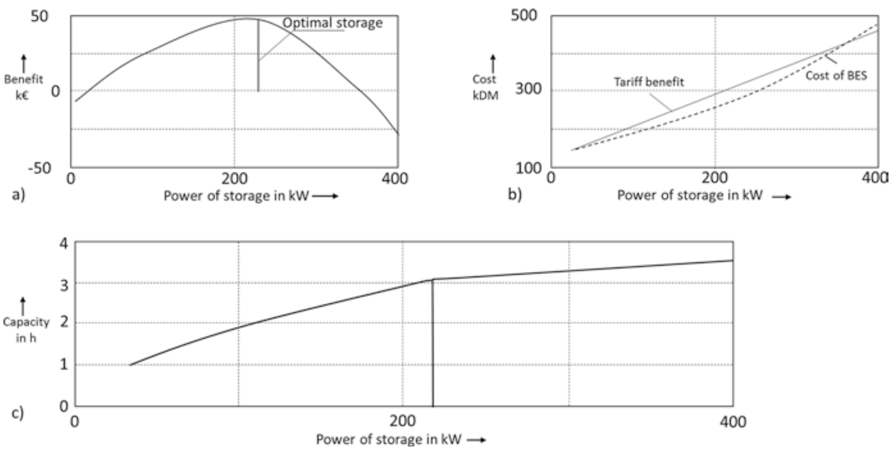

Fig. 2.12 Determining the optimal storage for the yearly load curve given in Fig. 2.11[4]

[3] Lifetime or service life (SL) depends strongly on the storage technology (also see Table 2.5).

[4] Results of a study carried out by the authors in 1994.

presented in Fig. 2.12b. The tariff benefits are shown by a continuous line, and the cost of BES is shown by a dashed line.

The benefit curve shown in Fig. 2.12a has only one maximum. The storage for which the benefits function reaches maximum is the optimal storage and is indicated by a vertical line in Fig. 2.12a. The storage capacity, computed using the yearly load curve, dependent on the storage power is shown in Fig. 2.12c. The optimal capacity energy of the storage corresponds to the optimal power, and it is indicated by a vertical line in Fig. 2.12c.

The optimal storage in this particular example has a nominal power of about 200 kW and the capacity of about 3 h, which correlates to 600 kWh of energy.

B: Determination of the Storage Module

Unification (assortment reduction) of rated quantities of the network elements and devices is an important factor for simplifying the exploitation of a power network. The power utilities have to keep equipment in reserve to be able to provide a quick exchange of elements after disturbances. The cost of these reserves depend on the level of unification.

The general problem of unification is to select the assortment of a given type in such a way that the total costs of investment, exploitation and reserve are minimal. To solve this problem for BES, it is necessary to determine the optimal sizes of an EES module for a particular network or network type.

A sensitive analysis is useful to determine the optimal storage module. First, the optimal storages have to be computed for the measured load curves, and then those sizes have to be standardized. In general, the modularization effects the expansion of the storage costs, and the target is to find a module size that makes it possible to minimize the cost increase for each scenario analyzed. The idea of unification is shown graphically in Fig. 2.13.

Unification of the storage size was carried out using the following algorithm:

- create the set of optimal storages for which the unification will be performed,
- group the optimal storages according to their types—sum up storages with the same value of power and energy,

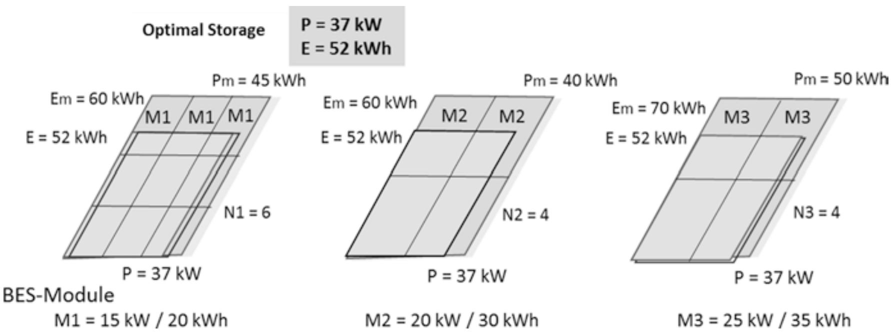

Fig. 2.13 Storage size unification process [21]

- propose a storage reserve equal to 1 % for each type of storage; at least five modules for each types of storage are necessary.
- propose a non-linear function to describe the converter costs which are dependent on converter power,
- determine the power and energy of the storage module for which unification will be performed, and
- perform unification computations whose result is the sum of the costs of optimal storages plus the storage reserve before the unification and the cost of all modules of the storage defined, taking into consideration its storage reserve after unification.

The unification procedure is given by Eq. (2.12) [22].

$$\Lambda\left(\mathrm{Module}_{\mathrm{opt}} : \mathrm{Module}_{\mathrm{opt}} = \mathrm{Module}_{\mathrm{i}} \rightarrow \mathrm{C}_{\mathrm{UNIF}} = \mathbf{min}\right) \tag{2.12}$$

i ϵ M

where: Moduleopt is the optimal module of BES, K_{UNIF} is the cost after unification and M is the number of considered modules of storage.

Three sets of planning data were used as an example for the unification procedure: German measurement data and Polish measurement data, both representing a typical urban distribution network; and model data obtained from the LOAD-MODEL program [23].

The general characteristics of the input data are given in Table 2.6.

The analyzed German network consists of ten medium voltage nodes; the Polish network has eight medium voltage nodes; and the modeled network has ten medium voltage nodes. The values of the average power are in the range 216–1997 kW in the German network nodes, 38–264 kW in the Polish network nodes and 59–444 kW for the network modeled with synthetic load curves.

Table 2.6 General characteristics of the input data

Type of data	Number of nodes	Name of node	Medium power in node, kW	Minimum power in node, kW	Maximum power in node, kW
German	10	n1	1049	710	1294
		n2	765	390	1154
		n3	1997	935	2931
		n4	910	281	1746
		n5	216	47	436
		n6	421	171	670
		n7	1002	561	1465
		n8	1097	904	1325
		n9	711	140	1948
		n10	1529	1263	1963

Table 2.6 (continued)

Type of data	Number of nodes	Name of node	Medium power in node, kW	Minimum power in node, kW	Maximum power in node, kW
Polish	8	p1	125	78	215
		p2	70	28	108
		p3	133	2	242
		p4	39	22	58
		p5	264	173	375
		p6	38	12	90
		p7	131	61	194
		p8	101	26	156
Model	10	m1	400	178	547
		m2	210	143	300
		m3	283	197	409
		m4	313	217	423
		m5	231	137	360
		m6	213	133	287
		m7	444	317	581
		m8	113	72	156
		m9	229	106	337
		m10	59	27	92

The following additional assumptions for all three networks were made:

- period of planning—20 years,
- yearly load growth—either 1, 2 or 3 %,
- time of storage service—6, 7, 8, 9 or 10 years, and
- discount rate—8, 9 or 10 %.

Due to the computations performed for all combinations of the values mentioned above, about 900 optimal storages were obtained for each of the nodes. In order to obtain the number of optimal storages for a particular data set, one has to multiply 900 by the quantity of nodes present in these particular sets of data.

The power of optimal storage in most cases did not exceed 10 % of the maximal power-peak value in the network node. Generally, the longer the period of economical exploitation (here time of storage service), the bigger the expected size of the BES. However, with the growth of the discount rate, the power and energy of optimal storage decrease slightly. The capacity of optimal storage, defined as a ratio of energy to storage power, is in the range of 0.67 and 2.39 h. This data and the information from converter and battery producers are authoritative for the pre-selection of a module set.

The reference BES cost K_{REF} for the comparison of the results is introduced. This cost is computed as the sum of all storage costs during the whole planning period of 20 years. A discount method was used to sum up the costs.

The reference costs of optimal storage together with the storage reserve are:

- for the German power network data—2.76 million EUR,
- for the Polish power network data—0.61 million PLN,[5] and
- for the model power network data—0.22 million EUR.

The reference cost for the German power network is about ten times higher than the reference costs for the Polish and model network. This correlates well with the values of the maximum power in the networks‘ nodes (see Table 2.6).

The results of unification computations are presented below in Table 2.7 and in Fig. 2.14. The set of preselected modules are listed in column 2. The costs after

Table 2.7 Storage module unification results

Case Number	Parameters of storage power/energy	Costs after unification					
		German		Polish		Model	
	kW/kWh	Mln EUR	k_{REF} in %	Mln PLZ[a]	k_{REF} in %	Mln EUR	k_{REF} in %
1	5/10	3.25	117	0.48	77	0.35	157
2	10/10	2.26	81	0.35	57	0.29	130
3	10/15	1.90	68	0.32	53	0.24	107
4	15/15	1.66	60	0.30	49	0.23	102
5	15/20	1.46	53	0.29	48	0.21	93
6	15/25	1.46	53	0.30	49	0.20	89
7	15/30	1.53	55	0.31	51	0.20	91
8	20/25	1.24	44	0.26	43	0.19	86
9	20/30	1.23	44	0.27	44	0.18	84
10	20/35	1.26	45	0.28	46	0.19	86
11	20/40	1.32	47	0.30	49	0.20	91
12	25/35	1.24	44	0.31	51	0.21	98
13	25/40	1.25	45	0.32	53	0.22	100
14	30/40	1.26	45	0.36	59	0.24	109
15	30/45	1.26	45	0.37	61	0.25	111

[a]PLN – Polish Zloty.

[5] Corresponds to about 0.15 Mio €.

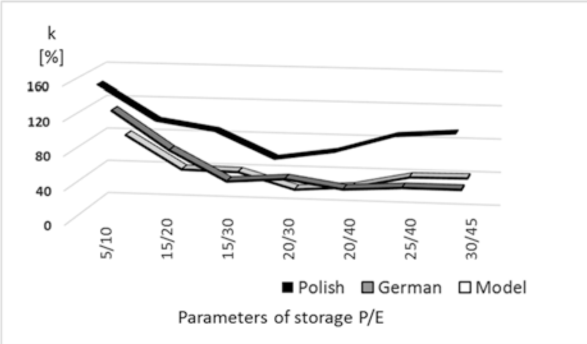

Fig. 2.14 The course of coefficient $\boldsymbol{k}_{REF}$ for German, Polish and model data

unification for the German, Polish and model data are given in columns 3, 5 and 7, respectively. The values of a coefficient k_{REF}, describing the percentage value of costs after unification in contrast to reference costs, are shown in the columns 4, 6 and 8.

The optimal size of the BES module is 20/30 kWh for the German and model data, and 20/25 kWh for the Polish network. We can see that unification of the storage size causes a large decrease in the global storage costs in all of the cases analyzed (up to threefold).

The course of the optimization curve is especially flat for the German data with larger storage sizes. The optimization curves for the Polish and model data have a more clearly defined minimum. Taking this into account, the choice of the optimal module for the German network depends more on the network structure and can differ from one power utility to the other.

C: Integration of Storage into the Distribution Planning Process

The objective of power utilities is to meet the electric energy needs of customers as economically as possible, with the required degree of reliability and quality. Expansion planning, which is a continuous task of these utilities, helps them reach this objective. It is decisive for power system optimization and consists of a sequence of network expansion scenarios for the future, usually 20 or 30 years.

On the medium voltage level, the distribution systems were initially planned as a loop, but most of them are afterwards operated radially. The loop construction is preferable from the reliability point of view, while the radial operation reduces the operation and protection complexity of loop systems.

The load growth is an important parameter when planning expansion. The network apparatus (cables, overhead lines, transformers) must be designed to take the peak load into account. The yearly load growth has slowed in recent years so that it is lower than previously and now amounts to 0.5–2 %. This requires changes in the planning methodology and a more careful planning of network expansion, which in turn affects the new planning scenarios [22].

In reality, the supply to customers has a characteristic daily cycle pattern. A power peak at noon and a lower demand at night (typical load curve for central Europe) cannot be avoided by changes in the network configuration. For this reason, several utility management techniques for peak load leveling are in use, such as power importation, demand-side management controlled by economic incentives or penalties and various energy-storage systems.

In principle, energy storage devices are used by the utilities to convert economical off-peak electrical power into other forms of energy from which electricity can be regenerated during periods of peak-power demand.

The influence of the storage devices on the expansion plans should be analyzed parallel to the network planning process. So the planning with energy storages requires an integration of new tools, such as load-curves forecasting, energy-storage models and storage-optimization methods with horizon planning of the power-network expansion. This only leads to the recognition of the usability of optimum storage before an expansion decision is made. Based on the developed models, the new network-planning procedure using dynamic programming can be applied which uses the simple property of multistage decision processes given by Bellman [24]. It is claimed that "an optimal policy has the property that whatever the initial state and initial decision are, the remaining decision must constitute an optimal policy with regard to the state resulting from the first decision". The elements of this three-step process are: optimal storage dimensioning in the network nodes, ranking of the nodes and storage placement in the horizon planning. The three steps of a developed procedure are shown in Fig. 2.15. The investigations do not depend on the kind of storage, but parameterization and calculations are only done taking into account battery storage, because this is the only industrially tested storage technique currently available in this range of power.

The planning process starts with the optimization of the storage dimension S_l in the l = 1 … m network nodes (step 1). It follows the procedure as given previously in this chapter and leads to the solution of Eq. (2.13):

$$\underset{l=1..m}{\forall}\left\lfloor S_l(P_l, E_l)\right\rfloor \Rightarrow f(C_l) = \min_{l=1..m}(\Delta C^{B}_{l}) \tag{2.13}$$

where: m is the number of the nodes in the analyzed network

$$\Delta C_l^B = \sum_{k=1}^{T}\left[B_k(\Delta E) + B_k(\Delta P) + C_{k,P_l}\right](1+i)^k \tag{2.14}$$

$B_k(\Delta E), B_k(\Delta P)$ are the benefits to energy and power losses, C_{r,P_i} is the tariff benefit for the peak shaving, P is the discount rate and L is the service time of BES.

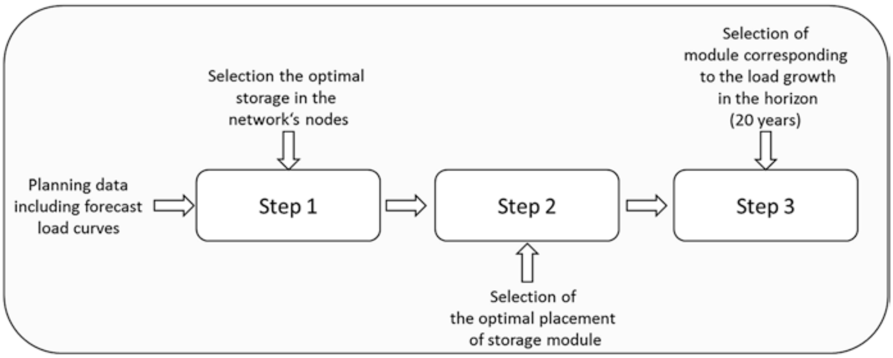

Fig. 2.15 Network planning with BES as a dynamic programming problem

The use of the BES in one of the loop's nodes influences the parameters such as the maximal load, the load factors themselves and the neighboring nodes. The level of influence depends on the correlation of storage size and times of peak-load behavior in the loop.

The order of the nodes in a distribution network loop can be determined by analyzing the peak-shaving aspects caused by the optimal storages selected previously. For this reason, the second step yields the order Γ of the nodes, which corresponds to the location's preferences of the different storage. Equation (2.15) describes this process when only the cost benefits have been taken into account:

$$\Gamma = \underset{\max,\, i=1..m}{\mathrm{sort}} \left\{ f(C_i) \right\} \tag{2.15}$$

If some other criteria needs to be considered during the ordering process (e.g., peak shaving in the neighboring nodes or peak shaving in the main station), a multicriteria decision has to be made.

The third step of the algorithm is a recursive placement of the storages corresponding to the order Γ, expected overload Po in the planning year, and the cost balance between costs of storage C and cable or overhead line C^L. This process, done separately for each loop M, corresponds to Eq. (2.16):

$$\underset{j\in M}{\forall}\left((E_j, P_j) \Rightarrow E_j^S = \sum_{i=1}^{m_j} E_j^i;\; P_j^S = \sum_{i=1}^{m_j} P_j^i \right) \tag{2.16}$$

subject to the set of constraints of the form:

$$E_j^S \geq E_j \tag{2.17}$$

$$P_j^S \geq P_j \tag{2.18}$$

$$C^L > C^S\left(E_j^S, P_j^S\right) \tag{2.19}$$

with explanations in the text.

A permissible overload Pj can be detected by analyzing the daily load in each of the loops j = 1 … m. The choice of the expansion strategy follows economic criteria. One of two strategies is used to avoid overloading:

- Installation of one or more distributed energy storages in the overload loop B and G, in the order corresponding to the node ranking Γ, or
- Reinforcement of the network using parallel cables of the same cross-section in the overload locations C.

A system of programs called GENPEX (*G*raphical *E*lectric *N*etwork *P*lanning *Ex*pert System) is used for the interactive planning of the distribution network, and it is extended for computation with energy storage. Additionally, the neural-network load-prediction model and optimization- storage model are implemented in this software system. The GENPEX database is prepared so that the characteristic of loop nodes using twelve characteristic daily load curves is possible.

The expansion planning with BES is shown in an example. An expansion scenario is computed for an existing 10 kV network. Starting in the year with the peak load in the networks loops *G, B* and *S* (see Fig. 2.16b), a 1 % yearly growth of load has been set.

The load curves in the nodes are predominantly urban-specific. The invariability of load curves in the network nodes during the planning period was assumed. Moreover, the following is given:

- Time of service (ToS) for battery subsystem of 8 years;
- ToS for cable and other BES subsystems of 30 years;
- specific cost of BSE: 580 $/kW and 260 $/kWh:
- specific cost of 10 kV/150 mm^2 cable of 160 $/km;
- discount rate of 8 % and discharge rate of BES of 80 %.

The expansion scenario uses a 20 kW/35 kWh-module BES and was computed using GENPEX. The results of the computation are presented in Fig. 2.16. The planning situations for the years seven and eight are traced in the geographically oriented Fig. 2.16a. The loops in Fig. 2.16b are also shown in an unfolded form for the visualization of time expansion of the network.

One can see in Fig. 2.16a that storage modules (triangles) are situated in different nodes of the loops because of the distributed plan for BES. In the loops *B* and *G*, the storages shifted the cable investment only once in the left and right part of both loops (Fig. 2.16b). The overloaded part of the loops, resulting from the yearly load growth, is always the cable parts that are close to the main station, for example, B1. We can see that the optimum storages selected using the order Γ are also situated far away from this part (e.g., B6, B9, G4) and that they influence the load flow in the loops in order to avoid overload.

It is important from the economic point of view that the modules remain in operation for eight years. A storage shifting into the other node is often required during this time period. For example, the three modules of BES from node G4 can be relocated in year seven to node B9. Another possibility corresponds to the five modules stored in node G2, which can be relocated to node B12 with a time break of 2 years. It is also certainly possible to manage single-module exchange, but this topic will not be discussed in this chapter.

A total of 35 BES modules were used in this network over a 20 year period, and the total combined time of use is 44 years. The maximum total power of the storages appears in year nine and is 400 kW, which corresponds to about 3 % of peak power of the loops analyzed.

The use of BES does not worsen the reliability indices of the power network. The reliability study has shown that the use of small decentralized module-battery storages (MS; see Fig. 2.17) improves the reliability indices compared to the other possible expansion measures, for example, diesel generator (DG; see Fig. 2.17).

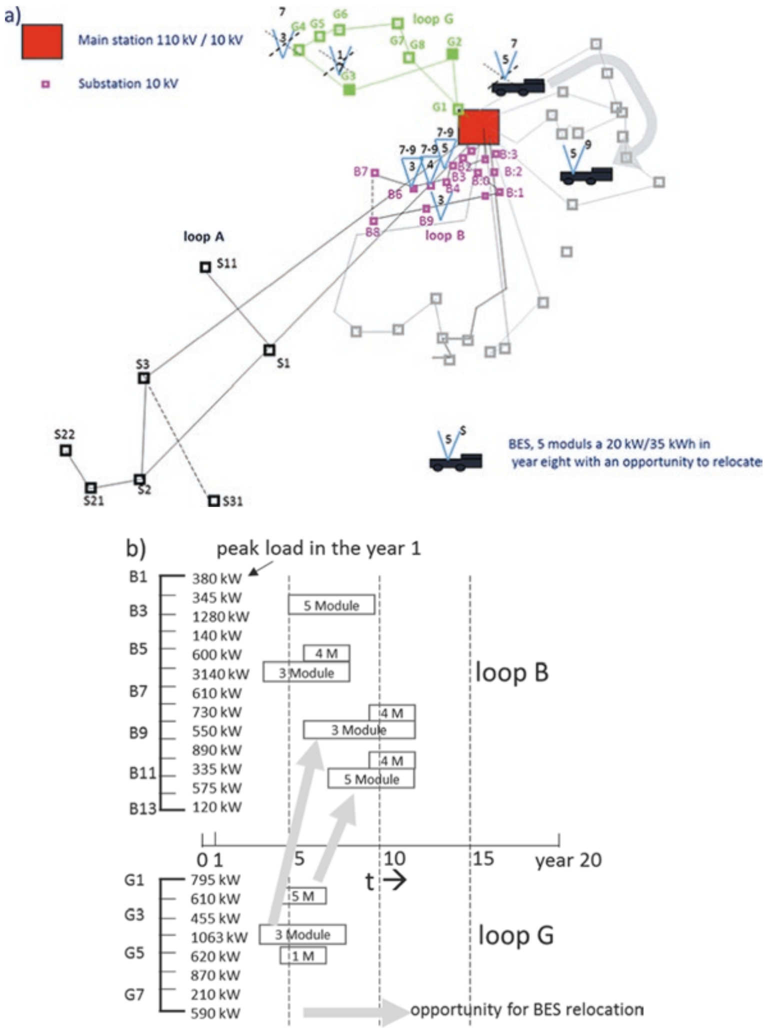

Fig. 2.16 Planning example: (**a**) network plan with dislocated module BES for planning year seven, eight and nine, and proposal for moving BES, (**b**) network loop expansion in a time horizon of 20 years and using module BES

2.3.4 Standardized Models of BES Using the Surface and Interface Structure (SIS)

An example of a detailed concept of the surface and interface structure is presented exemplarily in this chapter by modeling two types of BES. The first is a classic lead-acid battery and the second is a storage unit with higher energy density, namely a high-temperature battery (NaS). Today, Li-ion batteries are extensively used in

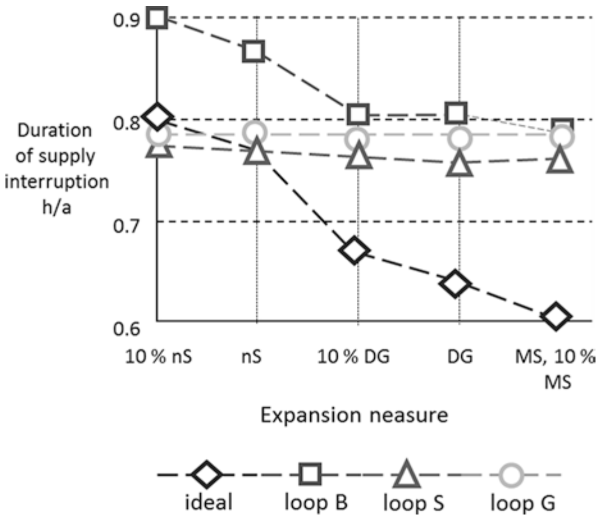

Fig. 2.17 A comparison of supply-interruption duration for various expansion measures

BES for the smart grid because they can be produced with high capacities. This battery type offers high operating voltages in comparison to other batteries, such as lead-acid batteries and sodium-sulfur batteries. Other benefits of these batteries include light weight and compact size, which will augment their adoption into the energy-storage system. The methodology presented here for the two battery types can also be used for the Li-Ion battery.

A: The Lead-Acid Battery Model

A simplified model of battery integration was used as a basic structure for the storage unit [25]. It is based on the main assumption that the battery, used primarily for peak-load shaving, will be brought again to the state of full charge after a 24-h cycle. Therefore, the losses for chemical into electrical energy conversion and self-discharge losses can be merged together.

The most important factor of the PhS of the battery model is its state of charge (SOC). The internal behavior of the battery is based on the dependence between charge and discharge power and the SOC and is controlled by the charge-control unit. The bi-directional flow of the energy is ensured through the inverter, which, together with the transformer unit, comprises the NCS for the battery-storage unit (Fig. 2.18).

The demands of energy are in the form of active power, which should be delivered from the battery to the network. This demand is transferred by the interface inside the battery model, so that the battery sees it as a discharging command. The model examines its SOC and, depending on it, provides the desired and/or the possible energy quantity. The power during discharging is nearly constant up to the adjustable threshold value of, for example, 30 % SOC. When this level is reached, the battery shuts off the discharge process in order to avoid excessive discharging.

The battery model disposes of the charge-control unit, building its IOS surface. The unit is responsible for the charging process, so that there is no charge permission

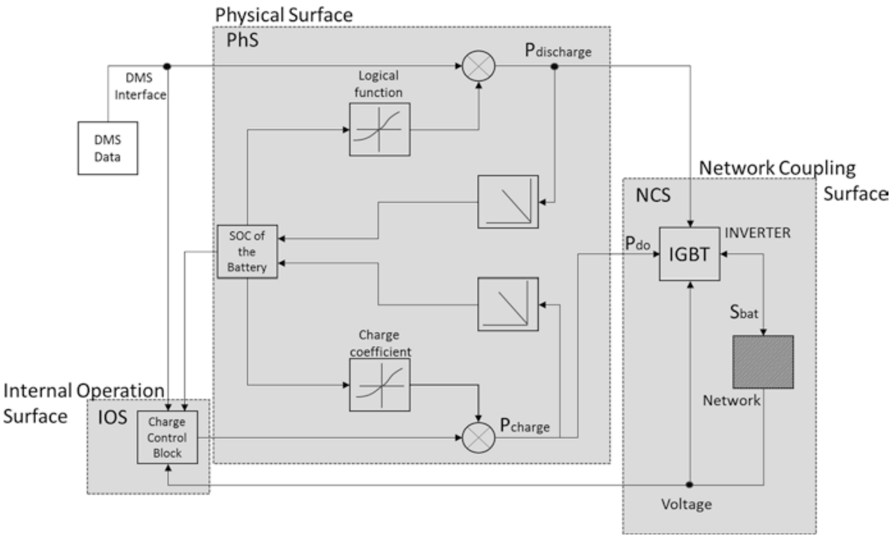

Fig. 2.18 The integration model of the lead-acid battery unit with integrated SIS

required from DEMS. However, the charging process is only possible when all of the following circumstances are fulfilled: the battery is not in a fully charged state, the voltage amplitude at the connection node in the network lies within the allowable band and there is no energy demand from the DEMS. During the process, the charge coefficient, which reflects the behavior of the inner battery resistance, is considered because it slows down the energy ingestion at high values of the SOC.

The battery-unit model is coupled with the network by an inverter and a transformer—the NCS surface of the unit. The inverter disposes of the voltage-control unit, which allows for voltage- amplitude control using reactive and/or active power injections. This control is made within various limits, drawn from the apparent power of the transformer, the maximal active power that can be delivered by the battery and the cos φ of the inverter module. The inverter losses are considered to be 3.5 % of the apparent running power.

B: The High-Temperature Battery

The high-temperature battery is a storage system with high energy and light weight. The operation temperature of the system is 250–350 °C, which requires a very good insulation of the system and the presence of a controlling unit, which observes and controls the battery temperature. A light weight is achieved through the usage of light alkaline metals for the negative electrode. It can be lithium, sodium or an aluminum dioxide that contains sodium ions, e.g., solid electrolyte aluminum. A high-temperature unit with a sodium-nickel-chloride battery is presented in this section.

A long-term model of a 30-Ah battery is presented exemplarily below. The battery consists of 220 cells connected in a series. The maximal power of this unit can rise to 17 kW by using the idle voltage of a single cell of about $U_0 = 2.58$ V.

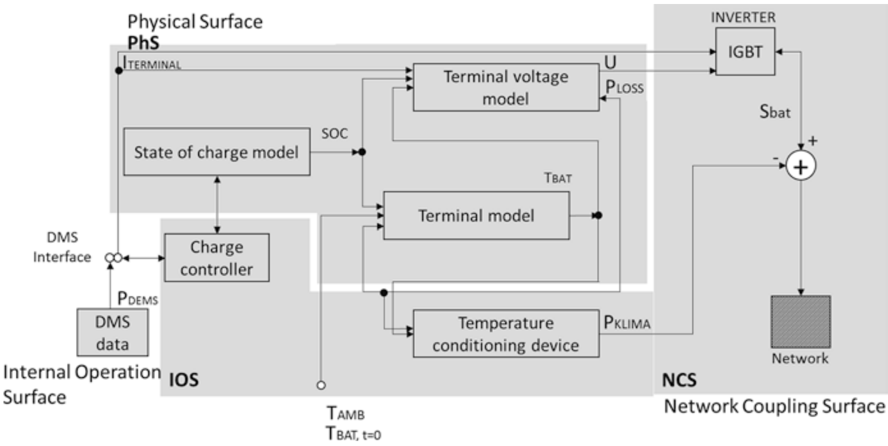

Fig. 2.19 Model of the high-temperature battery unit with integrated SIS

The model consists of four interconnected sub-models: the SOC model, the terminal voltage model, the thermal model and the model of a temperature conditioning device. All of the sub-models are then embedded in NETOMAC®-Macro software, which is additionally furnished with other interfaces and standardizes the model according to the structure shown below in Fig. 2.19.

The DEMS demands energy in the form of active power that should be delivered from the battery to the network. This demand is transferred by the interface to the inner battery-current demand, so that the battery sees it as a discharging command with the constant current. The battery can work between a fully charged state (30 Ah) and a null charged state (0 Ah). When the level of discharge is reached, the battery shuts off the discharge process. The model examines its SOC and, depending on this, the physical internal processes are simulated in the terminal voltage model and thermal model. The power during discharging is not completely constant, because of the strong influence of the internal losses (inner battery resistance), which, in turn, depend on the battery's SOC and its internal temperature.

The battery model additionally disposes of the charge-control unit and the temperature-conditioning device, comprising its IOS surface. The former is responsible for the charging process, which is possible only when the battery is not in a fully charged state and there is no energy demand from DEMS. During the charging process, the controller prevents an override of the inner cell voltage, which can be dangerous for this type of battery. The battery temperature-conditioning device maintains the inner temperature of the battery at 250–350 °C. A temperature drop (caused by lengthy stand-by operation) to the minimum value (250 °C) turns on the heating unit (about 100 W) to keep the temperature of the battery at this level. When the temperature approaches 350 °C (in a long charging or discharging process), the cooling unit turns on. The electrical demand of this unit is proportional to the maximal inner losses of the battery, which, in turn, depend strongly on the current demand. The electrical demand caused by the conditioning device is then subtracted from the total power produced by the battery (Fig. 2.19).

The resulting energy is transformed through an inverter and feeds the network. The inverter and a transformer form the NCS surface of the unit. There is no voltage control and, if needed, the inverter allows for the cos phi to be set to some other constant value.

2.4 Storage Systems in Isolated Power Systems

2.4.1 Introduction

Chapter 1 discussed how the use of electric-energy storage (EES) for niche implementations can help justify future widespread application of this technology. One of the best examples for such niche implementation is the use of EES in an isolated power system (IPS). When an IPS is equipped with renewable generation, a stabilizing element, such as EES, is necessary for smoothing volatile generation and enables secure operation of the IPS system.

Different methodologies can be used for the optimal design of IPS systems, e.g., dynamic programming, mixed-integer linear programing and iterative methods [26]. In this chapter, two methods focused on EES dimensioning will be presented, explained and discussed:

1. A case-based method for optimal dimensioning of EES in an IPS systems using an iterative algorithm for optimal storage calculation and selected indices for storage-site approximation.
2. A multi-criteria method for planning IPS systems.

2.4.2 A Case-Based Optimization of Electric Energy Storage Size in an Isolated Power System

Optimal dimensioning of EES, in the range of MW, will be illustrated in this chapter using a specially constructed case study [27]. This case study addresses the planning phase of an IPS within which the optimal size of the EES must be determined. The optimal size or dimension of an EES is characterized by two storage parameters: storage power and storage capacity. For the optimal dimensioning of EES, the generic model of storage presented in Sect. 2.3 is useful. After determining the optimal parameters of a generic EES, a storage technology can be chosen according to the application investigated [28]. In the case study specified here, a battery type of EES was considered (see also Chap. 5).

The input data in the IPS analyzed are generation mix, demand and energy-storage range (see Fig. 2.20). The generation mix consists of a combination of conventional generators (e.g., diesel engine or micro gas turbine) and generators based on renewable sources (e.g., photovoltaic: PV and wind turbines) [26, 28]. The IPS load profiles for typical working days, and Saturday and Sunday were used to calculate

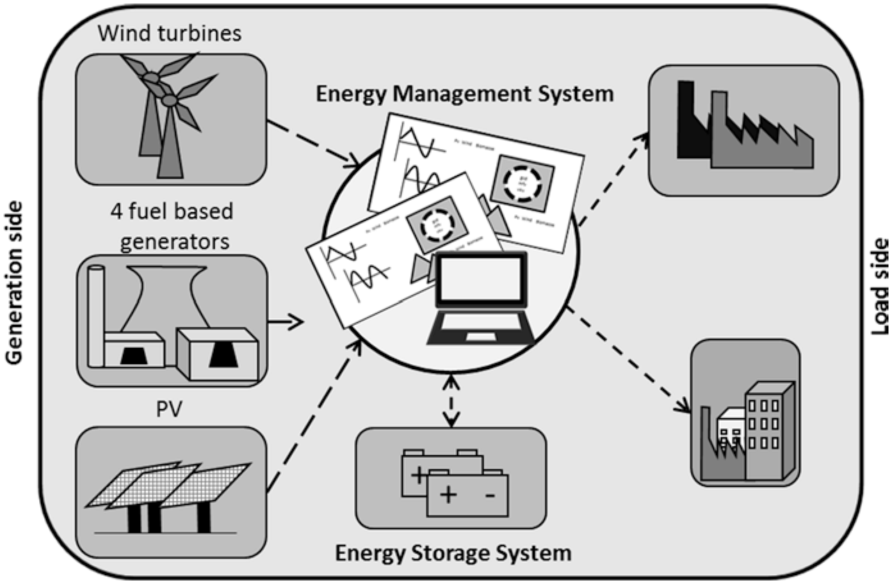

Fig. 2.20 Structural analysis of the isolated power system

the optimal schedule of generation. These profiles depict typical loads for industrial, residential and tertiary purposes. Additionally, through the data collected from solar irradiation and wind speed, it was possible to simulate the generation profiles of the plants based on RES.

Optimal Storage Capacity

The methodology for finding optimal storage parameters, in this case, power and capacity, is based mainly on the following procedure:

1. Set up an initial generation mix:
   i. Conventional generators can cover 60 % of the energy demand,
   ii. The PV and wind generators must be sized so that they cover the remaining portion of the load (considering a week-long energy demand)
2. Set up a time period of investigation. The investigation will be carried out for one typical representative week[6] in the year. The demand curves and generation profiles for wind and PV for the days in the representative week must be fixed.
3. Initial storage power is set up as 50 % of the basic load and four-hour capacity (about 15 % of the energy demand).
4. The optimal schedule for one week for both generation and storage, according to the given profiles (see step 2), should be found using integer linear programming [29].

[6] The representative week consists of five working days, each day with the same profile, and Saturday and Sunday. The week should be selected, depending on the region, in the maximal demand season. The necessary time profile's accuracy is ¼ h. The data for one year can also be used for this investigation, if they are available.

5. The capacity of storage will increase iteratively within the given range, and step 4 will be repeated.
6. The energy deficit in the IPS (the amount of energy that must be imported) is computed in each step, and the amount of RES power that was not fed into the grid is found. The aim of the optimization is to minimize both those values.
7. If the step of the storage capacity change is quite small, the accuracy of optimal storage determination will be high.

Case Study 1

In case study 1, calculation concentrates directly on optimal storage dimensioning considering the load curves for demand and generation—using the method mentioned previously—and will be carried out iteratively by increasing the storage capacity.

The results of such a calculation are presented graphically in Fig. 2.21. The following input data for case study 1 is fixed:

- max load—12 MW
- renewable generation
  - wind turbine—7 MW
  - PV—8 MW
- conventional generators—4 × 1 MW
- storage
  - capacity 4—6.5 h, with steps of 0.5 h
  - power 1—7 MW, with steps of 1 MW

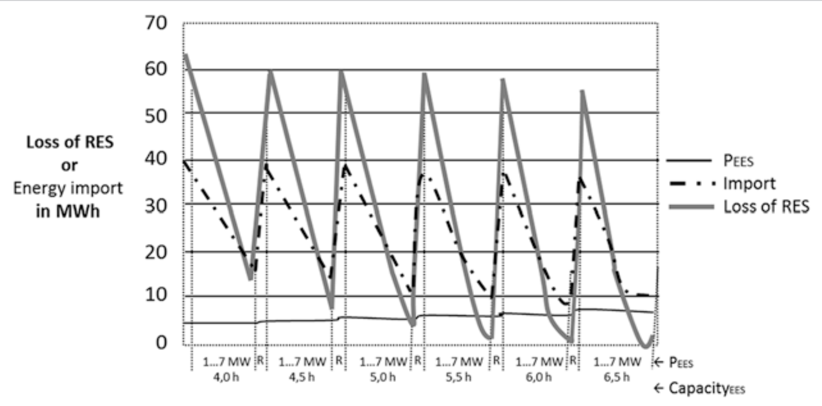

Fig. 2.21 Optimal power and capacity of EES. The result of iterative optimum search

The iterative algorithm was used in the investigation as follows:

```
for E_EES: = 4 steps 0.5. to 6.5
begin
   for P_EES: =1 step 1 to 7
   begin
      energy_schedule_for_week: = find_necessary_generation
(demand, generation, storage)
   end{P_EES}
end{E_EES}
```

The influence of storage parameters on the integration[7] of energy generated by RES was observed during the simulation. By increasing the storage capacity from 4 to 6.5 h (see black line in Fig. 2.21), the amount of electric energy generated by the RES that can be integrated into the IPS also increases. The dotted line in Fig. 2.21 illustrates the energy import, which decreases when storage capacity increases. The import of energy is reciprocally proportional to the integrated energy mentioned above. The minimal storage capacity that allows for all of the RES generated energy to be integrated into the IPS system during the test week amounts to 5.5 h (see Fig. 2.21, grey line by P_{EES} = 7 MW). However, it is still necessary to import energy into the IPS system with such storage capacity. This is simple to explain: The generation mix is too small to cover the full demand at all time periods. To avoid the import of energy, it is necessary to increase the size of the generators (e.g., nominal power of the wind generator). The new size for a wind generator that makes it unnecessary to import energy can also be found iteratively. Results of the corresponding calculation are presented graphically in Fig. 2.22. By powering up the wind generators to 11 MW (Fig. 2.22, grey line, step no. 5), the IPS system's own generators can cover loads fully every time (Fig. 2.22, black line) that the system reaches full autonomy.

Now, the new optimal energy storage size can be computed using the same methodology for the generation mix as before, but this time with an 11 MW wind generator. In this case, the optimal storage has parameters of: 8-MW power and 13-h capacity. With such a storage system, the IPS can also cover its own demand at all time periods. It should be noted that full integration of the RES inside the IPS was reached with smaller storage using 7-MW power and 5.5-h capacity, but with the necessity of importing energy.

[7] Energy integration means that the renewable generation quells demand. The surplus of renewable generation cannot be integrated directly and can, for example, be stored for feeding into the network when there is a generation deficit.

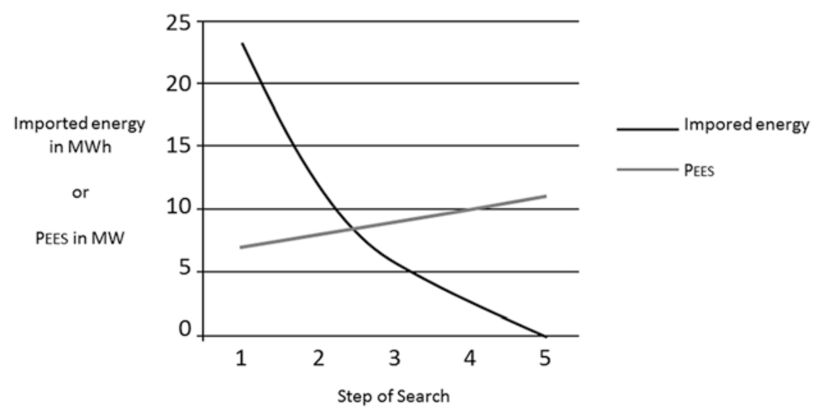

Fig. 2.22 Results of iterative optimization of wind generator nominal power for full autonomy of the IPS

Following the technical results, the economic calculations were carried out. Discounted costs C_{EES} of EES were calculated using the formula given in Eqs. (2.5) and (2.6). The discounted cost calculation for storage, import energy and losses was calculated for one week, taking into account a discount factor r = 5 % and a lifetime of the EES of T = 10 years [27]. The investment costs of generation were not considered in this calculation. The summarized cost index C_{index} is presented in Eq. (2.20).

$$C_{index} = C_{EES}^{week} + C_{import}^{E} + C_{loss}^{RES} \tag{2.20}$$

where:

- C_{import}—cost of imported energy for balancing the load,
- C_{loss}—cost of RES energy not integrated, and
- C_{EES}^{week} —weekly recalculated costs of storage [27].

The full integration of renewables in the IPS is reached at the cost index K_{index} and is equal to 84,380 Euro which corresponds to about 76 €/MWh. However, in order to ensure that the loads are always covered from local sources, a cost of about 158 €/MWh is needed, which presents a particularly high impact of storage costs on the total IPS energy costs. The results of this investigation show that full IPS autonomy is very costly, because the use of rather large storages is necessary in this system. This storage is only partially used (see also Fig. 2.24), which influences the economics.

Case Study 2

In this investigation, the IPS system given in Fig. 2.20 is first analyzed without considering EES. Only the generation and the demand profiles for one test week are considered. Two specific indices [30] that have an effect on storage dimensioning (sizing) indicated by the case study 1 investigation are calculated. These are

- the amount of unfed energy (not integrated into the IPS system) from RES, and
- the amount of imported energy.

These values are dependent on the time correlation between the load curve and RES generation curves and, taking into account the volatile RES generation, are stochastic. Smoothed (levelled) average values of these indices[8] can be obtained by simulating one week of IPS operation. Those values can be used further to approximate the storage power and capacity needed for the IPS analyzed. The unfed (not integrated) RES energy can be expressed by Eq. (2.21), while the imported energy can be calculated by Eq. (2.22):

$$E_{uf} = \int_{t=0}^{1week} ((P_t^{RES} - P_t^{Dem}) / P_t^{RES} \geq P_t^{Dem})dt \tag{2.21}$$

$$E_{imp} = \int_{t=0}^{1week} ((P_t^{Dem} - P_t^{Gen}) / P_t^{Dem} \geq P_t^{Gen})dt \tag{2.22}$$

where P^{Dem}, P^{RES} and P^{Gen} represent the power demand, the power generated by RES and the power generated by all generator curves, respectively, for a time period of one week.

Taking into account the peak import load expressed by $\max(P_{imp})$ and peak unfed power expressed by $\max(P_{uf})$, the storage parameters (storage power P_{EES} and storage capacity h_{EES}) can be estimated using Eq. (2.23):

$$\begin{aligned} P_{EES} &= \max(\max(P_{imp}), \max(P_{if})) \\ h_{EES} &= \max(\max(\frac{E_{imp}}{P_{imp}}), \max(\frac{E_{uf}}{P_{if}})). \end{aligned} \tag{2.23}$$

[8] By using of one year data sets, it is to be expected that the indices will be more levelled and more useful as a starting point for exact calculations.

Figure 2.23 provides the graphical results of the IPS operation for the data given in case study 1. The demand curves for one week (area in grey) and charge/discharge of the optimal storage 8 MW/13 h (area in black) are shown in this figure. Corresponding to this calculation, the storage state of charge (SOC) curve is presented in Fig. 2.24. Using the methodology given

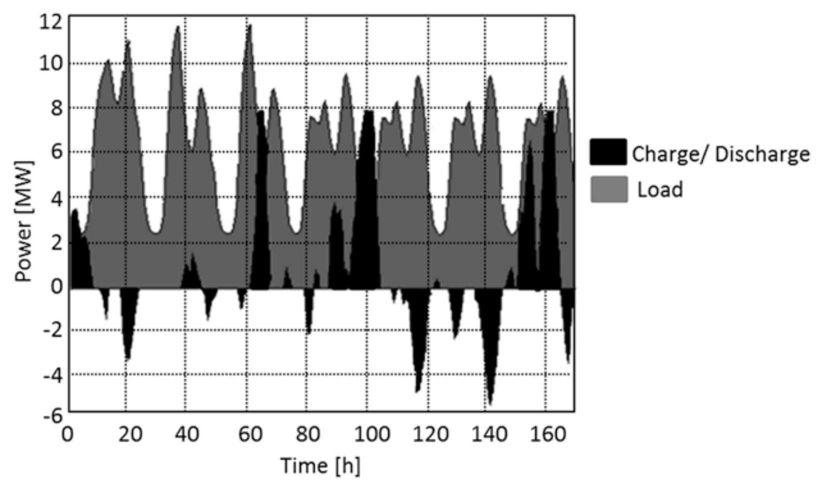

Fig. 2.23 Load curve for the test simulation and corresponding storage-operation diagram

Fig. 2.24 8 MW/13 h EES. State of charge (SOC) for one test week

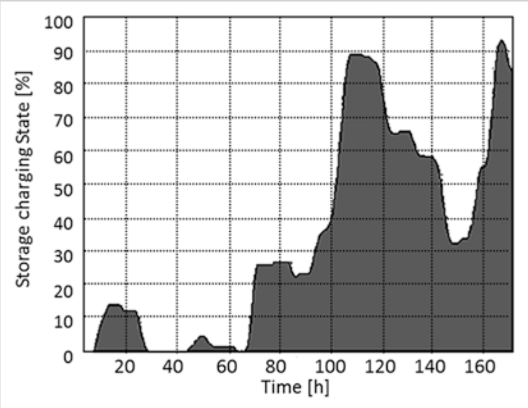

Table 2.8 Approximate storage size

Generation mix	Imported energy in MWh	Unfed RES energy in MWh	Approximate storage size MW/h
Demand 12 MW Wind 7 MW PV 8 MW CHP 4 MW	133	71.8	6/11 or 6/22
Demand 12 MW Wind 11 MW PV 8 MW CHP 4 MW	109	199	6/13 or 11/18

by Eqs. (2.21)–(2.23), the calculated storage sizes are depicted in Table 2.8. The resulting EES power values for the first-generation mix (wind generator 7 MW and energy import into IPS necessary) is 6 MW for both indices: the unfed RES energy and the imported energy. The corresponding values are 6 MW and 11 MW for the second-generation mix (wind generator 11 MW, no energy import into IPS). Therefore, the resulting storage size is 11 MW and 18 h and is higher than the storage size we calculated using the iterative methodology in case study 1.

The over-dimensioning of the storage size in this investigation can be explained by the use of a time-dependent integration of stored energy which allows for the assignment of the storage SOC. This simple methodology, useful in this case, does not fully consider the time correlation between demand and generation curves. A full model simulation using mixed integer linear programing, as used in the optimization method proposed before, allows for a more precise sizing of the storage. However, the approximation method gives a very good and fast starting point for an iterative algorithm and makes it possible to find a quick global optimum.

Case Study 3

A comparison of costs for the optimal EES investigated and calculated above, taking into account different storage technologies [28], was carried out. The results of this investigation are given graphically in Fig. 2.25. The best result (minimal costs) was obtained for batteries and CEAS technologies, which was expected considering the size of the IPS and planned operation mode of the EES. The use of flywheels or super-capacitors may be very expensive, since these technologies are more suited for power-quality purposes and are not easily adaptable for IPS purposes (see also Chap. 5). Construction of a hydro-storage is, coresponding to the size needed, not realistic.

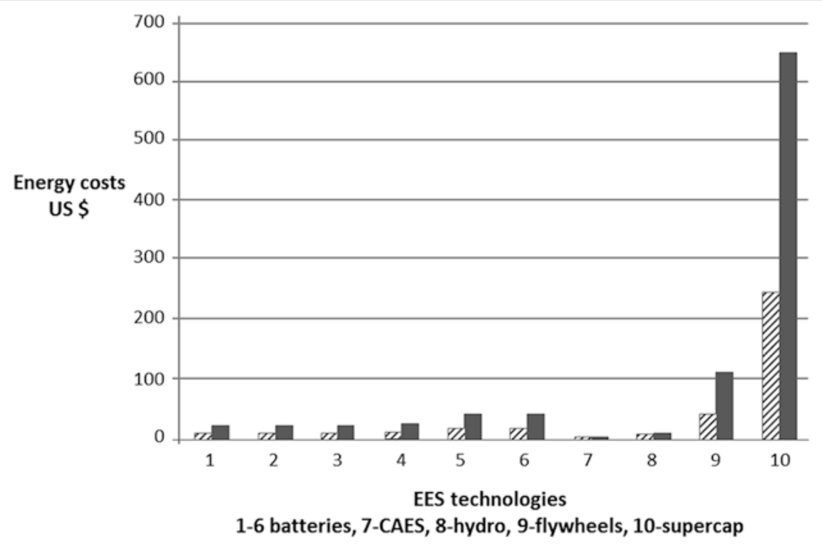

Fig. 2.25 Results of the economic comparison of ESS technologies for an IPS

2.4.3 Multi-Criteria Optimization of IPS

Multi-criteria decision analysis (MCDA) methods are used widely for planning and upgrading energetic infrastructures, such as power generators, transmission and distribution lines or storage systems, taking into consideration various criteria, such as economics, reliability and social issues. The MCDA analyses use various techniques for solving the optimum [Lombardi].

The MCDA can be divided in two categories: multi-objective decision-making (MODM) and Multi-attribute decision-making (MADM). The MODM is characterized basically by the existence of multiple and competitive objectives that have to be optimized against a set of feasible and available constraints. The analytic hierarchy process (AHP), which belongs to the category MADM, is one of the methods most used by the decision-makers for planning problems related to the energy sectors and, here especially, to micro-grids. It works by organizing the problem into a hierarchical structure in which the goal of the problem is set at the top level, the criteria

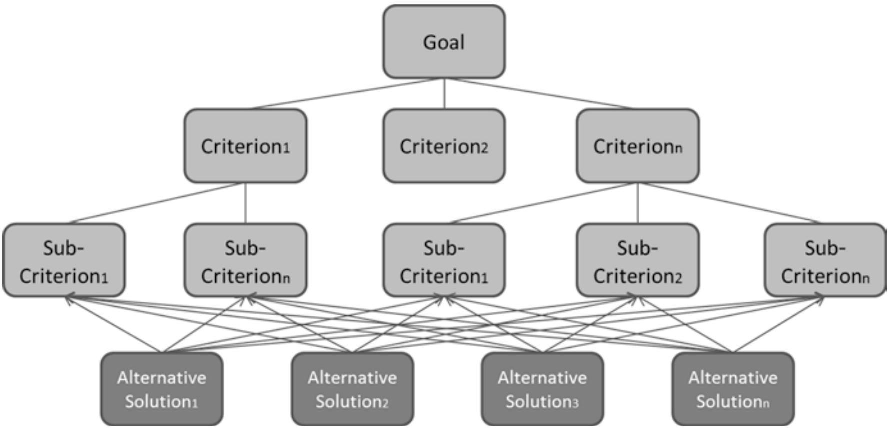

Fig. 2.26 Example of a hierarchy structure

and sub-criteria are set at the middle levels and the alternative solutions are set at the bottom level of the hierarchy (see Fig. 2.26). The aim of the AHP is to evaluate the alternative solutions according to a list of priorities which fulfil the main goal of the problem.

The AHP approach is composed of six steps. In the *first step* the objectives of the problem and the criteria considered have to be identified. In the *second step,* the problem is organized into a hierarchical structure, as depicted in Fig. 2.26. In the *third step*, the decision-makers, based on their own experience and knowledge, compare all the elements that belong to the same level in a pairwise fashion. The elements are compared by considering their order of importance. The Saaty scale is used to fill the order of importance (see Table 2.9). Based on the pairwise comparison, the n × n reciprocal judgment matrix **A** is set up, where n is the number of elements compared. In the *fourth step*, matrix **A**, the largest positive real eigenvalue λ_{max} and the corresponding eigenvector w (local priority vector) of the judgement matrix **A**are calculated for each reciprocal judgment with Eq. (2.24). The local priority vector establishes the ranking of local priorities among the elements within the same hierarchy level. In the *fifth step*, the consistency of each judgment matrix is checked.

In order to do this, firstly, the consistency index (C_i) is calculated with Eq. (2.25). Then, using Eq. (2.26), the consistency ration (C_R) is evaluated by rating the consistency index to the random consistency index (R_I), which is listed in Table 2.10. The random consistency index represents an average of the consistency index, which is obtained from randomly generated reciprocal matrices using the Saaty scale (1/9, 1/8, …, 1, … 8, 9). This varies according to the size of the matrix: For example, the random consistency index is 1.12 for a matrix with five elements. If the consistency ratio is smaller than 0.1, then the judgement matrix can be considered as consistent, otherwise, the decision-makers have to reevaluate the elements belonging to the same hierarchy level. After evaluating all the local priority vectors and proving that the judgment matrices are consistent (through steps three, four and five), then, in the *sixth step*, the global priority vector, which ranks the alternative solutions with respect to the main goal, is evaluated.

Table 2.9 Saaty scale for pairwise comparison

Intensity	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

Table 2.10 Random consistency index for corresponding matrix size

Matrix size	1	2	3	4	5	6	7	8	9	10
Random index	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

$$\begin{bmatrix} 1 & a_{12} & a_{13} & \dots & a_{1n} \\ 1/a_{12} & 1 & a_{23} & \dots & a_{2n} \\ 1/a_{13} & 1/a_{23} & 1 & \dots & a_{3n} \\ \dots & \dots & \dots & \dots & \dots \\ 1/a_{1n} & 1/a_{2n} & 1/a_{3n} & \dots & 1 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \dots \\ w_n \end{bmatrix} = \lambda \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \dots \\ w_n \end{bmatrix} \tag{2.24}$$

$$C_i = \frac{(\lambda_{max} - n)}{(n-1)} \tag{2.25}$$

$$C_R = \frac{C_i}{R_i} \tag{2.26}$$

Software Tool HOMER Energy®

The software HOMER Energy® [31] was used to evaluate the economic and environmental performances of the different IPS configurations that will be considered for the AHP process. HOMER Energy® was developed by the U.S. National Renewable Energy Laboratory (NREL) and can model the physical behaviors of micro-power systems and evaluate both their life cycle costs and their environmental impact (in terms of gasses emitted). In addition to the simulation of power systems, HOMER Energy® can also perform optimization and sensitivity analyses. HOMER Energy® can be used to model various micro-power-system configurations comprised of PV systems, wind turbines, combustion engines, river turbines and energy-storage technologies (batteries, flow batteries and flywheels). The micro-power system can be connected to the grid or operate in isolated modus. HOMER Energy® can consider both the electric and thermal loads. It can be proven through the simulation whether the micro-power system designed can supply the electric and thermal power according to the load and other constraints used by the designer. Moreover, the simulation also evaluates the life cycle costs (by evaluating the net present costs) of the system, as well as technical and environmental parameters, such as CO_2 emissions. Additionally, it can be used to compare different micro-power-system configurations to find the optimal configuration that minimizes the life-cycle costs.

Formulation of the Decision-Making Problem and Configuration of the IPS

A small IPS located in Siberia, Russia, was chosen as the case study for adopting the planning methodology developed. The IPS requires an annual electricity demand of 11,202 MWh with a maximum power demand of 3.0 MW. The highest and lowest electric power consumption occurs in winter and summer, respectively (see Fig. 2.27).

It is assumed that the electric load within the IPS was supplied by a diesel generator which, due to its age, should be replaced. The decision-makers have to evaluate

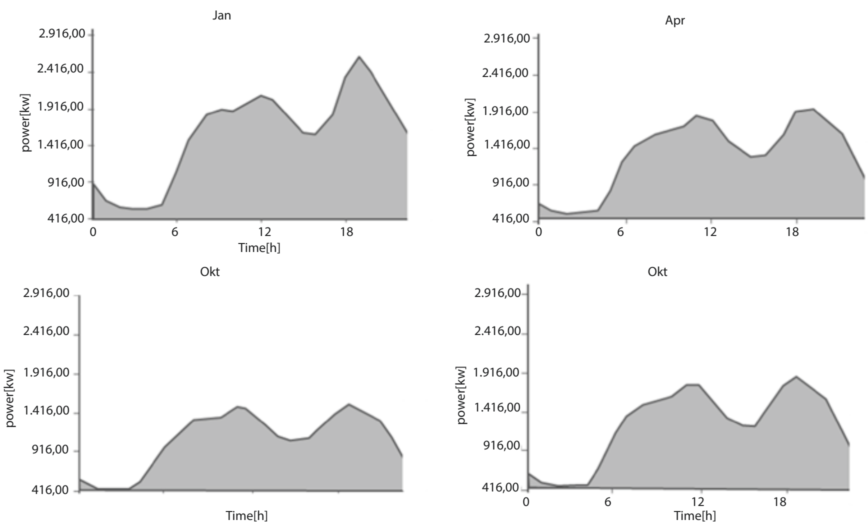

Fig. 2.27 Seasonal consumption patterns for the isolated power system analyzed

the best option (of power-system configuration) for upgrading the IPS. Three criteria will be considered by the decision-makers when selecting the best configuration: economic, ecological and social. The economic criterion is split into the investment cost (IC) and the cost of electricity (COE), while the ecological criterion is divided into CO_2, particulate matter (PM) and NO_x emissions.

The social criterion considers the creation of new jobs that can be generated by upgrading the IPS. The entire lifetime of the IPS will be considered for all the criteria. The first two criteria were evaluated using the HOMER Energy® software, while the evaluation of the social criteria is based on the technical study edited by the International Renewable Energy Agency (IRENA).

Four IPS configurations for upgrading the IPS were considered by the decision-makers: In configuration I, a diesel generator is considered as a replacement for the old one, while in configuration II the power is generated by a new diesel engine and a PV plant. Configuration III adds a storage system (battery plants) to configuration II. Configuration IV is similar to configuration III, with the additional possibility of generating electric power from wind turbines. The hierarchy structure for the best choice of the IPS is shown in Fig. 2.28.

Power Generators/Storage Characteristics and Energy Resources

The four IPS configurations considered reflect three different electric-power generation technologies and a storage system. The power-generator technologies are: diesel engine, wind turbine and PV plant, while a battery plant was considered for the energy-storage system. Such architecture does not consider the transformers used to increase and decrease the voltage before the power is transmitted and distributed to the loads. In order to integrate the power generated by the PV plant and the power discharged from the storage system into the AC network, 11–14 converters (400 Vdc–400 Vac), were considered. All the components analyzed can be selected from the library of the Homer® software.

Regarding the diesel generator, an engine with a nominal power capacity of 3200 kW and a maximal efficiency of 30 % was selected. The efficiency curve for

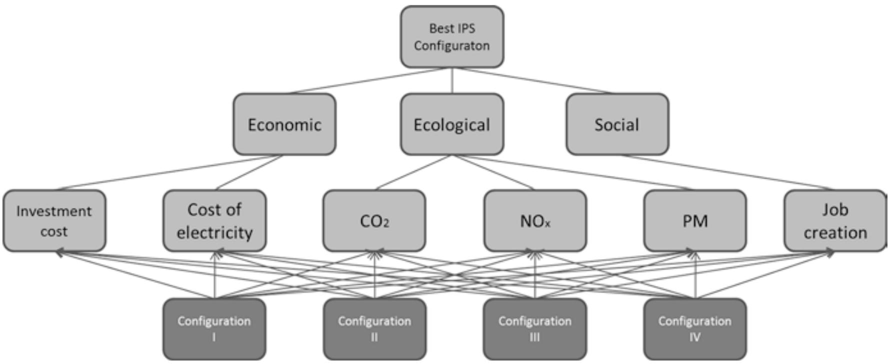

Fig. 2.28 Hierarchical structure for the choice of the best IPS configuration

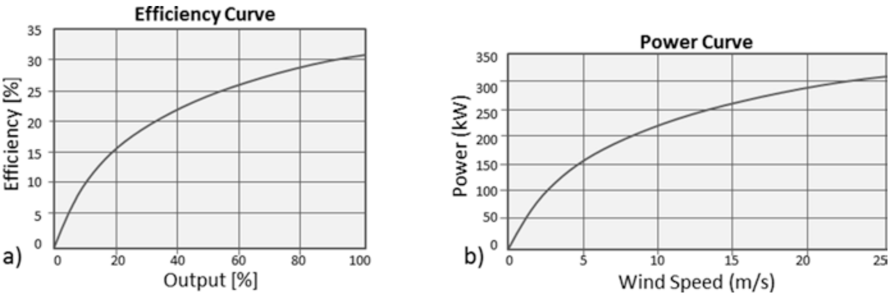

Fig. 2.29 Efficiency curve of the diesel engine (**a**); power curve of the wind turbine (**b**)

each power output of the diesel engine is shown in Fig. 2.29a. A flat plate polycrystalline PV plant without a solar tracking system and with efficiency at a standard test condition of 13 % was chosen. The Enercon E33 model was considered for the wind turbine. Such a model can generate up to 330 kW in the best meteorological conditions (see Fig. 2.29b). The battery selected has a storage capacity of 1 MWh with a maximal charge/discharge power of 1 MW and an all-round efficiency of 80 %. The technical and economical characteristics of the power generators and the storage system are shown in Table 2.11.

Table 2.11 Technical and economical characteristics of the generator and storage systems

	Diesel generator	Photovoltaic plant	Wind Turbine	Battery	Inverter
Nominal power [kW]	3200 [kW]	3200 [kW]	330 [kW]	1000 [kW]	300 [kW]
Storage capacity [kWh]				1000 [kWh]	
Number of units	1	1	1–10	1	11–14
Investment costs [€/kW]	700	2500	1515	1630	400
Maintenance & operation costs	0.1 [€/h]	100 [€/year]	2000 [€/year]	9200 [€/year]	
Lifetime	15,000 [h]	20 [years]	15 [years]	15 [years]	10 [years]
Hub height [m]			25		
Efficiency [%]	30	13		80	90
Minimal state of charge [%]				20	
Configuration I	√				
Configuration II	√	√			√
Configuration III	√	√	√		√
Configuration IV	√	√	√	√	√

Diesel-based generation is the power source most often used among the Russian IPSs. However, this energy resource is brought to the IPS via expensive transportation systems, such as boats, trucks or, in some cases, helicopters. This means that the electricity generation costs, in some cases, could reach a value ranging 500–2500 $/MWh. The integration of renewable energy sources, such as wind or sun, for these IPSs can influence the generation costs beneficially. However, the power technologies based on wind and sun are more expensive than the conventional diesel engines. Therefore, the stakeholders might have to face high investment costs in the early stage of the IPS upgrading. Added to this is the fact that the integration of a large amount of power generated by intermittent RES within autonomous systems requires energy-storage systems, which are still very expensive.

On the other hand, once everything has been set up, the use of RES and storage systems strongly decreases the operation costs of the IPS, while the reliability of the power supply increases. This is especially true when the availability of RES is high. For the particular location considered in this study, the availability of the sun and wind resources were estimated through the Atmospheric Science Data Centre of NASA. A Weibul shape factor of 2 was considered for the simulation of the power generated by the wind turbines. Based on these data, the full load hours of a wind turbine and a PV plant installed within the district of Irkutsk are 538 and 1275 h, respectively. These parameters have been used successively for sizing the PV and wind turbine plants. Figure 2.30 [Lombardi] depicts the hourly generation profiles for the PV plant and the wind park for the district of Irkutsk. Both the power plants have an installed capacity of 3000 kW.

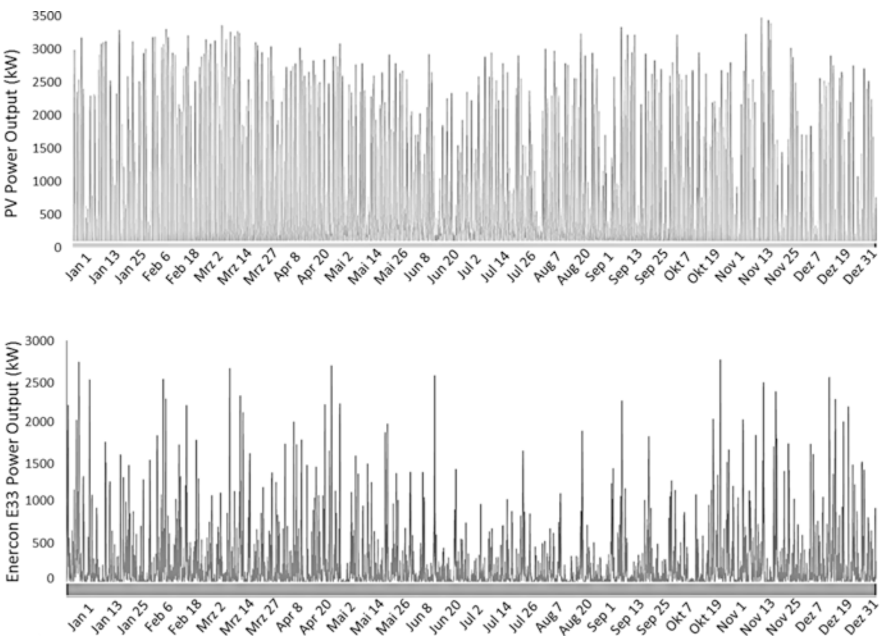

Fig. 2.30 Hourly generation profiles for the PV plant (*top*) and wind farm (*bottom*)

Analysis of Economic and Installable RES Power in the IPS Configurations
Four configurations were analyzed using the HOMER Energy® software mentioned before. The analysis consists of estimating the investment costs (IC) and the cost of electricity (COE) for each configuration. A discount factor of 6 % was considered in the calculation of the COE. HOMER Energy® is also able to identify whether the configuration modeled can cause stability problems in the electricity network.

By simulating all the IPS configurations, a diesel price ranging between 0.1 and 2.0 €/liter was considered. By only considering the cost of energy as a criterion, it could be asserted that the diesel price strongly influences the decision of whether to install a PV plant or not. Indeed, by comparing configuration II with configuration I, the investment in a PV plant (configuration II) can be justified only if the diesel price is higher than 1.7 €/liter. The maximal PV power capacity that configuration II can integrate without creating network stability problems is 600 kW. The case is different for configuration III. Here, the installation of a PV plant and a battery system is preferable if the diesel price is higher than 0.8 €/liter. Thanks to the battery system, it is possible in configuration III to integrate up to 3200 kW of PV power into the IPS. Configuration IV could only be considered if the diesel price was higher than 0.9 €/liter. The maximal number of wind turbines that is possible to integrate in configuration IV is 10, which equals 3300 kW of electric power. Table 2.12 shows the summary of the investment costs and related costs of electricity needed for each configuration analyzed, while the installed power and storage capacity for each configuration are depicted in Table 2.13.

Ecological and Social Analysis of the IPS Configurations
As previously depicted, the diesel price influences the IPS configuration strongly. The higher the diesel price, the more economically justified the use of renewable energy is. For this study, the price of 1.00 €/liter of diesel was used. The emissions of CO_2, NO_x and PM, which were evaluated by HOMER Energy®, are depicted in Table 2.14.

The job creation (JC) criterion was used to evaluate the social aspects related to the IPSs. The IRENA report was used to do this; it states that 30 and 22 new jobs could potentially be created for each MW of PV plant or wind turbine, respectively, installed and operating as an IPS in a rural area.

Sub-Criteria Weights and Evaluation of the Best IPS Configuration
Six sub-criteria in total were considered by the decision-makers to choose the best IPC configuration (see also Fig. 2.29). Since the main aim of this case study is to show how the developed framework for upgrading IPS could be used, the weighting of the criteria reflects a purely numerical application and is not related to any real project. Table 2.15 shows the pairwise comparison matrix of sub-criteria with respect to the main goal of the decision problem (choice of the optimal IPS configuration).

The pairwise comparison matrix has a consistency ratio (C_R) lower than 10 %, therefore, it could be considered as consistent. The resulting local priority vector is evaluated as follows:

$(0.2321, 0.2946, 0.0992, 0.0215, 0.0515, 03011)^T$

Table 2.12 Economic analysis of the IPS configurations

Diesel price [€/litre]	Investment cost [k€]				Cost of electricity [€/kWh]			
	Conf. I	Conf. II	Conf. III	Conf. IV	Conf. I	Conf. II	Conf. III	Conf. IV
0.1	2100	3380	3380	3380	0.293	0.302	0.302	0.302
0.2	2100	3380	3380	3380	0.337	0.346	0.346	0.346
0.3	2100	3380	3380	3380	0.38	0.389	0.389	0.389
0.4	2100	3380	3380	3380	0.424	0.433	0.433	0.433
0.5	2100	3380	3380	3380	0.468	0.477	0.477	0.477
0.6	2100	3380	3380	3380	0.512	0.521	0.521	0.521
0.7	2100	3380	13013	13013	0.555	0.564	0.56	0.56
0.8	2100	3380	13013	13013	0.599	0.608	0.594	0.594
0.9	2100	3380	13013	18013	0.643	0.652	0.627	0.625
1.0	2100	3380	13013	18013	0.687	0.696	0.661	0.655
1.1	2100	4880	13013	18013	0.73	0.738	0.695	0.684
1.2	2100	4880	13013	18013	0.774	0.781	0.729	0.714
1.3	2100	4880	13013	18013	0.818	0.823	0.762	0.743
1.4	2100	4880	13013	18013	0.862	0.865	0.796	0.773
1.5	2100	4880	13013	18013	0.906	0.907	0.83	0.802
1.6	2100	4880	13013	18013	0.949	0.949	0.864	0.83
1.7	2100	4880	13013	18013	0.993	0.992	0.897	0.859
1.8	2100	4880	13013	18013	1.037	1.034	0.931	0.888
1.9	2100	4880	13013	18013	1.081	1.076	0.965	0.917
2.0	2100	4880	13013	18013	1.124	1.118	0.998	0.946

Table 2.13 IPS Configurations

	Diesel generator [kW]	Photovoltaic plant [kW]	Battery plant [kW]; [kWh]	Number of wind turbines model Enercon E33
Configuration I	3000	–	–	–
Configuration II	3000	600	–	–
Configuration II	3000	3200	1000; 1000	–
Configuration IV	3000	3200	1000; 1000	10

Table 2.14 Emissions analysis for each configuration

	Configuration I	Configuration II	Configuration III	Configuration IV
CO_2 [tons/yr]	12,914	12,460	9959	8697
NO_x [tons/yr]	284	274	219	191
PM [tons/yr]	2.43	2.31	1.85	1.618

Table 2.15 Pairwise comparison matrix of sub-criteria

	Investment cost	Cost of electricity	CO_2	NO_x	Particular matter	Job creation
Investment cost	1	1/3	5	9	4	1
Cost of electricity	3	1	3	9	3	1
CO_2	1/5	1/3	1	9	3	1/5
NO_x	1/9	1/9	1/9	1	1/3	1/9
PM	1/4	1/3	1/3	3	1	1/9
Job Creation	1	1	5	9	9	1

$\lambda_{max} = 6.597$; CR = 0.092.

The local priority vector shows that the job creation sub-criterion is the most important of the sub-criteria and that the economic criterion is the most important among the criteria for the decision-makers. The pairwise comparison matrices to each sub-criterion and their respective local priority vectors are shown in Tables 2.16, 2.17, 2.18 and 2.19.

Table 2.16 Pairwise comparison of the IPS configuration to the investment cost sub-criterion

	Configuration I	Configuration II	Configuration III	Configuration IV	Priority vector
Configuration I	1	3	5	9	0.583
Configuration II	1/3	1	5	7	0.29
Configuration III	1/5	1/5	1	3	0.085
Configuration IV	1/9	1/7	1/3	1	0.042

$\lambda_{max} = 4.165$; CR = 0.06.

Table 2.17 Pairwise comparison of the IPS configuration to the cost of the electricity sub-criterion

	Configuration I	Configuration II	Configuration III	Configuration IV	Priority vector
Configuration I	1	3	1/5	1/8	0.0914
Configuration II	1/3	1	1/3	1/8	0.0579
Configuration III	5	3	1	1/3	0.2535
Configuration IV	8	8	3	1	0.5972

$\lambda_{max} = 4.273$; CR = 0.1.

Table 2.18 Pairwise comparison of the IPS configuration to the CO_2, NO_2 and PM sub-criteria

	Configuration I	Configuration II	Configuration III	Configuration IV	Priority vector
Configuration I	1	1/3	1/5	1/8	0.0503
Configuration II	3	1	1/3	1/8	0.0984
Configuration III	5	3	1	1/3	0.2401
Configuration IV	8	8	3	1	0.6112

$\lambda_{max} = 4.125$; CR = 0.046.

Table 2.19 Pairwise comparison of the IPS configuration to the job-creation sub-criterion

	Configuration I	Configuration. II	Configuration. III	Configuration. IV	Priority vector
Configuration I	1	1/3	1/5	1/8	0.0491
Configuration II	3	1	1/3	1/8	0.0778
Configuration III	5	3	1	1/3	0.2175
Configuration IV	8	8	3	1	0.6556

$\lambda_{max} = 4.163$; CR = 0.06.

The local priority vectors of each IPS configuration have to be multiplied by the local priority vector of the sub-criteria in order to rank the best IPS configuration (see Eq. (2.27)). Consequently, the ranking of the best IPS configuration is obtained.

In this case study, the IPS that best satisfies the decisional criteria of the decision-makers is configuration IV (48.83 % of preferences), followed by configuration III (20.12 % of preferences), configuration I (17.52 % of preferences) and, lastly, by configuration II (12.47 % of preferences).

$$\begin{bmatrix} 0.583 & 0.0914 & 0.0503 & 0.0503 & 0.0503 & 0.0491 \\ 0.29 & 0.0579 & 0.0984 & 0.0984 & 0.0984 & 0.0778 \\ 0.085 & 0.2535 & 0.2401 & 0.2401 & 0.2401 & 0.2175 \\ 0.042 & 0.5972 & 0.6112 & 0.6112 & 0.6112 & 0.6556 \end{bmatrix} \begin{bmatrix} 0.2321 \\ 0.2946 \\ 0.0992 \\ 0.0215 \\ 0.0515 \\ 0.3011 \end{bmatrix} = \begin{bmatrix} 0.1752 \\ 0.1247 \\ 0.2012 \\ 0.4883 \end{bmatrix} \quad (2.27)$$

Test Questions Chap. 2

- Have storage systems been used in the past and are they used in present power systems? For which applications?
- What are the main storage-characteristic parameters?
- What are the characteristic features for the generic storage-surface model?
- Give an example of a use case for storage. Which energy market players, in such a use case, must be taken into account?
- What are the main parameters of the mathematical model of storage?
- How can optimal storage be calculated?
- Which data are necessary for dimensioning storage in IPS systems?

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Chapter 3
International Development Trends in Power Systems

3.1 State of the Art

The power-system structure is composed mainly of generation, transmission and distribution. This is also due to the unbundling process which takes place in many countries. Many power networks are unbundled commercially, with a separation of generation from the operation of the network. The power in a traditional power system is produced by a few large power plants located near primary energy sources (e.g., coal mines, water). The power is then transmitted at very high or high voltage for long distances (e.g., 500 km) and, finally, distributed to the end users. Generation is the main part of the power system. More than 50 % of the total costs of the power system are related to generation, which is also responsible for most of the polluting emissions. The general structure of the primary energy sources has changed during the last 30 years (see Fig. 1.2), but still fossil energy dominates the sources with a share of about 80 %.

The net electricity generation total reached a value of 23,816 TWh in 2014. The electricity generation forecast from renewable energy sources (RES) is displayed in Fig. 3.1. Among the technologies that use renewable sources, the highest proportion of generation is provided currently by hydropower plants (see Fig. 3.1). Nevertheless, it is not expected that there will be a significant increase in hydroelectric generation in the coming years, because hydropower stations, especially large plants, are geographically limited, and there are not many suitable new sites available. The main contribution to an increase in the share of the renewable energy will be provided by both solar (e.g., photovoltaic: PV and concentrated solar power (CSP)) and wind-based technology (Fig. 3.1). European and Chinese targets aim to increase generation from wind by tenfold by 2050. The PV electricity generation forecast for 2050 should reach about a 10 % share of the global electricity generation, and this contribution would be 50 times higher than today's status.

The massive use of renewable-based generators will change the power-system structure as well. The current power structure is characterized by large, centralized

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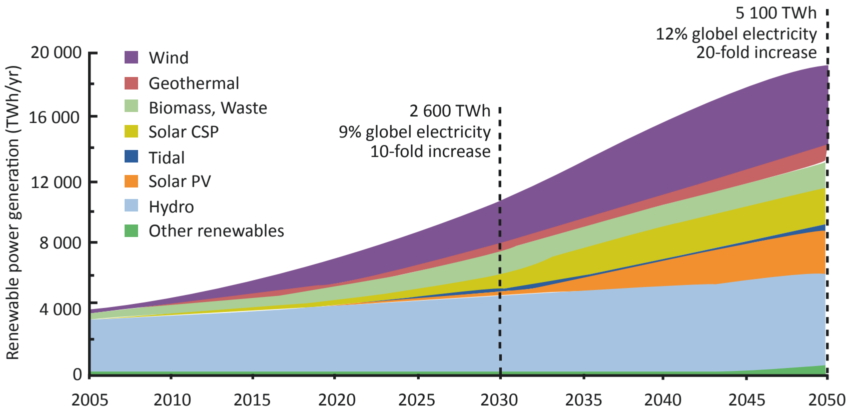

Source IEA (2008a).

Fig. 3.1 Electricity from renewable energy sources (RES) until 2050 in the ETP 2008 BLUE Map scenario [1]

electricity generators that subsequently transmit the electricity at high voltage and distribute it to the end user at medium and low voltage. Renewable sources, on the other hand, will be provided mainly from decentralized generators at the distribution level, thus, the distribution system will have more importance than today. It will be necessary to use more and more knowledge and information and communication technology to get accurate data and control with so many decentralized generators distributed in various segments areas of the power network. Those changes will lead to a new, intelligent (smart-) grid structure. Energy-storage systems and other measures, such as load adjustment, will be necessary to compensate for the stochastic generation from wind and PV plants.

3.2 Smart Grid Concept for the Future Grid

The concept of a "smart grid", described in detail in Sect. 1.2, has many definitions and interpretations depending on the drivers and the outcomes desired in the specific country or by industrial stakeholders. Smart grid refers to the entire power grid from generation through transmission and distribution infrastructure, all the way down to the wide array of consumers. It is often described in terms of elements of traditional and cutting-edge power engineering, technologies, solutions and applications employed (e.g., distributed energy resources, microprocessor protection, advanced automation, sensing and monitoring, energy management), functionalities and capabilities enabled, robust communications, cyber security and data/information management (e.g., data mining and architecture, data analytics) to provide better grid observability, performance and asset utilization. Although the details of the technologies, solutions and applications employed may differ from one stakeholder to another, the general characteristics of a smart grid are typically similar. Furthermore, many smart-grid stakeholders define a smart grid not only by what technologies or functionalities it incorporates, but also by what value it brings to all smart-grid participants. Energy storage plays an important role in the realization of the smart-grid concept. Key smart-grid applications that benefit from the integration of energy storage include:

- Microgrid and island concept: energy-sustainable communities, grids and islands operating effectively based on the mix of renewable-energy generation, energy storage and well-defined protection, automation, monitoring and control design and engineering standards/principles.
- Demand response: demand response enabled through the virtual power plant concept; effective and optimum dispatchability and controllability of distributed energy resources (distributed generation and energy storage) to reduce energy peak demand, minimize distribution grid losses, and improve overall system efficiency and asset utilization.
- Management of intermittent renewable-energy generation: Integration and management of embedded energy storage within the grid, such as various battery-based technologies, flywheels, compressed air and capacitor banks, to enable intermittent, renewable generation dispatchability and controllability.
- Ancillary services support: support of primary and secondary frequency control provided by traditional power plants.

3.3 European Scenario

Renewable energy production is becoming more and more important in Europe, and its market share is increasing continuously.[1] Wind and solar power especially are contributing significantly to the growing ecological energy production. More than 97.1 GW of solar power and about 142 GW of wind power were installed during 2014 and 2015, respectively, in several European countries, and this is shown in Fig. 3.2. It is evident that wind is dominant, but PV is also widely used throughout these European countries.

The use of renewable energies is supported broadly within Europe. In addition to encouraging the installation of renewable power, the European Union (EU) also aims to take the leadership in the research and development of green technologies to stay competitive in a global market and to fulfil the two major EU goals:

- 2020 target: reduce the greenhouse gas emission by 20 % and ensure 20 % of RES in the EU energy mix;
- 2050 target: complete decarbonization (vision).

[1] Based on the contribution given by Dr. Franziska Adamek within the Cigré WG C6.15 [3].

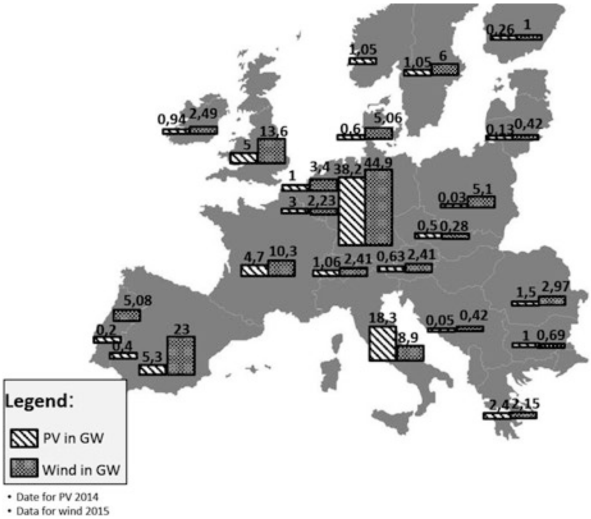

Fig. 3.2 Installed power from wind (in 2015) and photovoltaic (in 2014) in GW [2]

The EU supports the use of renewable energy resources, and it is likely that they will dominate the future energy supply. Different scenarios have been elaborated to depict the future European scenarios. One of them is the European SET Plan which was described in detail in Sects. 1.2.2 and 1.2.3.

The goal for the share of renewable energy in gross power generation amounts to 27 % in 2050. A major part is generated by wind (Fig. 3.3). Wind will, in 2050,

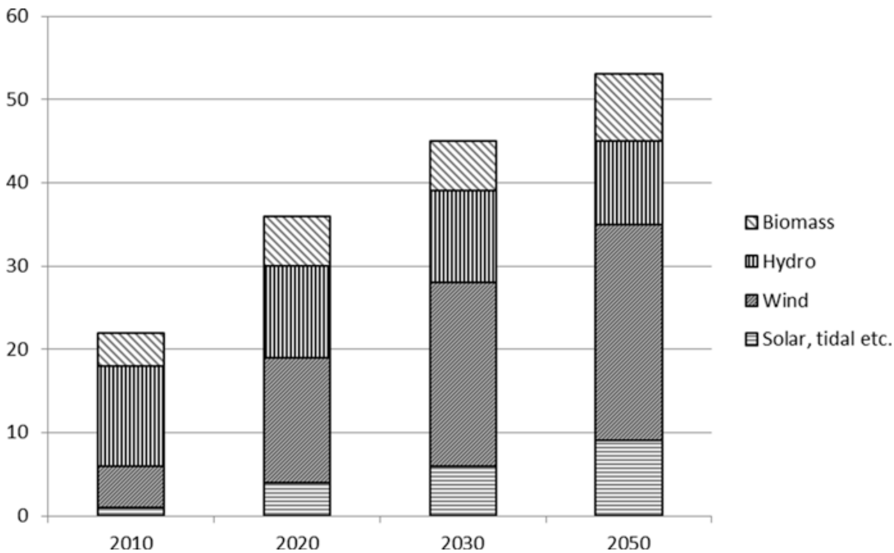

Fig. 3.3 Share of renewables in electricity production in % [1, 2]

produce about five times the amount of energy it produced in 2010. Only the share of hydropower drops a little because of potential limitations and environmental restrictions. Biomass and solar PV increase considerably.

Increasing the electricity demand, as well as the higher penetration of intermittent RES, requires a substantially higher power generation capacity than is needed currently. The net capacity increases by 31 % and is generated mainly by renewables and natural gas. The installed capacity of renewables increases by more than 1.5 times from 2005 to 2030. The capacity of about 325 GW of renewables is provided mainly by onshore wind (39 %) and hydro (34.5 %).

3.4 Renewable Energy Development in the Iberian Pensinsula

Renewable energies have always played a key role in the electricity-generation mix on the Iberian Peninsula.[2] The volume of renewable generation has soared in the last few years, mainly with the increase of wind generation, and it is foreseen that this trend will continue in the coming years. Portugal particularly has one of the highest levels of solar radiation, wind and hydro resources among all the EU member states. The renewable energy investments there have boomed recently and, consequently, have become a crucial area for the Portuguese economy. Specifically, Portugal had installed 11,904 MW of renewable-based power plants by the end of 2015: thus, the renewable energy share is 52.1 % of the total electricity demand (one of the highest percentages in Europe) [2]. The goals defined by governmental institutions for the renewable share in the electricity demand for 2010 and 2013, corresponds to 39 % and 45 %, respectively. Considering that there are presently 4945 MW of hydropower capacity in Portugal, the accomplishment of the 2020 targets requires the installation of another 2055 MW, adding up to a total of 7000 MW. Concerning wind generation, it is very likely that the goals defined for that sector will be reached by assuming a yearly development rate of the installed capacity around 20 % through 2010 (and a grid capacity schedule for wind power enhancement). This will lead to an installed capacity of about 8000 MW by 2020. Regarding Spain, their 2010 targets pledged—in the Plan of Renewable Energies (PER)—for renewable generation to increase, with the aim of reaching at least 12 % of total energy use from renewable sources by that year. Additionally, the PER aspires to reach 40 % of electricity generated from renewable sources by 2030 [3]. Moreover, it is agreed unanimously that about 40,000 MW ought to be installed by 2020. Concerning the contribution to demand, wind generation fulfilled 10 % of the electricity load in 2006, ahead of hydropower (9 % of the load). In 2015, 5079 MW of new wind-power capacity was installed (double the amount registered in 2006) [2]. The total installed capacity of wind power was 23,025 MW in January 2014 [2].

[2] Based on the contribution given by Prof. Pecas Lopes within the Cigré WG C6.15 [3].

3.5 The Danish Scenario

Denmark has been a world leader in power generation from wind turbines since the first oil crisis in the 1970s.[3] More than 35.8 % of the primary production of renewable energy in Denmark is covered currently by its wind-turbine generators.

The goal of the Danes is to have more than 50 % of their electricity consumption generated by wind by 2020. Part of the explanation of how this can be achieved is the location of Denmark and its strong electrical connections to its neighbors. They have a total exchange capacity of up to 5.3 GW, which should be compared to a peak load of 7.3 GW, and an average load of 4.1 GW. Denmark plans to add an extra 2.5 GW of exchange capacity before 2017. Denmark copes with the fluctuation of the wind power by using its transmission lines to Norway and Sweden in the north and Germany in the south, using their neighbors as a storage option. In Norway, they have a large amount of hydropower, some of it reversible, and, since Germany is so large compared to Denmark, the excess production or demand, can be absorbed relatively easily. This is no longer possible due to the large number of wind-power plants that have been installed during the last few years, especially in Northern Germany. Every exchange of power is based on solid commercial grounds, operated and controlled by the "Nordpool" energy marketplace. The grid and "Nordpool" working together result in an electricity market where prices shift on an hourly basis, depending on demand and production capacity, e.g., high winds in Denmark or lots of rain (which equals fuel for the hydroelectric power plants) in Norway. The prices can fluctuate greatly, making electricity one of the most volatile "raw materials" in the world. If a problem occurs in the transmission grid, it can have a very large influence on the price of electricity (see Fig. 3.4). In this regard, an online picture of the actual grid situation can be found on www.nordpoolspot.com (see Fig. 3.5).

Electricity production in Denmark from wind turbines was a little over 7 GWh in 2007. Export to its neighbors was around 11 GWh and import was around 10 GWh.

The lesson to be learned from the Danish case is that a strong transmission grid, securing the possibility to export electricity in high-wind periods and import in low-wind periods, makes a high penetration of renewables, e.g., wind power, possible. The grid and the surrounding countries act like large-scale energy storage. This will no longer be possible if the neighboring countries are situated in the same climatic zone.

3.6 North American Scenario

Aggressive programs are in place in North America to incentivize the growth of RES with a primary focus on wind followed by solar and biomass.[4] Inclusion of storage programs to support these recourses is still in its early stages, but support

[3] Based on the contribution given by Henrik Vikelgaard within the Cigré WG C6.15 [3].

[4] Based on the contribution given by Prof. Ravi Seethapathy and Dr. Bartosz Wojszczyk within the Cigré WG C6.15 [3].

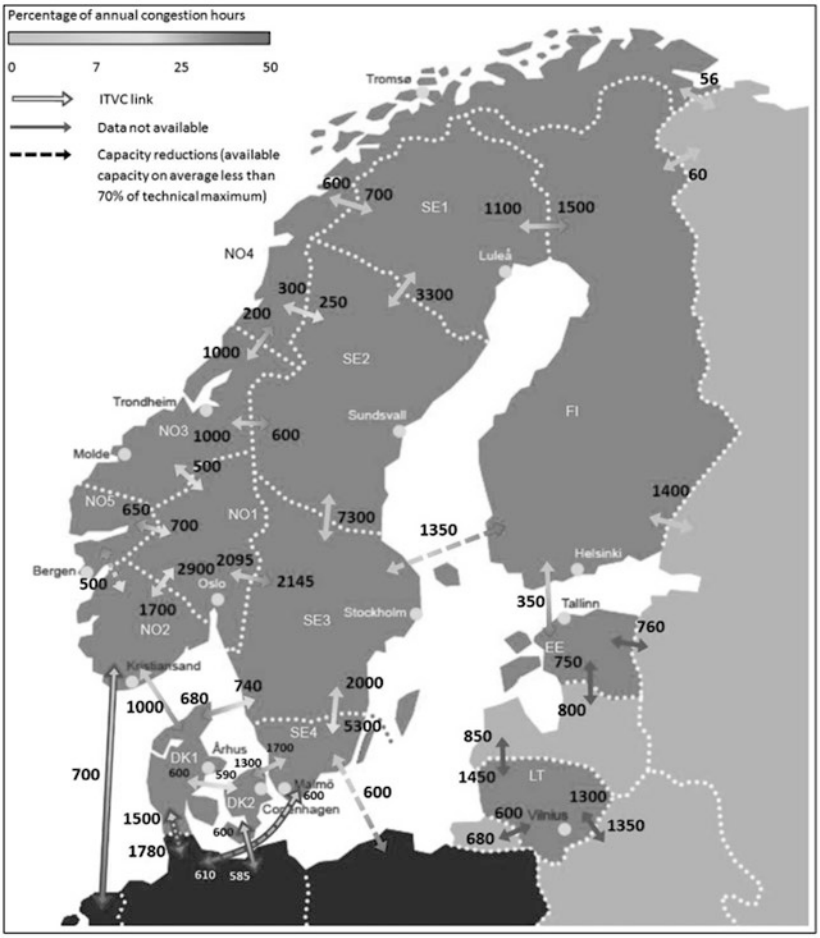

Fig. 3.4 Critical exchange points in the north European countries [2]

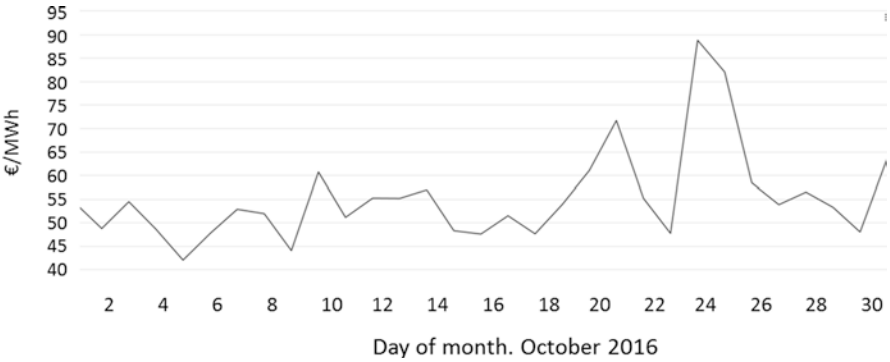

Fig. 3.5 Electricity prices in the Nordpool spot market [4]

from the federal government in the US has commenced. The need for storage in the US utility grid came to the forefront in 2007 with the passage of the Energy Independence and Security Act (EISA) by the US Congress in 2007. The law calls for a significant increase in funding to support R&D and storage demonstration programs for grid power and transportation. In response to the growing interest in this area, the US Department of Energy formed the National Electricity Advisory Committee and elevated energy storage to one of the top three issues, along with smart-grid technology and generation adequacy.

The US has a fairly large base of storage in the form of pumped hydro with 21 GWs currently installed, which represents a little more than 2 % of the total generation capacity (2008) in the US. One of the world's two compressed-air energy-storage (CAES) systems is installed in the US with a capacity of 110 MWs. Other battery-storage systems in the US totaled just over 280 MWs by the end of 2016. Virtually all these schemes support utility projects not focused on renewables. Smaller pilot programs for adding storage to solar systems are underway, but limited information is currently available.

The US Congress passed the Financial Bail-out Bill in October 2008, which included renewal of the Production Tax Credit for renewable sources and a 30 % tax credit for adding storage to a solar-power system. The impact of these incentives has yet to be assessed. Approval to proceed with the drilling of test wells was given to the Iowa Municipal Utilities CAES project in 2008. The 268 MW plant will be built in conjunction with a 200 MW wind farm. The project is being jointly funded by municipal utilities in Iowa, plus others in adjacent states. This region of the US has a rapid growth in wind farms and will have wind-penetration levels at or above 30 % in the next decade. The largest area of growth of storage systems in the US is for ancillary services. Lithium-ion batteries and larger flywheels appear to be cost competitive with natural gas plants to provide ancillary services (mainly frequency). Two major studies conducted during 2008 show that, as renewable-energy penetration increases, the need for fast response systems in the timeframe of 5–15 minutes will increase. This 15 minute "non-spin" option is ideal for energy storage systems such as batteries and flywheels. This market will develop fastest in the US.

One of the key drivers to facilitate storage use in the US grid, at every level from utility substation scale down to residential sizes, is smart-grid technology developments. At least one utility project is underway to test grid automation coupled with storage to demonstrate system reliability and "islanding" of large sections of a distribution grid.

The Hawaiian Islands are a unique test bed for storage with very high levels of wind penetration. The very-high cost of delivery of fossil fuels provides the incentives to add storage. At least one of the smaller islands has indicated a commitment to 100 % renewable power in the near future. The largest storage activity in the US is the development of batteries for transportation. The batteries for electric vehicles (EVs) and plug-in hybrid EVs (PHEVs) will help stimulate fixed-battery opportunities, and one potential application offered for used PHEV batteries is a residential application to work with PV arrays. One possible scenario is that PHEV battery packs will be replaced in automobiles at about a 60 % capacity point, resulting in a “second life” as battery packs in homes to support PV systems that power the load during peak periods.

The overall power generation market in Canada has a unique mix of generation. The provinces of Quebec and Manitoba both have over 90 % of their production provided by hydropower. Both provinces are also ideal locations for wind farms. Because of the large expanse of Canada, the distances between the wind power or hydropower generation plants and the loads can be quite long. The control of nodal voltages will be a growing issue for Canadian grid operations as the penetrations of renewables increases. One approach to a solution is adding storage to the generator “fuel mix” with appropriate incentives.

3.7 South American Scenario

Because of its vast territory, Argentina has a rich variety of climates.[5] Geographic factors influence the climate directly, determining the climatic characteristics of various regions, and the broad range of latitudes covered has a special influence on the climate. Argentina lies almost entirely within the temperate zone of the Southern Hemisphere, unlike the rest of the continent to the north, which lies within the tropics. Tropical air masses only occasionally invade the north-eastern provinces. The southern extremes of Argentina also have predominantly temperate conditions, rather than the cold continental climate of comparable latitudes in North America. The South American landmass narrows so markedly toward the southern tip that the climate is moderated by the Pacific and Atlantic oceans, and average monthly temperatures remain above freezing in the winter. The temperate climate is interrupted by a long, narrow north-south band of semiarid-to-arid conditions and by tundra and polar conditions in the high Andes and in the southeast. The Andes Mountains, which extend from north to south along the west of the country, constitute a relief factor that facilitates the circulation of air masses in the east, thus, determining various types of winds. Three winds, which originate beyond the Argentine boundaries, influence the climate in a permanent way: These are the warm and humid winds coming from the Atlantic anticyclone and affecting the regions located to the north of Patagonia; the west winds coming from the Pacific anticyclone; and cold winds from the Antarctic anticyclone. Among the most noticeable characteristics of such winds are the strong prevailing winds from the west in Patagonia, which blow all year around and reach an average 8 m/s on a yearly mean basis (at heights of 30 m above ground). In some regions of Patagonia, the wind speed exceeds an average 10 m/s. Thus, having this available wind power, there is the potential capacity to produce the same or even higher energy annually than offshore installations at much less cost.

Four major local winds in Argentina influence the climate in such a way that restricted areas with specific wind potential are formed. These include the Zonda,

[5] Based on the contribution given by Prof. Pedro Enrique Mercado within the Cigré WG C6.15 [3].

which is warm and dry, generally blowing between May and October and originating to the west of Cuyo area; the Sudestada, which originates in the Pampa littoral and is characterized by its high humidity content; the Pampero, coming from the south-west, which is cold and dry, and blows mainly in the summer, after several days of constant increase of temperature and humidity; and tornadoes, which consist of an air mass in the form of a vertical funnel reaching a rotating movement of about 500 km/h (310 mph), originating between October and March in the Plata Basin.

A map of estimates of annual average wind resources at heights of 30 m above the ground has been developed employing a geographical information system to assess the potential of wind-energy sources in Argentina.

The Argentinean installed capacity of grid-connected, wind-power generation did not exceed 29.8 MW in late 2008 [5], and the total amount of power installed in the country in secure operation was 18 GW, composed mainly of hydraulic, thermal and nuclear generation. Thus, wind power represents only an insignificant fraction of the total power installed, having slightly more than 40 wind generators in the entire territory. The onshore energy potential from wind generation is exceptional. The potential capacity of wind power in Argentina is estimated at about 2.1 GW, with a penetration not higher than 12 % in order to not perturb the adequate operation of the existing Argentinean high-voltage interconnected system (SADI) [6]. Most of this onshore power capacity is in the southern sections and particularly in the Patagonian region, and would correspond to an investment of approximately US$ 2,000,000,000. In this way, the development of the wind industry in Argentina would constitute an additional important factor for reactivating the national economy, beginning with base industries and ending with service areas. Presently, only two Argentinean enterprises developing their own technology for large wind power generators exist.

Argentina has a significant natural potential for solar-energy use. The central region of the country has an insolation of about 1600 kWh/m^{2}year, an excellent resource compared with most regions of Europe. Additionally, some western, largely mountainous, provinces, such as Jujuy in the north and San Juan near the center, enclose areas that mostly exceed 2200 kWh/m^{2}year, making them undoubtedly among the sunniest places in the world. A map of estimates of annually-averaged, daily global insolation on a horizontal surface has been developed, employing a geographical information system. So far, PV solar- power applications in Argentina have been in isolated areas primarily through the rural electrification program called PERMER (Renewable Energies Program for Rural Markets) launched by the Energy Department in 1995 and funded by the World Bank and by subsidies from the Global Environment Facility [7]. The installed capacity of isolated solar power generation exceeded 9 MWh in late 2008 [8], and there is a potential capacity estimated at about 1.45 GW considering the restrictions. As is clear, this potential remains largely untapped. There has been no experience of PV installations connected to the grid in Argentina. Regulatory obstacles and the lack of specific incentives to promote solar power have so far inhibited this development. Nevertheless, there exist some pioneer projects currently aimed at spreading this technology with connections to the grid, although a national support program is clearly needed.

3.8 Japanese Scenario

Japan's energy-supply and demand structure and CO_2 emissions have been forecasted for 2030, considering the progress of energy technologies and their applications, and assuming that the Japanese economy achieves a stable growth despite high energy prices.[6] In this forecast, the yearly economic growth rate is assumed to be 2.1 % in 2005–2010, 1.9 % in 2010–2020 and 1.2 % in 2020–2030, while crude oil prices are estimated to be $90 per barrel in 2020 and $100 per barrel in 2030 [9]. On May 24, 2007, the Japanese Prime Minister released “Cool Earth 50,” a new initiative regarding the climate-change issue that proposed to set up a worldwide initiative to halve the emissions of global gases by 2050 [10]. It is difficult to address such a long-term objective with only conventional technologies, and so the development of innovative technologies is considered essential. In order to achieve the long-term target to reduce CO_2 emissions by 2050, “Innovative Photovoltaic Power Generation” has been identified by the Japanese government as one of the prioritized technological areas under the “Cool Earth-Innovative Energy Technology Program.” For Japan, many energy-related organizations have modeled the future energy system and some reports are available on their websites. However, the “Outlook for Resources and Energy Supply and Demand” report issued by the Agency for Natural Resources and Energy, Japan, in May 2008, is considered here for the energy forecasts, also called scenarios. In this report, the energy scenarios for the time frame up to 2030 have been divided into three types depending upon how efforts to improve the energy efficiency are made and implemented:

- The reference scenario is based on “business as usual,” where no new efforts and/or technologies are implemented.
- The continued promotional effort scenario considers the efforts to improve the efficiency of equipment based continuously on the trajectory of existing technologies.
- The maximum introduction scenario considers the deployment of equipment with a significant improvement of energy-efficiency performance by using cutting-edge technologies.

The main features of the individual scenarios are discussed in the following sections.

This section describes the forecasts regarding energy scenarios with some renewable energy penetration, with the usual efficiency-improving measures and where no new major technologies are adopted.

The reference scenario assumes a yearly economic growth rate of 2.1 % in 2005–2010, 1.9 % in 2010–2020 and 1.2 % in 2020–2030, while the population is projected to decrease by about 10 % compared to 2005. All the scenarios seek a decrease in the dependency level of the oil-based primary energy share to the extent

[6] Based on the contribution given by Dr. Suresh Verma within the Cigré WG C6.15 [3].

of about 20 % by 2030 compared to 2005 by using the other energy sources, such as renewables. The forecast data pertaining to 2020 is also included for each scenario.

The share of energy sources in the total primary energy is shown in Table 3.1.

The primary energy consumption increases by about 98 MkL[7] between 2005 and 2030. The renewable share increases to 40 MkL by 2030 from 34 MkL in 2005, and the primary energy consumption rises to almost 7 % in 2030. Of this 7 %, the share of each renewable type is shown in Table 3.2. The share of renewables, including hydro, in gross power generation amounts to 9 % in 2030. A major part, about 7 %, is generated by hydro.

This scenario focuses on the reduction of CO_2 emissions by continued promotional efforts, such as shifting coal power plants to other type of generation, building additional nuclear power plants, increasing the share of renewables and introducing high-efficiency energy-utilization technology. When the measures above are taken into consideration, the CO_2 emissions can be reduced by 5 % by 2030 compared with 2005. Regarding the share of renewables in 2030, there is about a 1 % increase in primary energy and 2 % increase in power generation. This is despite there being a decrease (about 12 %) in primary energy consumption in 2030 compared to the reference scenario, due to the introduction of high-efficiency technologies. However, the primary energy consumption shows a rise of about 2.5 % compared to that in 2005. The share of energy sources in the total primary energy is shown in Table 3.3. The primary energy consumption decreases by about 61 MkL from 587 MkL in 2005 to 526 MkL in 2030, due to the efficiency measures assumed to be applied to both the energy supply and demand sides. The renewable share increases

Table 3.1 Share of energy sources in total primary energy in % [3]

Year	Coal	Oil	Gas	Nuclear	Renewables
2005	21	43	18	12	6
2020	21	38	19.5	15	6.5
2030	21	36	21.5	14.5	7

Table 3.2 Share of renewables in total primary energy in % [3]

Year	Hydro	Wind	Solar	Biomass, waste, geothermal, etc.	Total
2030	41	5	15	39	100

Table 3.3 Share of energy sources in total primary energy in % [3]

Year	Coal	Oil	Gas	Nuclear	Renewables
2005	21	43	18	12	6
2020	20	37	17	18	8
2030	18	35	17	19	11

[7] Million kiloliters (1.172 Mkl is equivalent to approximately 1 Mtoe on an energy basis).

Table 3.4 Share of renewables in total primary energy % [3]

Year	Hydro	Wind	Solar	Biomass, waste, geothermal, etc.	Total
2030	33	5	22	40	100

from 34 MkL (6 %) in 2005 to 58 MkL (11 %) in 2005 and the solar type of renewable resources show a significant increase of about 35 times compared to 2005. The share of each renewable type of this 11 % increase is shown in Table 3.4.

This scenario exhibits about a 49 % share of gross power generation, with an increase of 18 % compared to 2005. The share of renewables shows a four-fold increase compared to the 2005 scenario. This is due mainly to the significant increase of about 37 times in solar-energy systems compared to 2005. There is a sharp increase in the share of solar (PV)-type renewables envisaged by NEDO, the Agency for Natural Resources and Energy under the Ministry of Economy, Trade and Industry, which has provided PV technology development targets.

3.9 Russian Scenario

A project of a virtual power plant with smart-grid technologies is also supported by the Russian Federal Grid Company (FGC UES) [11].[8] The smart-grid concept is especially important for Russia, because there are many power-supply problems in the energy sector, such as the ever more unreliable electric-power grids. Energy resources in Russia are frequently wasted. Various authorities show that losses during energy distribution in Russia are significantly higher than in the European countries. Russia is the fourth largest electricity producer in the world after the USA, China and Japan, with a total electricity-generation capacity of about 243.2 GW. It produced about 1064 TWh of electric power in 2014. It has a unique interconnected power system that links 70 local energy systems and provides energy transfer across eight time zones. The Russian electricity-generation capacity consists of 68 % thermal-plant power generation, 21 % hydropower generation, 10 % nuclear and about 1 % renewables (geothermal, wind and waste heat). The vast area of the Russian Federation with various different landscapes has a huge development potential for RES. There is large wind- energy potential in Russia, especially along the seacoasts, in the steppes and in the mountains, of about 700 GW. The total technical potential for biomass is about 15,000 MWe. The operational reorganization of paper plants and the utilization of wood waste are becoming more popular. The geothermal potential is also significant, about 3000 MWe. The solar potential depends on the location, with the most favorable regions situated in southern Russia (Caucasus, Tuva, Astrakhan region, and the Chita region). Russia has a huge hydro

[8] Based on the contribution given by Prof. Nikolai Voropai within the Cigré WG C6.15 [3].

potential, about 9 % of the global hydro resources. Thus, the hydropower stations are the most popular of the renewable sources. The hydropower energy generation is currently 21 % of total energy production (it is about 1 % in Germany). The usage of combined heat and power systems (CHP) is very promising in Russia. This is due to the predicted increase of tariffs for electricity (the CHP systems are paid off quite rapidly, and if the tariffs are increased 10–15 %, the payback period would be reduced significantly). The application of natural gas CHP into the local heating systems is currently popular. Russia has huge natural gas resources and needs power supply in remote regions, therefore it has a good ability to solve the power-supply problem by using small-scale CHP units (up to 30 MW). The advantages of CHP are the low cost of heat and electric energy, short distances to the consumers, absence of expensive power lines and substations, environmental friendliness and simple installation.

The Russian Government Order of January 8, 2009, determined the main values of energy generation from renewable sources up to the year 2020 (excluding the hydropower stations with installed power of more than 25 MW) as follows: 1.5 % in 2010, 2.5 % in 2015 and 4.5 % in 2020. Therefore, the renewable energy sector in Russia is expected to expand in the coming years.

3.10 Chinese Scenario

China is in a period of fast economic growth.[9] The annual growth rates of its GDP remained above 10 % from 2003 to 2006. Rapid economic development in China is accompanied by a high level of energy consumption. China is becoming the world's largest coal-production and consumption country, and, simultaneously, it is also the second largest energy-production and consumption country, and the second largest oil-consumption country. The average annual energy-consumption increase rate in China since 2000 has reached about 10 %. In 2006, the total energy consumption of China was up to 2.46 billion tons of the standard coal equivalent. China aims to achieve the goal of quadrupling its GDP from 2000 levels by 2020. Facing the new round of growth in the chemical industry, transferring the international manufacturing industries and the acceleration of the urbanization process, economic growth in China will increasingly depend upon energy consumption.

The GDP of China has quadrupled and energy consumption doubled in the past 20 years. In 2004, the economic growth rate of China reached 9.5 %, however, the annual output of coal exceeded 1.9 billion tons in this scenario. Additionally, China's dependency on imported oil has risen in recent years. It increased drastically up to 50 % in 2007 compared to 30 % in 2000. The coal-dominated energy consumption in China results in huge CO_2 emissions, which has put increasing pressure on the Chinese government. Although the per-capita emissions of CO_2 in China are still

[9] Based on the contribution given by Prof. S. Cheng within the Cigré WG C6.15 [3].

far less than that of the developed countries, the total gas emissions have already surpassed the United States, which makes China the largest emitting country among the developing countries. The main reason for this is the low-efficiency utilization of the energy. Electricity generation per kWh results in 418 grams of CO_2 emissions in Japan and 625 grams in the United States. However, this amount reaches 752 grams in most of the top ten power generation companies in China. China's strong economic growth and heavy reliance on coal for its power generation and other energy consumption industries leads the IEA to predict that China's CO_2 emission will double in the period from 2004 to 2030. Accordingly, the following countermeasures have been taken in China to solve the problems mentioned above. In the last three and a half years, China has decommissioned some of the least-efficient coal-fired power plants with a total power generation capacity of 54.07 GWh, which exceeds the total installed capacity of electricity in Australia. The Chinese government has requested that the power generation companies phase out all the inefficient coal-fired electrical-power generation units with a capacity lower than 100 megawatts before 2012. By taking these measures, China will be able to reduce 90 million tons of coal consumption and 220 million tons of CO_2 emissions every year. In view of the constraints of the increasing energy production capacity and the environmental protection capacity of China, as well as the effect of the implementation of energy conservation, a large gap will appear between China's traditional fossil-energy supply and the energy demand. Based on the estimation of the Energy Research Institute of the National Development and Reform Commission of China, this gap will reach 18, 20 and 30 % in 2020, 2030 and 2050, respectively. Renewable energy will bear the responsibility of bridging the gap between energy supply and demand, ensuring energy security, optimizing the energy structure and protecting the environment. Energy development in China will follow one of these development strategies and programs:

- Conventional development program: This is a normal energy-development program in which the pressure of greenhouse-gas emissions is basically not considered.
- Intermediate development program: The total energy supply will be partially shared by the increasing renewable-energy supply, while the energy-saving emission reduction of traditional energy will be carried out continuously.
- Affirmative development program: China will increase the R&D and marketing efforts in renewable energy, such as wind, solar and bio-liquid fuel. Much effort will be placed on the development of new energy and RES.

The following gives a description of the three kinds of development programs in accordance with the development feature of energy systems. This is a conservative program in which the pressure to reduce emissions of greenhouse gases is not considered. In accordance with the conventional development, China may learn from the experience of developed countries in renewable-energy policy to save investment. In this program, the demands for oil, natural gas and electricity will maintain rapid growth into the future. In accordance with the conventional development, the proportion of the renewable energy accounting for the total energy requirement is shown in Table 3.5.

Regarding the statistics, without taking hydropower generation into account, the proportion of renewable energy, accounting for the total energy requirement, increases from 1.2 % in the base year (2006) to 17.7 % in 2050. Taking hydropower generation into account, the portion of renewable energy will increase from 7.6 % in the base year up to 26.4 % in 2050. A fast growth trend can be seen from this statistical result. In the conventional development program, the prediction of the installed power-generation capacity of all kinds of renewable energy is shown in Table 3.6.

Table 3.5 Proportion of renewable energy accounting for the total energy requirement in accordance with conventional development [3]

	2006	2020	2030	2050
Total energy (tons of standard coal equivalent)	24.6	35	42	50
Proportion of renewable energy: with hydro	7.6	15.5	20.5	26.4
Proportion of renewable energy: without hydro	1.2	5.3	9.5	17.7

Table 3.6 Prediction of the installed power-generation capacity of all kinds of renewable energy in accordance with the conventional development program [3]

	2006	2020	2030	2050
Installed power-generation capacity [GW]	132.9	347	570.0	1250.0
Wind	2.6	30.0	120.0	300.0
Solar	0.1	2.0	20.0	500.0
Biomass	2.3	15.0	30.0	50.0
Hydro	128.0	300.0	400.0	400.0
Generation capacity [TWh]	472.2	1280.4	2042.0	3240.0
Wind	3.4	63.0	264.0	690.0
Solar	0.1	2.4	28.0	700.0
Biomass	7.9	75.0	150.0	250.0
Hydro	460.8	1140.0	1600.0	1600.0
Generation capacity proportion [%]	100.0	100.0	100.0	100.0
Wind	0.7	4.9	12.9	21.3
Solar	0.0	0.2	1.4	21.6
Biomass	1.7	5.9	7.3	7.7
Hydro	97.6	89.0	78.4	49.4

In this program, both the possibility of development and practical demands are considered. It represents a considerable number of compromise proposals between the conventional development program ("business as usual") and the affirmative development program. According to this program, the national-average coal consumption for electricity will drop from 397 grams standard-coal equivalent per kilowatt-hour in 2000 to 360 grams standard coal equivalent in 2010 and even lower to 330 grams standard-coal equivalent in 2020. Compared to 2000, 350 million tons of coal can be saved correspondingly. Before the mid-1990s, in addition to the factor of scientific and technological progress, the motivation for the rapid decline in energy consumption per unit output rested mainly with the efficiency realized by the phased adjustment of the economic structure with respect to the process of institutional transformation, which means the system adjustment from a planned economy to a market economy and the transition towards the law of the industrialized economies. It seems that the energy savings obtained from the economic restructuring in China will be very limited over the next 10 years, and that the product structure is highly dependent on the policy orientation. The energy saving in China is shown in Table 3.7. An estimate of energy saving obtained from the technological progress over the next 20 years is unlikely to exceed 20 %. Therefore, it is necessary for China to develop different kinds of renewable energy to bridge the gap in the energy demand.

According to this development program, the total utilization of renewable energy in China in 2020 will increase to 620 million tons standard-coal equivalent, of which hydropower accounts for 58 %, biomass for 19 %, solar energy for 14 %, wind energy for 8 % and others for 1 %. The total utilization of renewable energy in China in 2030 will reach 1 billion tons standard- coal equivalent, of which hydropower accounts for 45 %, biomass for 23 %, solar energy for 19 %, wind power for 11 % and others for 2 %. The total utilization of renewable energy in China in 2050 will reach 1.7 billion tons standard-coal equivalent, of which hydropower accounts for 26 %, biomass for 20 %, solar energy for 34 %, wind power for 18 % and others for 2 %. In accordance with the intermediate development program, Table 3.8 shows the share of renewable energy as part of the total energy in China. Regarding the statistics, without taking hydropower-power generation into account, the proportion of renewable energy, accounting for the total energy requirement, increases from 1.2 % in the base year (2006) to 25.4 % in 2050. Taking hydropower-power generation into account, the proportion of renewable energy accounting for the total energy increases from 7.6 % in the base year to 34.1 % in 2050, which is obviously increasing faster than that obtained from the conventional development program.

Table 3.7 Energy savings in China [3]

Industrial sector	1980 (%)	1990 (%)	2002 (%)
Agriculture	28.2	27.1	14.5
Industry	48.1	41.6	51.8
Tertiary industry	23.7	31.3	33.7

Table 3.8 Prediction of the installed power-generation capacity in China for all kinds of renewable energy in accordance with the intermediate development program [3]

	2006	2020	2030	2050
Total energy (tons of standard coal equivalent)	24.6	35	42	50
Proportion of renewable energy: with hydro	7.6	17.6	24.5	34.1
Proportion of renewable energy: without hydro	1.2	7.5	13.5	25.4

The prediction of the installed power-generation capacity for all kinds of renewable energy in the intermediate development program for the purpose of comparison with the conventional program is shown in Table 3.8.

Bowing to strong environmental pressure, China will greatly increase its R&D efforts. A significant amount of investment will be put into R&D and the market to promote the solar and bio-liquid fuel technology in this program. The proportion of solar power and bio-liquid fuel in the energy structure will grow rapidly. China has very rich renewable energy resources, which could make renewable energy the mainstream of the energy supply, or even enable renewable energy to dominate the energy requirement in China in the future. The renewable energy market in China is generally only just beginning to enter its rapid development period. Investment in the development of renewable energy is increasing drastically and is accompanied by the rapid development of the manufacturing industry. Significant effort is placed on the large-scale utilization of renewable energy. China is currently launching a variety of projects supporting affirmative development of new energy power generation, focusing on wind power, solar power generation and biomass power generation. It is planned that there will be 10,000 MW of power generation by 2010 to promote the new energy power generation, of which wind power makes up 4000 MW. The capacity of the renewable power generation will be 40,000 MW, including 20,000 MW of wind power. It is anticipated that the annual average growth rate of the wind power generation will be between 15 and 20 %, which means that the installed capacity of wind power connected to the state grid will reach about 8000 MW by 2020. Developing new energy resources affirmatively becomes an important alternative measure to solve the problem of the energy supply shortage in China. Since the 1990s, utilization of solar energy has been growing faster than all other kinds of renewable energy in China. The PV power generation represents the development trend of the solar-energy utilization. The photovoltaic power-generation capacity will increase from 4000 to 8000 MW by 2050.

3.11 Australian Scenario

Australia has access to vast RES and shows spatial distribution of renewable energy.[10] Renewable energy supplies 5 % of the total energy consumption demand currently, and this includes about 6.5 % of power-generation needs. Most of this

[10] Based on the contribution given by Dr. Marian Piekutowski within the Cigré WG C6.15 [3].

energy is delivered by hydroelectric and wind generation (see Fig. 3.6). Biomass and solar energy are also used for power generation, however, this constitutes a small portion of overall demand. Other energy sources (geothermal and marine) are being investigated and tested in pilot projects. The significant deployment of these technologies would mitigate Australia's greenhouse-gas emissions substantially, as electricity generation accounts for the largest part of the country’s carbon emissions. Australian governments have developed policies and initiatives to encourage investment in renewable or environmentally friendly forms of generation infrastructure to reduce carbon emissions. A Mandatory Renewable Energy Target (MRET) scheme introduced in 2006 offered incentives for up to 9500 GWh of new renewable generation annually by 2010 and continuing through to 2020. In 2008, State and Federal Governments partially funded a few more renewable-energy projects, which were funded mostly by private companies: a solar thermal-energy plant and several wind farms, now operational and contributing to the grid supply. Legislation was proposed for a national feed-in tariff, however, the bill has not yet been enacted by government. The Federal Government has announced that an Emissions Trading Scheme (called the Carbon Pollution Reduction Scheme), which has been implemented in 2010, will further stimulate the industry and viability, induce cost parity, reduce greenhouse-gas emissions and act against climate change. A new design for a national Renewable Energy Target (RET) scheme that expands on the MRET scheme has been agreed to. In developing the non-scheduled generation projections, it has been assumed that the national RET scheme will support meeting the expanded target of 45000 GWh nationally by 2020. To meet the emissions targets stemming from these initiatives, future projections used by the Australian Energy Market Operator (AEMO) assume that, apart from traditional large plants (wind farms), there will be a considerable increase in installations of less than 1 MW, including small renewable-energy generating units (PVs), small-scale solar

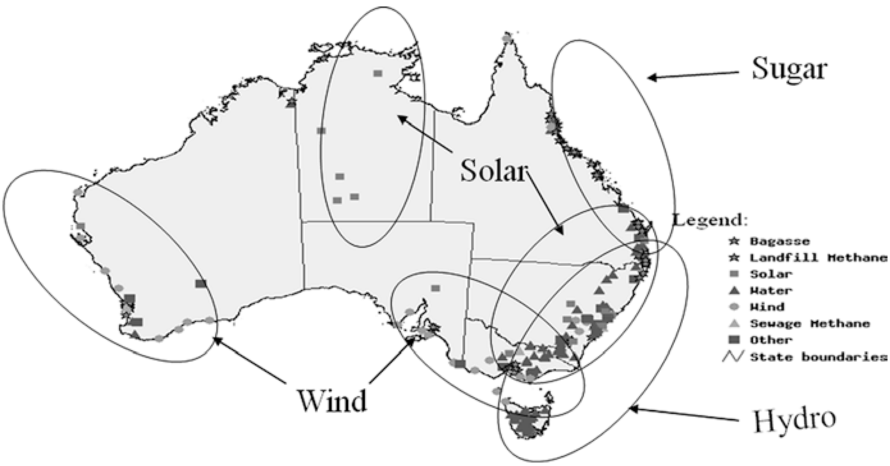

Fig. 3.6 Australian locations of renewable-energy resources [3]

hot-water systems and nonscheduled renewable generating units with a capacity of 1 MW or more, exporting into a local network.

The nonscheduled energy projections do not include new generation from wind farms and other large-scale intermittent generating systems. New intermittent generation, including wind farms with a capacity of at least 30 MW, is to be classified as semi-scheduled. This results in lower projections of energy supplied by significant nonscheduled generation.

Tables 3.9 and 3.10 present projections of semi-scheduled, nonscheduled and exempt generation which will contribute to achieving RETs. Current assumptions indicate that wind-farm generation will be a dominant technology until 2020. There are very limited opportunities to develop new hydro, and there are also concerns about the impact of the ongoing drought on the output of the existing hydro plants. The other renewable category includes commercial-sized solar-thermal generation, solar water heaters, solar photovoltaic, biomass/bagasse electricity generation, wave and tidal generation and geothermal generation. Geothermal sources based on hot fractured-rock technologies have attracted strong interest, particularly in South Australia. The technology is still largely unproven, and potential sites are located remotely from the grid, contributing to high access costs. The projections include small-scale nonrenewable schemes that are based on the gas-fired generation, predominantly open cycle, which operates during peak loads and has an annual

Table 3.9 Projections of the capacity (MW) of semi-scheduled, nonscheduled and exempted generators in the NEM and Jurisdictions, 2008/2009 to 2018/2019 [3]

	2008/2009	2009/2010	2010/2011	2014/2015	2018/2019
Hydro	441	461	461	466	466
Wind	1209	1762	3268	7321	7388
Other renewables	755	755	912	1226	1298
Other nonrenewables	538	535	541	562	562
Total	2940	3513	5182	9575	9714

Table 3.10 Projections of the energy (GWh) generated by semi-scheduled, nonscheduled and exempted generators in the NEM and Jurisdictions, 2008/2009 to 2018/2019 [3]

	2008/2009	2009/2010	2010/2011	2014/2015	2018/2019
Hydro	1203	1253	1253	1266	1266
Wind	3522	5054	9227	20,561	20,733
Other renewables	1322	1322	2059	2853	3156
Other nonrenewables	1243	1243	1268	1333	1333
Total	7290	8872	13,807	26,013	26,488

capacity factor below 20 %. Other small-scale non renewables, such as waste-energy recovery and cogeneration, are also included.

New power and energy projections represent only the NEM system and exclude the Western Australia and Northern Territory systems. These projections have been used in preparation of AEMO's 2009 statement of opportunity.

Test Questions Chap. 3

- What are the aims for renewable energy use for Europe in 2020 and 2050?
- What are the aims for renewable energy use for China in 2020 and 2050?
- What is the highest potential for the use of renewable energies in Australia?
- How is North America investing in renewable energies?

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Chapter 4
Need for Storage. Practical Examples

4.1 Methodology of Investigation

The modeling of an energy storage system (ESS), as already mentioned in Chap. 2, consists mainly of determining two parameters: the storage power and the storage capacity. After having determined these two parameters, which are based generally on the analysis of specific load curves and a general storage model, an optimal storage technology, considering the economic, technical and ecological criteria (also see the example in Sect. 2.4) can be chosen depending on the application (e.g. power quality and/or energy management) that they need to cover.

In this chapter, a few examples from international praxis concerning the local and global integration of renewable energy sources (RES) are treated. The aim is to show the international experiences regarding energy storage and to estimate, only from a theoretical point of view, the needs of energy storage on an international scale. The electric energy storage in these investigations can also be optimized for the full integration of the RES in a power system. The storage size, in this case, depends on the RES share in the energy mix.

A simple methodology follows explaining how to design an ESS for integrating volatile generation by RES. A power-balance profile ($P_{balance}$) is shown in Fig. 4.1.[1] The power balance is defined as the difference between the power generation and the power demand. The value zero depicts the situation in which the system is balanced. Positive values represent an unbalanced situation in which the generation is higher than the demand, while the negative values depict the opposite situation, in which the demand is higher than the generation. The ESS may be used to reduce these unbalanced situations. The storage power (P_{st}) can be evaluated using Eq. (4.1).

$$P_{st} = max\left|P_{balance}\right| \tag{4.1}$$

[1] Compare also with the investigation of optimal storage size in a medium-voltage power network described in Sect. 2.2.2, e.g., see Fig. 2.9.

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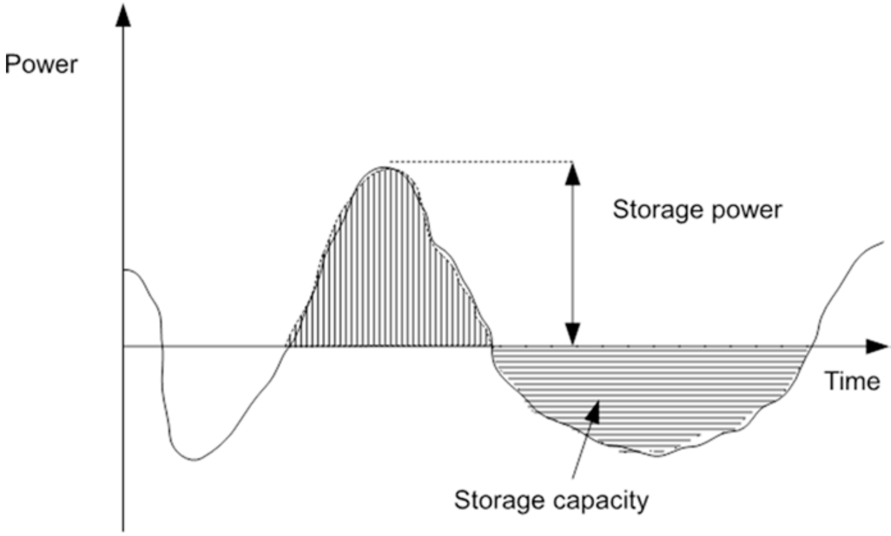

Fig. 4.1 Power-balance profile for estimating the power and energy capacity of an energy storage system

The storage capacity (E_{st}) is evaluated as depicted in Eq. (4.2), where η_{st} is the storage efficiency for charging and discharging.

$$E_{st} = \frac{max\left(\int |P_{balance}| dt\right)}{\eta_{st}} \tag{4.2}$$

For some ESS, such as batteries, the installed storage capacity may be much higher than the capacity evaluated according to Eq. (4.2). The reason for this is due to the relationship between the depth of discharge and the lifetime of the ESS (for more information, also see Chap. 5). In fact, some batteries, such as those belonging to the lithium-ion family, deteriorate quickly if they are charged to their maximum capacity and then totally discharged. Consequently, the capacity used is generally 60–70 % of the total installed capacity.

The useful energy also for flywheel systems and compressed-air energy storage systems (CAES) is generally lower than their maximum storage capacity. Regarding the CAES systems, it depends on the minimal value of the air pressure inside the cavern (for more information, see Chap. 5). In fact, this value must be higher than the maximum inlet air pressure in the turbine.

4.2 Example: Network-Upgrade Deferral

An example for a medium-voltage network deferral during the planning process has been given in Sect. 2.3.3. An example concerning the storage size for deferring the upgrade of a concrete part of the high voltage network is given in the following. A wind farm (plant) is to be installed with a 3.5 GW of installed capacity in a part of the network. The wind generation supplies a region that has a 1 GW maximum and 300 MW minimum load. Both the yearly energy produced by the wind generation (1600 full-load hours) and energy consumption are equal. In order to supply the maximum load of 1 GW, a net transfer capacity (NTC) connection of 1 GW is necessary for a reliable supply (2 GW physical capacity is necessary to fulfil the n-1 conditions). It is possible to obtain the storage energy and power capacity (according the Eqs. (4.1) and (4.2)), which is necessary for the full integration of the wind energy produced, without net-security management systems (NSM) activities, by calculating the energy flow during one year (see Fig. 4.2). The storage size required will be smaller if the NTC of the interconnection is increased by network extensions. For example, if 1 GW NTC is considered, and the renewable generation is fully integrated, then storage of 70 GWh is needed. If the NTC changes to 1.5 GW and 2 GW, storage capacities of 35 GWh and 15 GWh, respectively, are required. Setting the storage costs at 0.10 €/kWh, the generation costs of a wind farm connected by a line with NTC 1 GW will almost double if the strategy for full integration of the wind energy is assumed. Depending on the connection length, increasing the NTC could also be a good strategy for the integration of renewable generation from a region with overcapacity to those where the load can be economically transported. The optimal (technical and economical) capacity of the storage in the generation region analyzed will also depend on the utilization of the storage (number of cycles), which was not considered in this example. Therefore, a complex control strategy for the storage device has got to be modeled that should also include system services to lower the costs. The negative consequence of the full integration of wind overcapacity without storage or necessary NTC capacity was demonstrated on November 4, 2006, in Europe, and resulted in a pan-European power system disturbance close to a blackout. The costs of this disturbance could be specified in a similar manner to the cost of the storage calculated here.

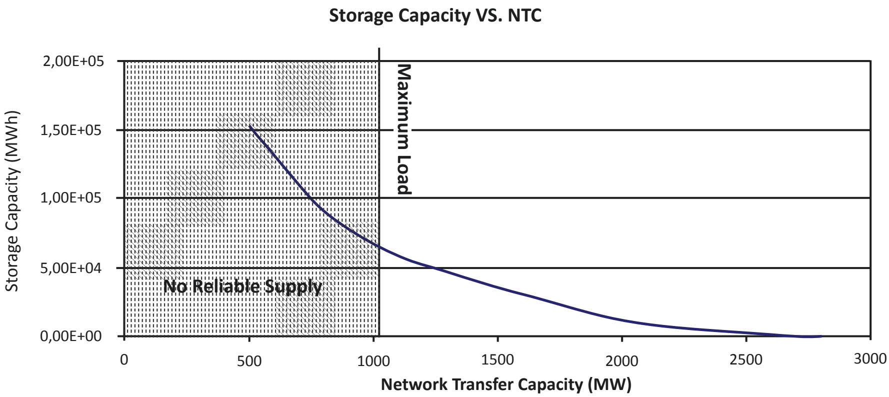

Fig. 4.2 Sizing of energy-storage capacity for network-upgrade deferral

4.3 Technical Aspects. Examples from Japan

Two projects in Japan are depicted in the following as examples of practical large storage realization.[2] The projects are related to the energy storage usage to integrate intermittent renewables to the grid. The first one deals with the "*Rokkasho-mura Futamata Wind Farm*," in which a sodium-sulfur (NaS) high-temperature battery had been installed. The Japan Wind Development Co. has been operating a large-scale wind farm located in Rokkasho-mura in Japan since 2008. The installed capacity of this wind farm is 51 MW and is combined with a 34 MW- NaS battery system supplied by NGK Insulators Ltd. In this wind farm, the NaS battery system has been used primarily to achieve the following objectives:

- to stabilize power output fluctuating due to wind power and
- to increase the firm capacity of wind power.

It is clearly demonstrated from the field data shown in Fig. 4.3 that the NaS-battery system is quite effective in stabilizing the fluctuation in the power output and delivering the scheduled firm capacity. The battery system can store the surplus power during the night and release it during peak hours during the day. The micro- weather

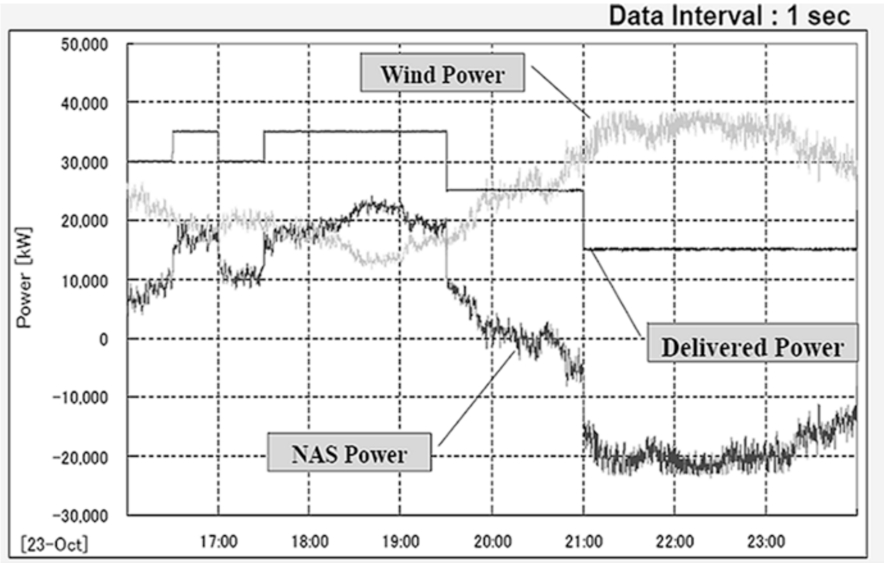

Fig. 4.3 NaS-battery application for a wind farm [1]

[2] Based on the contribution given by Dr. Suresh Verma within the Cigré WG C6.15 [1].

forecast system, energy-storage management system, wind-farm management system and power-management system have all been instrumental in achieving these objectives.

The second example deals with the "*Wakkanai Mega Solar*" project, in which an NaS battery has also been installed. In the *Wakkanai Mega Solar* project, a PV plant with an installation capacity of 5 MW and an NaS battery of 1.5 MW is working to test the grid stabilization functions within large-scale PV-power generation. The project is sponsored by the New Energy and Industrial Technology Development Organization and is being carried out by the Hokkaido Electric Power Co., Inc. The NaS battery is used to absorb the surplus PV generation until noon (12:00 midday) and release energy during peak demand, which is around two hours later (2:00 p.m.) in the summer. The NaS battery combined with the electric double-layer capacitor due to be installed is to smooth the fluctuation in power generation. It is planned to add a NaS battery system with a capacity of 1.5 MW to bridge the supply-demand gap and to smooth the power-output fluctuation.

Figures 4.4 and 4.5 show the operating performance of the 2 MW PV with a 0.5 MW-NaS battery. The PV output can be made constant, and firm capacity can be maintained over nine hours with the help of NaS-battery system.

In conclusion, the NaS battery offers applications that include the suppression of power fluctuation and constant-power output by matching supply demand or peak shifting, etc. to integrate the intermittent renewable resources. The NaS batteries used in both the projects have been an on-site installation, and the main factors that influence the decision regarding the dimensions of the NAS® battery system are as follows;

- To stabilize power-output fluctuation (fluctuation data of demand and supply), and
- to increase the firm capacity or constant power (supply-demand match on a daily basis).

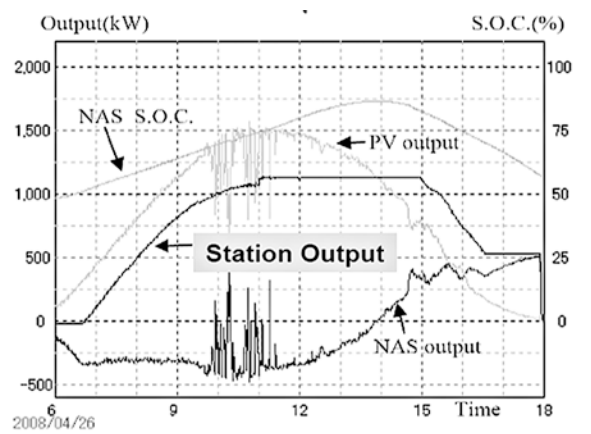

Fig. 4.4 Fluctuation suppression using a NaS battery for PV generation

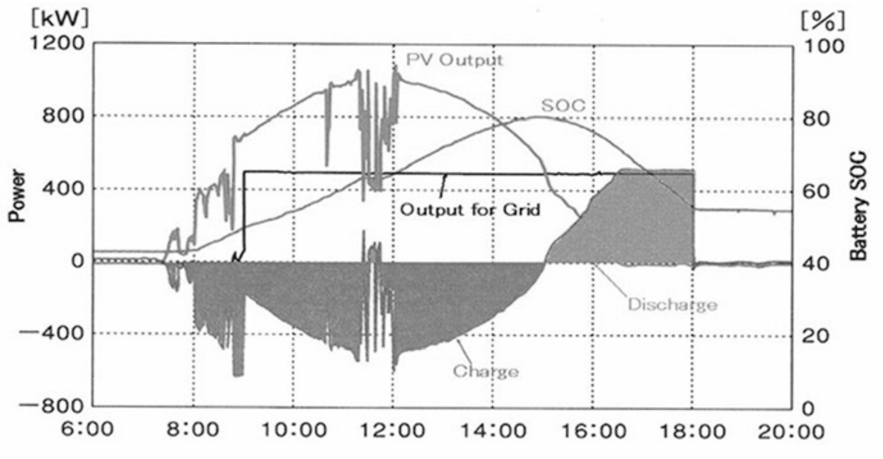

Fig. 4.5 Output by a NaS battery for PV generation

Finally, it is expected that the following additional aspects to optimize the storage systems may become important and require proper attention as the number of large-scale wind farms and mega solar plants with storage systems increase:

- Hybrid storage systems;
- Clustered/distributed storage installation;
- Centralized/distributed control; and
- Coordination of functionality

4.4 Storage for Full RES Integration

In the following section, an example regarding the estimation of the storage capacity worldwide will be given. It is important to note that this example is of a theoretical nature and only has a didactic function; it does not have the aim of forecasting the energy storage capacity needed to integrate the volatile energy sources.

The example aims at estimating the energy storage capacity needed if the electricity demanded is generated by wind energy and some conventional power plants. Three scenarios have been analyzed:

- Scenario 1: The wind energy covers 50 % of the total electricity demanded;
- Scenario 2: The wind energy covers 70 % of the total electricity demanded; and
- Scenario 3: The wind energy covers all the electricity demanded.

The input data for the estimation are the electricity consumption and the installed power. The data collected in [2] were considered for Germany, while data collected

Table 4.1 Energy storage sizing for the scenarios defined

		Germany	Europe	North America	Central & South America	Eurasia	Middle East	Africa	Asia & Oceania
$E_{(wind)}$ 50 %	P_{Con} [GW]	62.47	302.54	416.97	73.59	109.75	51.20	44.05	504.88
	P_W [GW]	215.58	1044.00	1438.90	253.96	378.72	176.69	151.99	1742.20
	$P_{Storage}$ [GW]	182	886.7	1222	215	321	150	129.1	1479
	$E_{Storage(\eta = 80\%)}$ [TWh]	23.04	111.7	154	27.18	40.53	18.91	16.268	186.46
$E_{(wind)}$ 70 %	P_{Con} [GW]	37.48	181.53	250.18	44.16	65.85	30.72	26.43	302.93
	P_W [GW]	301.81	1461.6	2014.4	355.54	530.21	247.37	212.79	2439.1
	$P_{Storage}$ [GW]	256	1241	1711	310	450	210	180.7	2071
	$E_{Storage\ (\eta = 80\%)}$ [TWh]	32.26	156.43	215.6	36.05	56.74	27.15	22.77	261.05
$E_{(wind)}$ 100 %	P_{Con} [GW]	0	0	0	0	0	0	0	0
	P_W [GW]	431.16	2088	2877.8	507.92	757.44	353.39	303.99	3484.5
	$P_{Storage}$ [GW]	366	1773	2444	431	643.3	300.1	258.3	2959
	$E_{Storage\ (\eta = 80\%)}$ [TWh]	46.204	223.48	308	54.36	81.064	37.82	32.53	372.93

in [3] were used for North America, Central and South America, Europe, Eurasia, the Middle East, Africa, and Asia and Oceania. The German data concerns 2008, while the data for the other geographic areas concerns 2006. A wind-generation profile was used that is characterized having a full load of 1600 h, and a conventional power plant was used with a profile of 5450 full-load hours. Both the electricity generation profile and the electricity demand profile come from the measured data of two German networks and from data found in literature [1]. The electricity-demand profiles concern both residential and industrial sectors. The methodology used in Sect. 4.1 has been used to size the ESS, and an ESS with an efficiency of 80 % has been considered. Table 4.1 shows the results of the simulation for the three scenarios.

Regarding Europe and the first scenario, a total storage capacity of 886 GW is needed. Assuming a charge-discharge efficiency of 80%, a reservoir capacity of 111.7 TWh is also required. According to [4.1], the hydro-pumped reservoir capacity in Europe was 179.7 TWh in 1998 and was concentrated mainly in the Scandinavian countries. It is hypothetically possible to conclude that 50 % of the total electricity demand in Europe can be supplied by wind energy. It should also be mentioned that the actual NTC between Scandinavia and Central Europe is only a few GW, and the generation capacity from hydropower in these countries is only on the order of a few tens of GW, whereas a charging power of 887 GW would be necessary.

Considering a distributed location of storage systems, i.e., batteries in electrical vehicles (EVs) with a storage capacity of 18 kWh (three-phase charging), and the first scenario, then more than 50 million EVs should be connected to the network in Europe to absorb the electrical surplus power of nearly 900 GW produced by wind turbines. Table 4.2 shows the necessary number of EVs. With respect to the stored energy, these 50 million EVs would only represent a storage capacity of less than 5 TWh, even if a huge car battery of 100 kWh was considered.

Table 4.2 Number of electric vehicles used as a storage system

	E(wind) 50 %	E(wind) 70 %	E(wind) 100 %
	Numbers of V2G [millions]		
Germany	~11	~15	~24
Europe	~50	~70	~97
North America	~70	~96	~136
Central & South America	~20	~17	~25
Eurasia	~18	~25	~36
Middle East	~9	~12	~17
Africa	~7	~11	~15
Asia & Oceania	~97	~115	165

In conclusion, the simulations above give a rough estimate of the storage capacity required in various geographical areas. Three different scenarios have been analyzed, considering the wind energy as the only renewable source that supplies the power to the grid. Both the storage capacity and the storage capacity reservoir have been estimated. Moreover, a rough evaluation of the number of EVs that could also work as a storage system has also been estimated.

Test Questions Chap. 4

- Do you know of any fully realized EES in Japan? What are the challenges to these applications?
- It is possible to determine, if only theoretically, a storage for full integration of renewable energy? Which methodology should be use for this issue?
- The theoretical needs for storage depend on different factors. Please list these factors and explain their influence on the final storage size.
- What is the theoretical need for storage in Europe when there is full integration of renewables with a 50 % share of RES in the energy mix? Which storage technologies could fulfill these capacity requirements?

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Chapter 5
Storage Technologies and Systems

5.1 Overview

Energy storage systems have been instrumental in the modernization of our society. Energy storage systems have been essential for decoupling electricity generation from consumption since electrification began. Their use will grow yet more predominant in the future; the greatest amount of electricity is being generated by volatile renewable-energy sources, such as wind and solar power. This will entail the use of new solutions to optimally decouple the power generated by renewables from the power demanded. Multi-energy systems and virtual-power plants constitute the most promising solutions; both of them employ energy storage systems as well as demand-side and demand-response programs.

The power exchanged with the bordering country is decisive for balancing the power generated by renewable-energy sources (see Fig. 5.1).

Demand-side and demand-response programs integrate consumers actively in the balancing of electric power. Energy storage systems make it possible to convert electricity into other forms of energy and to store it. The stored power is generally successively reconverted into electricity and supplied to the grid (see Fig. 5.2). The power stored in multi-energy systems can be released in a different form than its original one, for example, in power-to-gas or power-to-heat storage solutions. A power-to-gas system converts electricity into gas (hydrogen and/or methane) and supplies it to the natural gas infrastructure (pipelines, caverns and tanks). A power-to-heat system converts electricity into hot water, steam or even ice and delivers it to the thermal infrastructure (pipelines and storage).

Electricity can be converted and stored in a variety of other forms. Potential, kinetic, mechanical, thermal and chemical storage systems are used predominantly. Pumped-hydroelectric storage is the most advanced technology. This technology has been developed in parallel with hydropower plants in Europe in order to use hydropower reserves better also in periods of low rainfall. The use of nuclear power has increased the need for energy storage systems. This has entailed the construction of new pumped-storage plants. They are the sole solution for decoupling the

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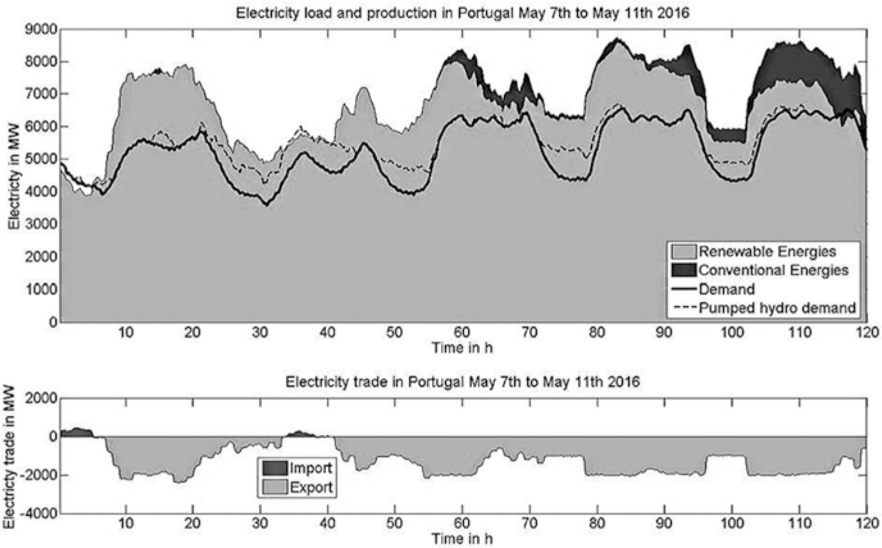


Fig. 5.1 supply of power by renewables in Portugal in May, 2016.

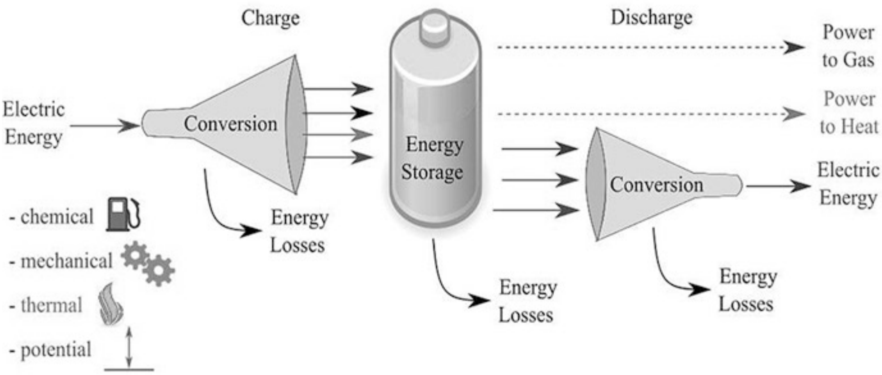


Fig. 5.2 The energy-storage process

power generated by nuclear power plants from electrical loads. Large pumped storage plants store power at night (when low electricity prices exist), thus, enabling nuclear power plants to work continuously near their nominal value. The stored power is gradually released during the peak hours during the day (when high electricity prices exist). Consequently, pumped-storage plants are also used as peak-power plants.

In addition to this first option, electricity can also be stored as kinetic energy by using flywheels. Flywheels are one of the oldest energy storage systems to be used by mankind (see Fig. 5.3). They were largely used in the production of ceramics by

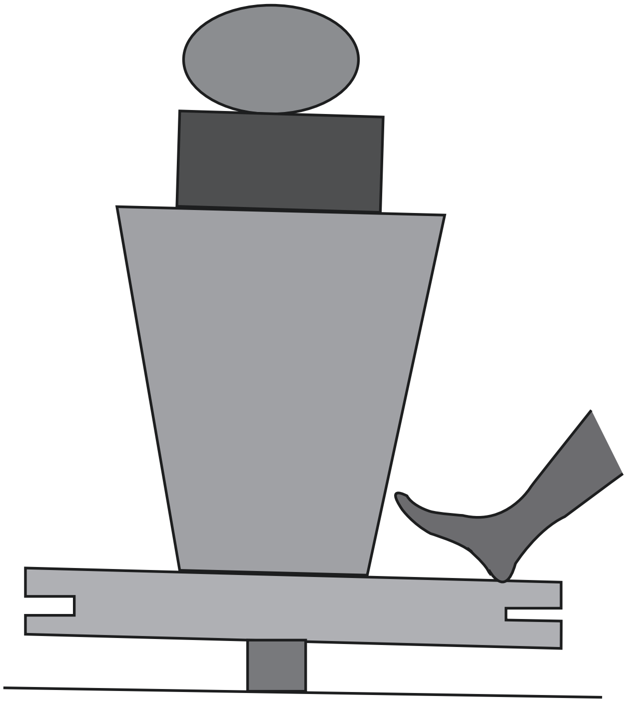


Fig. 5.3 Ptolemaic potter's wheel

constantly accumulating the angular velocity of the potter. Flywheels are now being used in many applications, ranging from automotive to aerospace systems. They are mostly used in electrical grids to supply power to uninterruptible loads and to control an electrical grid's frequency.

Compressed air is another (mechanical) form of electricity storage. Two diabatic compressed-air energy storage (CAES) systems are in operation worldwide. The first diabatic CAES in Huntorf, Germany, commenced operation at the end of 1978. It was the first energy storage plant installed on flat terrain. Its main function was to cover the peak-hour demand for power. A more efficient diabatic CAES system in McIntosh, Alabama, USA, commenced operation in 1991. Both convert electricity into compressed air, which is stored in underground caverns. The heat generated during the compression phase is released into the air. During the discharge phase, the compressed air is warmed inside a combustor and then expands inside a turbine that drives an electric generator. Such energy storage systems store and release large quantities of power (in the range of megawatts) for various time periods. Similar to pumped-hydroelectric storage (PHS) systems, CAES systems have geographic constraints as compressed air has to be stored in caverns.

Unlike energy storage systems that convert electricity into potential and mechanical energy, thermal-storage systems are unidirectional. Rather than being reconverted into electricity, the stored energy is supplied as steam, hot water or ice. Such (seasonal) storage systems store energy long-term. They are used mainly in industrial processes and for the heating and cooling of rooms. They are easily coupled with demand-side management programs at industrial parks.

Electricity converted into chemical form (i.e., hydrogen or methane) can be stored for a long time. Such (power to gas) solutions utilize the entire natural-gas infrastructure (pipelines, caverns, compression stations and tanks). The storage systems can discharge the electricity stored as either heat or electricity. Combined heat and power plants release a combination of heat and power. It is also a solution for transportation, as a variety of combustion engines have been designed to burn methane.

Apart from gas, batteries are another solution that stores electricity chemically. Experience acquired in the electronic-devices sector has helped enhance the performance of battery systems. More and more large battery plants (in the MW domain) have been connected to the grid in recent years. Batteries and gas are also solutions for green transportation. Unlike gasoline-powered models, however, electric vehicles can support the grid when they are connected to it, thus becoming an added resource for grid operators.

5.2 Energy-Storage Performance Indicators

Energy storage systems can be compared and classified technically using key performance indicators. The main indicators used are listed in the Table 2.3. Below three of them, which are used for general storage descriptions, are described in detail.

Round-trip efficiency is the most common one. It describes the losses measured during the charging, discharging and standby phases (see Eq. (5.1)). It is the ratio of the output energy to the input energy. High round-trip efficiency means low energy losses. The energy losses may be of different natures. Generally they are in form of heat and are released into the surrounding environment.

$$\eta = \frac{E_{out}}{E_{in}} \tag{5.1}$$

The state of charge (SOC) represents the amount of energy (E(t)) that can be withdrawn from or stored in an energy storage system over a specific time (t). The SOC is usually related to the maximum storable energy (E_{max}) and is specified as a percentage: A 100 % SOC is a fully- charged energy storage system, while a 0 % SOC is an empty one (see Eq. (5.2)).

$$SOC(t) = \frac{E(t)}{E_{max}} \cdot 100 \tag{5.2}$$

The depth of discharge (DoD) is the ratio of the maximum amount of energy that could be discharged from an energy storage system to the maximum storable energy

(E_{max}). It is usually specified as a percentage: A 100 % DoD indicates that the energy storage system can discharge all of the energy stored (see Eq. (5.3)).

$$DoD = \frac{E_{disch\_max}}{E_{max}} \cdot 100 \tag{5.3}$$

5.3 Electric-Energy Storage System Classification

Energy storage systems are generally classified according to two criteria: power rating and rated energy capacity (see Fig. 5.4). Using these criteria, three application domains can be identified: power quality, bridging power and energy management. Energy storage systems for power quality have to be able to charge and discharge electricity within short periods of times (i.e., minutes). The power rating and energy capacity is slightly higher for bridging power, while power rating and rating capacity are much higher for energy management. Rating power can reach the GW range and capacity covering days to months. Energy storage systems can additionally be classified as short-term (for power quality and bridging power) or long-term (for energy management) storage systems.

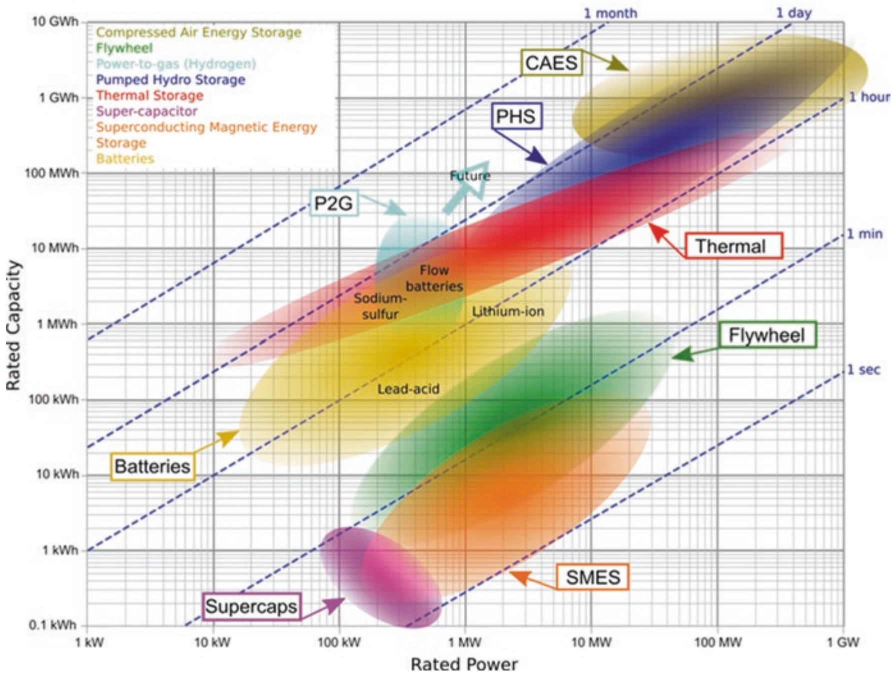


Fig. 5.4 Classification of energy storage applications

The most suitable energy storage technologies for power quality are supercapacitors, superconducting magnetic-energy storage (SMES) systems, flywheels and batteries. Some batteries, for example, sodium-sulfur, lithium-ion and flow batteries, can be also used for bridging power and energy management. Compressed air energy storage, PHS and power to gas systems are energy management applications.

5.4 Pumped-Hydroelectric Storage

Pumped-hydroelectric storage systems are the most advanced energy storage technology worldwide. More than 170 GW are currently in operation. Such energy storage systems store electricity as potential hydraulic energy. During the charge phase, a water system pumps water from a low-level reservoir to a higher-level reservoir. During the discharge phase, the water returns to the lower reservoir, passing through turbines that drive electric generators. As pictured in Fig. 5.5, PHES systems usually consist of an upper reservoir, penstocks, a turbine, a generator, a pump, a motor, a lower reservoir and a connection to the electric grid. There are two main types of PHES facilities: Pure (closed loop) PHES, in which the water pumped into the upper reservoir is the only source of the storage plant, and the hybrid v, in which both the pumped water and natural stream-flow water flow into the turbine to generate electricity.

This technology's round-trip efficiency ranges 70–85 %. The main losses are caused by friction, turbulence and viscous drag inside the turbine, pump and penstocks. Other losses are also caused by the water's kinetic energy, which is not fully recovered in the turbine, and losses of electricity in the generator and motor. A PHES system's efficiency can be calculated with Eq. (5.4), in which ξ_t represents the turbine's overall efficiency and ξ_p the pump's efficiency.

$$\eta = \frac{E_{out}}{E_{in}} = \frac{E_t}{E_p} = \xi_t \cdot \xi_p \tag{5.4}$$

The energy consumed by the pump during charging (E_p) can be calculated with Eq. (5.5) and depends on:

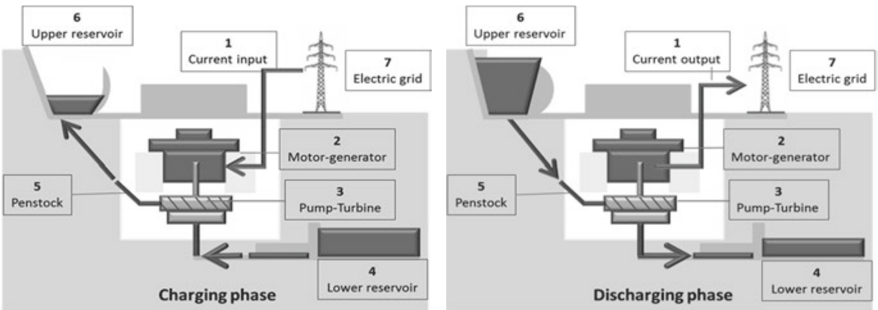


Fig. 5.5 Pumped-hydroelectric storage: charging (*left*) and discharging (*right*)

- the volume of water pumped (V);
- the elevation (h) up to which the water has to be pumped;
- the pump's overall efficiency (ξ_p) ; and
- the water density (ρ).

$$E_p = \frac{\rho g h V}{\xi_p} \tag{5.5}$$

The energy generated by the turbine (E_t) and fed into the electric grid can be calculated with Eq. (5.6):

$$E_t = \rho g h V \xi_t. \tag{5.6}$$

The maximum speed (v) of the mass (m) of the water entering the turbine depends on the elevation (h) of the upper reservoir. It can be calculated by matching its potential energy (W_{pot}) with the kinetic energy (W_{kin}) (see Eqs. (5.7) and (5.8)) it attains at the turbine inlet. It can be evaluated with Eq. (5.9).

$$W_{kin} = W_{pot} \tag{5.7}$$

$$\frac{1}{2} m v^2 = W_{pot} = mgh \tag{5.8}$$

$$v_{max} = \sqrt{2gh} \tag{5.9}$$

The first PHS plants were installed in the alpine regions of Italy and Switzerland at the end of nineteenth century. They were comprised of two units, the motor-pump and the generator-turbine, which were mounted on two separate shafts. Such a scheme is rarely utilized today because of the high capital expenditure required. Reversible binary and ternary machine schemes are most frequently used instead. A reversible binary machine consists of a single reversible pump/turbine and motor/generator unit mounted on the same shaft (see Fig. 5.6 left). The pump-generator can operate either as a pump or as a turbine, depending on its direction of rotation. The advantage of such a scheme is the capital expenditure required, and the disadvantage is its lower overall efficiency. A variable-speed generator motor can be utilized to increase efficiency. It can be an asynchronous or synchronous motor-generator with a frequency converter. Its use raises the pump's rotational speed and extends the turbine's operating range. A torque converter can be used to start pumping without disrupting the system voltage.

The ternary unit consists of a motor-generator, a turbine and pump on the same shaft mounted vertically or horizontally (see Fig. 5.6 right). Such a configuration is roughly 20 % more expensive, but also more efficient than a binary one. Francis and Pelton turbines are normally used. Francis turbines are designed for water heads of up to 700–800 meters, and Pelton turbines cover larger heads. The machine is

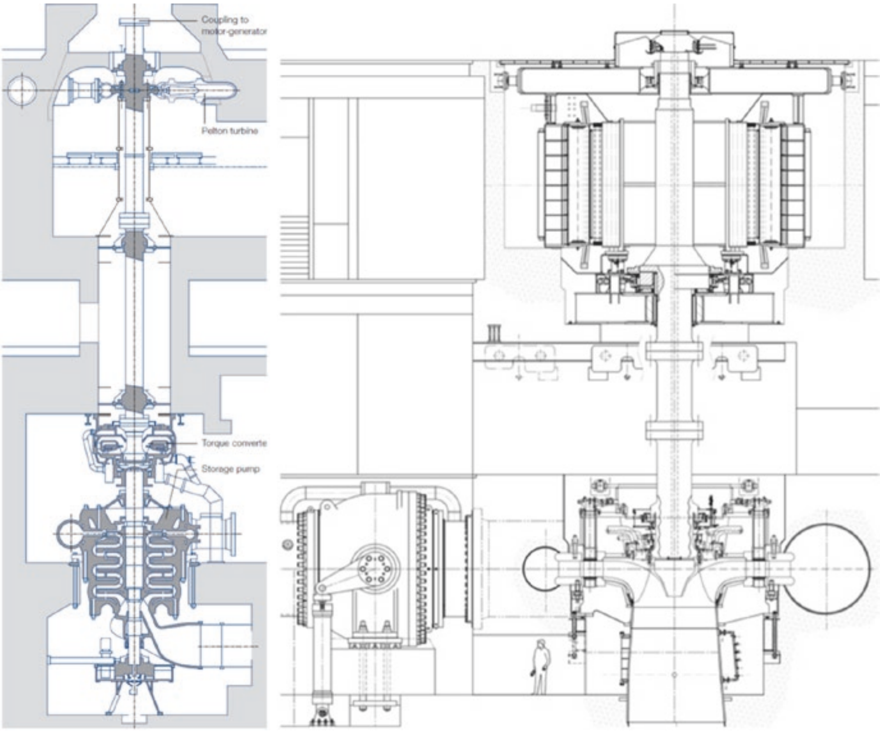


Fig. 5.6 Reversible binary machine (*left*) and a ternary system (*right*) [1]

started by activating the pump, and the load is subsequently progressively transferred to the motor-generator. Both the turbine and the pump can be regulated from 0 to 100 % of unit output.

The highest pumped-hydropower capacity is installed in Japan, China and the USA, respectively (see Table 5.1). Apart from orographic reasons, the main motive for the use of PHES in these countries is the decoupling of power generated by nuclear power plants from loads. The world´s first 30 MW-seawater PHS system has been in operation in Okinawa, Japan, since 1999 (see Fig. 5.7). Using the sea as its lower reservoir, It pumps seawater to an upper reservoir 150 meters above sea level.

5.5 Flywheel-Energy Storage

A flywheel system stores electricity as kinetic energy. Its capacity to store energy depends on its rotating mass, shape and rotational speed. The rotating mass is connected to a motor-generator that causes the flywheel to accelerate (when charging) and to decelerate (when discharging). When the flywheel is not in use, it idles at its idle speed. Flywheels generally consist of a cylindrical rotor or dish (mechanical

Table 5.1 Pumped-hydroelectric storage capacity installed worldwide [3]

Country	Installed capacity [MW]	Country	Installed capacity [MW]	Country	Installed capacity [MW]
Japan	27,438	Poland	1745	Lithuania	900
China	21,545	Portugal	1592	Philippines	709
USA	20,858	South Africa	1580	Greece	699
Italy	7071	Thailand	1391	Serbia	614
Spain	6889	Belgium	1307	Morocco	465
Germany	6388	Russia	1246	Ireland	292
France	5894	Czech Republic	1145	Croatia	282
India	5072	Luxembourg	1096	Slovenia	185
Austria	4808	Bulgaria	1052	Canada	174
Korea, South	4700	Iran	1040	Romania	53
United Kingdom	2828	Slovakia	1017	Chile	31
Switzerland	2687	Argentina	974	Brazil	20
Taiwan	2608	Norway	967		
Australia	2542	Ukraine	905		

Fig. 5.7 Seawater pumped-hydropower plant in Okinawa, Japan [2]

or magnetic), bearings, a motor-generator and power electronics enclosed inside a low-pressure vacuum (see Fig. 5.8). The vacuum reduces the aerodynamic friction between the flywheel and the air. The use of magnetic bearings affects efficiency similarly. Flywheels can have a round-trip efficiency of more than 80 % and self-discharge of less than 3 %/hour. Superconducting magnetic bearings can

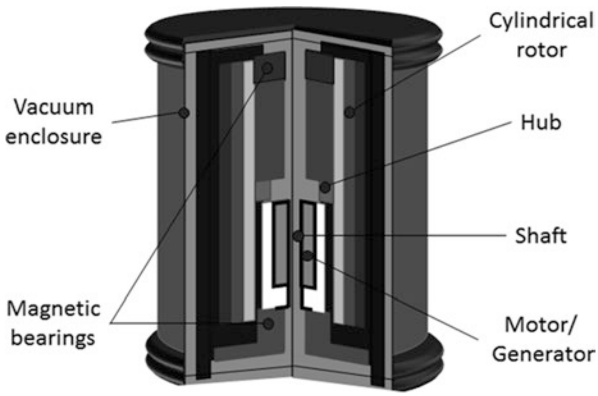


Fig. 5.8 Model high-speed flywheel

reduce self-discharge to less than 0.5 %/hour, but require higher capital expenditure. Flywheels are generally classified into two categories: low-speed and high-speed. Low-speed flywheels are usually made of metals such as steel and have mechanical bearings. They have an operating angular velocity in the range of 6000 rpm. High-speed flywheels are made from composites and have magnetic bearings. They have an operating angular velocity in the range of 100,000 rpm.

As mentioned above, flywheels store electricity as kinetic energy. If J is the moment of inertia of a mass (m) rotating with an angular velocity (ω), then the stored energy can be calculated by Eq. (5.10):

$$E = \frac{1}{2} J\omega^2. \tag{5.10}$$

The moment of inertia is a function of the mass and the shape of the mass. It can be calculated by Eq. (5.11):

$$J = \int x^2 dm_x. \tag{5.11}$$

where x is the distance of the differential mass (dm_x) from the rotating axes. The moment of inertia of a flywheel with its mass m concentrated at the edge of the radius (r) is calculated by Eq. (5.12):

$$J = \int x^2 dm_x = mr^2. \tag{5.12}$$

The maximum energy that a flywheel can store depends on its material, which determines the upper angular velocity. A rotating mass is subject to tensile stress. The tensile stress (σ) of a flywheel with its mass (m) concentrated at the edge of the radius r is calculated by Eq. (5.13):

$$\sigma = \rho r^2 \omega^2 \tag{5.13}$$

where ρ is the density of the material. When the maximum tensile stress (σ_{max}) of the material is known, then the maximum angular velocity (ω_{max}) is also known. The maximum stored energy is calculated by Eq. (5.14):

$$E_{max} = \frac{1}{2} m \frac{\sigma_{max}}{\rho}. \tag{5.14}$$

Along with the maximum storable energy, knowledge of the specific energy per unit mass (E_m) is also important. It is calculated by Eq. (5.15). Table 5.2 presents the tensile strength and the maximum specific energy density for different materials.

$$E_m = \frac{1}{2} r^2 \omega^2 \tag{5.15}$$

The minimum, operating angular speed depends on the drivetrain torque (T). When power (P) is constant, the angular speed drops when the drivetrain torque (T) increases (see Eq. (5.16)):

$$P = T\omega. \tag{5.16}$$

The higher the angular velocity is, the more energy is stored. Given the limitation on the drivetrain torque, the speed ratio, i.e., the ratio between the minimum and the maximum operating angular velocity ($s = \omega_{min}/\omega_{max}$), is usually never lower than 0.2. The useful stored energy is calculated with Eq. (5.17):

$$E = \eta_{st} E_{max} \left(1 - s^2\right). \tag{5.17}$$

Figure 5.9 shows the correlation between the discharge energy and the speed ratio. Slowing down the angular velocity up to 50 % of its maximum value, the discharged energy is about 75 % of the nominal value. It means that the DoD in this case is 75 %.

A single flywheel generally has an energy storage capacity which ranges from 0.25 to 6 kWh. The storage capacity increases if more flywheels are connected in parallel. Currently, some companies are commercializing flywheel systems with a storage power of 20 MW and an energy storage capacity of 5 MWh (15 min at maximum rated power).

Table 5.2 Data on various rotor materials [4]

Material	Density [kg/m³]	Tensile strength [MPa]	Maximum specific energy density [kWh/kg]
Monolithic material: 3040 steel	77,000	1520	0.05
Composites			
E-glass	2000	100	0.014
S2-glass	1920	1470	0.21
Carbon T1000	1520	1950	0.35
Carbon AS4C	1510	1650	0.30

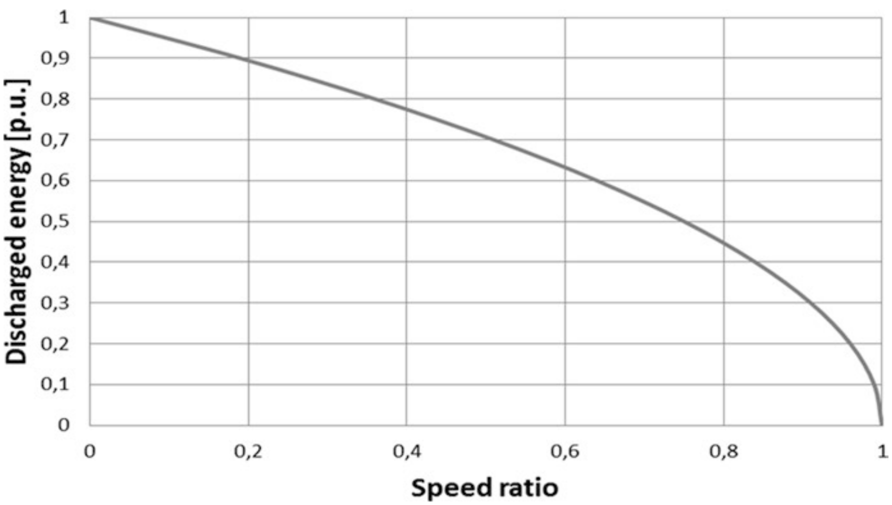


Fig. 5.9 Correlation between discharged energy and speed ratio

The flywheels in power systems currently in use are employed mostly for power applications (rapid charge and discharge), such as frequency control. A demonstration project in 2008 tested the use of a 1 MW (250 kWh) flywheel system for frequency regulation in the Independent System Operator New England electric grid. A larger flywheel (20 MW, 5 MWh) has been in operation in the New York ISO grid since 2011. Table 5.3 summarizes the main performance characteristics of flywheels.

5.6 Battery-Energy Storage Systems

Battery-energy storage systems are the most established energy storage technology. They are classified as primary or secondary batteries, the main difference being the recharging capability. Primary batteries can only be discharged. Since secondary

Table 5.3 Main performance indicators of flywheels [5]

Indicator	Value
Power footprint [kW/m²]	1.4–490
Energy footprint [kWh/m²]	0.35–0.54
Round trip efficiency	80–90 %
Standby energy loss [h^{-1}]	1–3 %
Ramp rate [sec^{-1}]	>25 %
Operational life [cycles]	>100,000

batteries can be charged and discharged many times, only they can be labeled as energy storage systems.

The main components of batteries are the electrodes (anode and cathode), the electrolyte and the external circuit. The electrodes and the electrolyte may be made of solid or liquid materials. The electrodes have contact with the electrolyte. During discharge, the anode supplies positive ions (cations) to the electrolyte, thus, oxidizing and charging itself with electrons (see Eq. (5.18)). At the same time, the cathode receives electrons through the external circuit and reduces itself (see Eq. (5.19)). It also receives positive ions from the electrolyte and supplies negative ions (anions) to the electrolyte.

$$E(A)_{red} \rightarrow E(A)_{ox} + n \cdot e^{-} \tag{5.18}$$

$$E(C)_{ox} + n \cdot e^{-} \rightarrow E(C)_{red} \tag{5.19}$$

The energy delivered to the external circuit as current and to the surrounding ambient as heat is the difference in the bonding energy between the commencement and the conclusion of the battery's reaction (see Eq. (5.20)).

$$\left(E(A)_{red} + E(C)_{ox}\right)_{sta} - \left(E(A)_{ox} + E(C)_{red}\right) = electricity + heat \tag{5.20}$$

During charging, the electrons move from the cathode to the anode through the external circuit. The positive ions move from the cathode to the anode through the electrolyte, and the negative ions move from the anode to the cathode also through the electrolyte (see Fig. 5.10).

The substances reacting are usually stored in the electrodes or in the electrolyte. This is the case in lead-acid batteries. The substances reacting are stored in separate tanks in flow batteries.

The electromotive force of a battery enables electrons to move, contingent on the difference between the electric potentials of the electrodes. The voltage to the terminals equals the difference between the electromotive force and the internal resistance. Then lower is the value of the internal resistance, then higher is the round-trip efficiency of the battery.

Lithium-ion batteries are some of the most widespread secondary battery technologies. The cathode is made of lithiated metal oxide ($LiCoO_2$), and the anode is layered graphitic carbon. The electrolyte consists of lithium salts dissolved in organic carbonate. During charging, the lithium in the $LiCoO_2$ is ionized, and the ions move to the cathode where they intercalate in the graphite layers (see Fig. 5.11). During discharging, the lithium ions move from the anode to the cathode where they intercalate in the crystal structure. Equations (5.21) and (5.22) present the main chemical reactions:

$$Cathode: LiCoO_2 \leftrightarrow Li_{1-x}CoO_2 + xLi^{+} + xe^{-} \tag{5.21}$$

$$Anode: xLi^{+} + xe^{-} + xC_6 \leftrightarrow xL_iC_6. \tag{5.22}$$

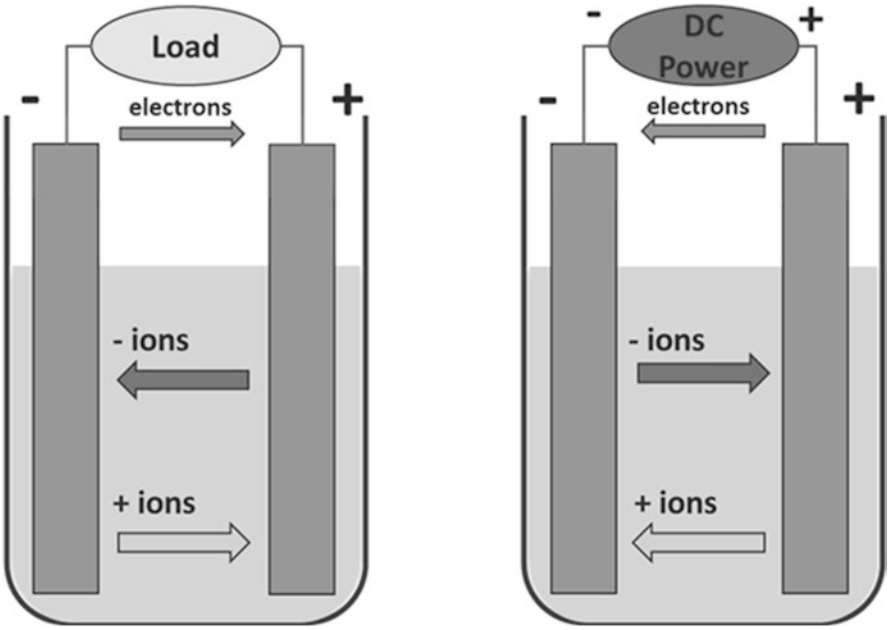


Fig. 5.10 Movement of electrons and ions during discharging (*left*) and charging (*right*)

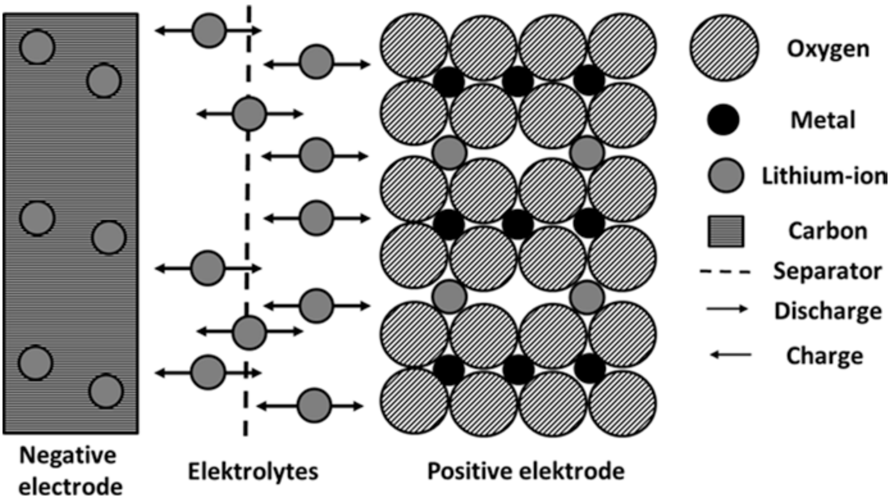


Fig. 5.11 Charging and discharging of a lithium-ion cell based on LiMeO2 cathode material and a carbon-based anode

Commercially available lithium-ion batteries have a round-trip efficiency of between 80 and 85 % and a life of 5000 full cycles. The specific energy density ranges between 100 and 250 W/kg, while the specific power density varies between 300 and 1500 W/kg. Round-trip efficiency is expected to reach 90 % and a life of 10,000 full cycles by 2030. An example of lithium-ion battery is depicted in Fig. 5.12.

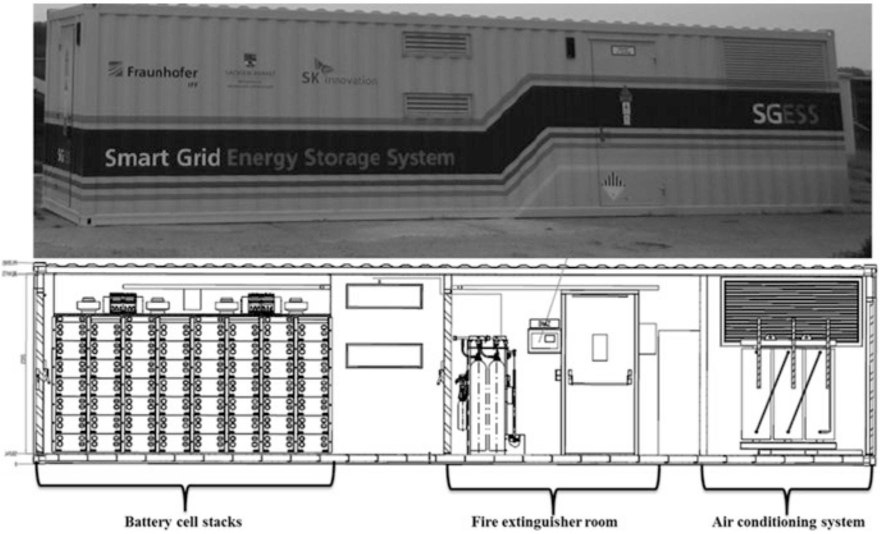


Fig. 5.12 Lithium-ion battery (1 MW, 500 kWh) in operation at Fraunhofer Institute IFF Magdeburg, Germany (*top*) and its layout (*bottom*)

Lithium-ion batteries can be used for power quality (frequency and voltage control), as well as energy-management applications (integration of volatile renewables). A variety of large lithium-ion batteries (up to different tens W and tens MWh) have been installed all over the world in recent years.

Research on lithium-ion batteries has concentrated primarily on testing new materials for electrodes and electrolytes that cut costs, improve efficiency, and increase life and safety.

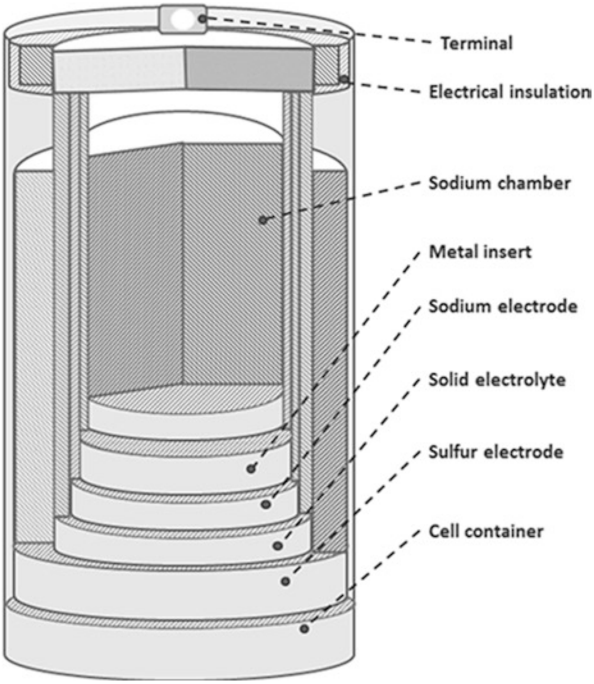
In addition to lithium-ion batteries, more and more high-temperature batteries have been connected to the grid in recent years. Sodium-sulfur (NaS) batteries are used most frequently. To date, over 300 MW in NaS batteries have been installed worldwide. Unlike lithium-ion batteries, high-temperature batteries use a beta alumina solid material (β''-Al_{2O3}) as the electrolyte and have molten (sulfur and sodium) electrodes. Since these batteries have to have a temperature of 270–350 °C in order to keep the electrodes in a liquid state, they must be thermally insulated. They use an internal ohmic heater to maintain high temperatures during standby.

During the discharging phase, the sodium is oxidized and the sulfur is reduced to form sodium polysilfides Na_{2S_x} (x = 3–5) in the positive electrodes (see Eq. (5.23)). This reaction is highly exothermic, which contributes to keeping the temperature of the whole battery at a high level.

$$2Na + xS \leftrightarrow Na_2S_x \tag{5.23}$$

Only one company manufactures NaS batteries at the present time. The structure employed stores the sodium inside a tubular container made of a solid electrolyte surrounded by the sulfur (cathode) (see Fig. 5.13). Its round-trip efficiency ranges

Fig. 5.13 A NaS battery



between 75 and 80 %, and its life can reach 10,000 full cycles. The energy and power density are in the range of 150–250 W/kg and 150–230 W/kg, respectively. High-temperature NaS batteries can be used for power quality and energy-management applications. Their pulse power capability is five times higher than the nominal value for 30 s (Fig. 5.14).

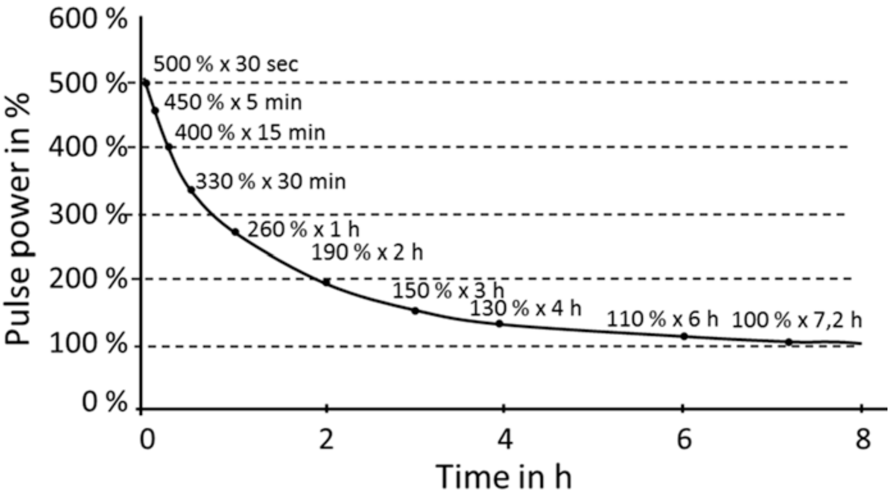


Fig. 5.14 Pulse factor of a high-temperature NaS battery

In addition to lithium-ion and sodium-sulfur batteries, lead-acid batteries are often used in power applications, mostly as backup systems. The electrodes in lead-acid batteries consist of lead and lead coated with lead dioxide (PbO_2) (see Fig. 5.15). The electrolyte is a dilute solution of sulfuric acid (H_2SO_4). During discharging, both electrodes are converted into lead sulfate ($PbSO_4$), consuming sulfuric acid from the electrolyte. During charging, the lead sulfate is converted into sulfuric acid, forming a layer of metallic lead in the anode (see Eq. (5.24)) and a layer of lead dioxide in the cathode (see Eq. (5.25)). During charging, the electrolyte's water is additionally split into hydrogen and oxygen and released into the atmosphere. This makes it necessary to add water to the system. This problem can be circumvented by adding silica to the electrolyte to form a gel.

$$P_bSO_4 + 2H_2 + 2e^- \leftrightarrow H_2SO_4 + P_b \tag{5.24}$$

$$P_bSO_4 + 2H_2O \leftrightarrow P_bO_2 + H_2SO_4 + 2H_2 + 2e^- \tag{5.25}$$

Although the round/trip efficiency between 75 and 80 % is similar to other battery technologies, the life of a lead-acid battery is very limited and ranges between 500 and 2000 cycles. It depends mostly on the DoD. High DoD intensifies corrosion and electrode material shedding. Temperature also affects the storage capacity, e.g., storage capacity at −4 °C is 70–80% of what it is at 24 °C. Energy and power density, 33–42 W/kg and 180 W/kg, respectively, are also limited.

Unlike conventional batteries, flow batteries employ liquid electrolytes stored in two separate tanks. During charging and discharging, the electrolytes are pumped into the stack, which contains an ion-exchanger membrane or an electrode array. Energy is stored in the active materials dissolved in the electrolytes.

Vanadium is one of the active materials used most commonly in electrolytes. Vanadium redox couples (V^{2+}/V^{3+}) are pumped into the anode half-cell and the V^{4+}/V^{5+} in the cathode half-cell. Active materials are fully dissolved in sulfuric acid electrolyte solutions. During discharging, the V^{2+} in the anode half-cell is oxidized into V^{3+} and one electron is released to the external circuit (see Eq. (5.26)). At the

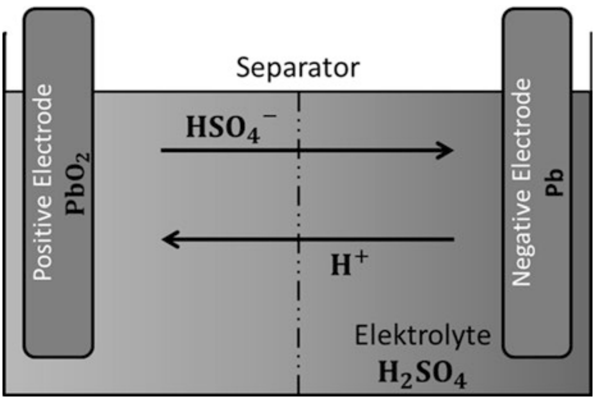


Fig. 5.15 A lead-acid cell

same time, the V^{5+} (in the form of VO_2^{+}) in the cathode half-cell accepts one electron from the external circuit and is reduced to V^{4+} (in the form of VO^{2+}) (see Eq. (5.27)).

$$V^{2+} \leftrightarrow V^{3+} + e^{-} \tag{5.26}$$

$$VO_2^{+} + 2H^{+} \leftrightarrow VO^{2+} + H_2O - e^{-} \tag{5.27}$$

Unlike conventional batteries, the energy capacity of flow batteries is limited only by the size of the tanks and the number of electrolytes. An additional benefit is avoiding the need to balance the cells, which is typical of multi-cell batteries. Flow batteries have a round-trip efficiency of 65–72 %. It is lower than the round-trip efficiency of other batteries because flow batteries have additional auxiliary loads, for example, electrolyte pumps. The life of flow batteries is only limited by the service life of the two pumps and the membrane, which should be replaced about every 10,000 cycles. The energy density ranges between 10 and 20 W/kg, lower than that of lead-acid batteries.

5.7 Superconducting Magnetic Energy Storage

The SMES stores the electricity in form of a magnetic field created by the flow of direct current (DC) in a superconducting coil. Different from the other energy storage technologies, the only conversion process presented in the SMES is the conversion from the alternating current (AC) to DC. As a consequence, the associated

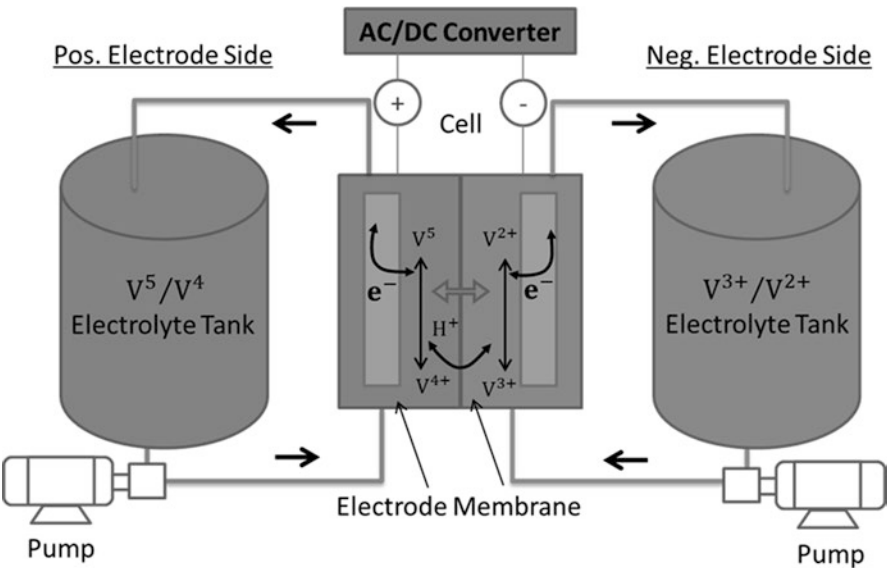


Fig. 5.16 A vanadium-redox flow battery

losses are very low and the storage efficiency very high (about 95 %). Even if SMES systems are capable of storing large amounts of energy and, therefore, could be used for energy applications such as load leveling, thanks to their rapid discharge capability, they are mostly used for power applications such as system stability.

The SMES systems are composed of four main components: a superconducting coil, a refrigerator, a power conversion system (PCS) and a control system (see Fig. 5.17). The energy is stored in the superconducting coil in the form of a magnetic field generated by the flow of DC. As indicated in Eq. (5.28), the stored energy (E) is linearly proportional to the inductance of the coil (L) and squarely proportional to the circulating current (I). The storage capacity is determined by the size and the geometry of the coil, while the storage power is determined by the characteristics of the superconductor, which, in turn, determines the maximum current. The superconductor is typically made from an alloy of niobium and titanium (Nb-Ti) (see Fig. 5.18), which operates at about 4.2 °K (–269 °C). At this temperature, the resistance is typically zero. A cryogenic refrigerator is needed in order to reach this temperature. It is composed of various compressors and a vacuum enclosure. Helium is used as the cooling medium because it is the only material which is not a solid at that temperature. The compressed helium in the vacuum enclosure changes its phase in the liquid one, which is used for cooling the coil. The PCS works as an interface between the power grid (AC) and the superconducting coil (DC). The control system manages the SMES according to the signals received from the grid and the status of the SMES.

$$E = \frac{1}{2} L I^2 \tag{5.28}$$

The energy storage capacity for SMES systems ranges from a few MJs to hundreds of MJs. A SMES system is able to discharge its total energy in a second.

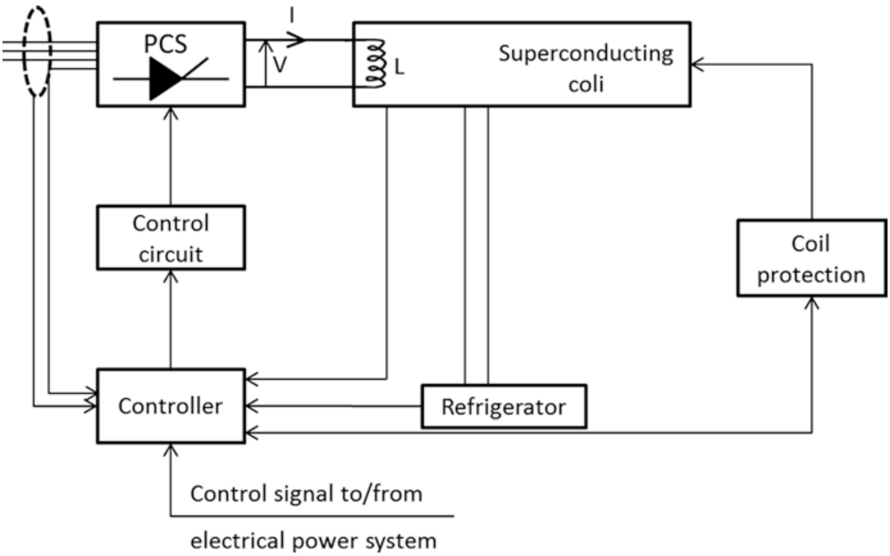


Fig. 5.17 Scheme of a SMES system

Fig. 5.18 Superconducting wire (www.luvata.com)

5.8 Power-to-Gas

The term "power-to-gas" generally refers to two different methods of electricity storage. In the first, electricity is converted and stored as hydrogen. In the second, electricity is converted into hydrogen and, subsequently, this hydrogen is methanated and stored as methane. Both processes require an electrolyzer system that uses electricity to convert deionized water into hydrogen and oxygen (see Eq. (5.29)):

$$2H_2O \leftrightarrow 2H_2 + O_2. \tag{5.29}$$

Part of the electricity used to split the water into hydrogen and oxygen is lost in the electrolyzer as heat. Other parts are lost in the rectifier and in auxiliary equipment, e.g., the compressor. All of these effects decrease the electrolyzer system's efficiency, which is generally referred to as the higher heating value (HHV) of the gas. (Hydrogen's HHV is 39.44 kW/kg.) Two different types of industrial electrolyzers are normally used: alkaline and proton-exchange membrane (PEM) electrolyzers. The overall efficiency of these systems ranges from 56 to 73 %, depending on the type of electrolyzer (the PEM electrolyzer has the lowest efficiency value).

The methanation process is based on combining four moles of hydrogen to one mole of carbon dioxide (CO_2) to obtain one mole of methane and two moles of steam (see Eq. (5.30)). Also known as the Sabatier reaction, this exothermic process (0.045 kW/mol) requires high temperature and high pressure to produce a large amount of methane. The efficiency of the reaction ranges from 75 to 80 %.

$$4H_2 + CO_2 \leftrightarrow CH_4 + 2H_2O \tag{5.30}$$

The overall efficiency of the power-to-gas process (with methanation) ranges from 42 to 58 %. This value does not factor in the transformation of the gas into electricity. When

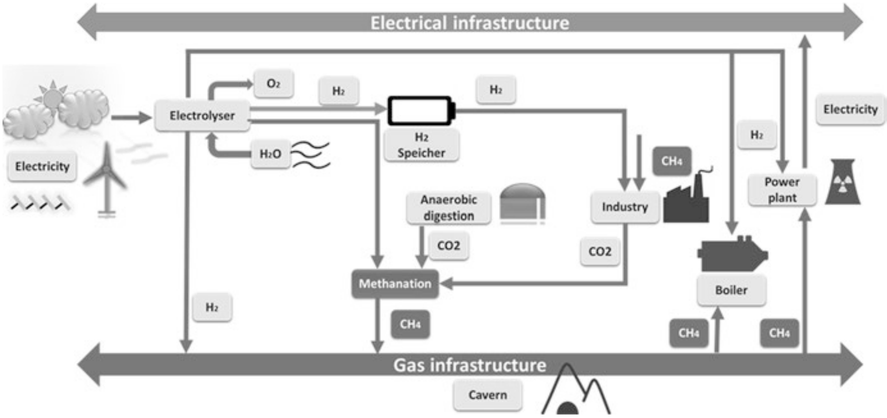


Fig. 5.19 Power-to-gas scheme [6]

the stored methane is burned in a combined-cycle power plant with an electric efficiency of 60 %, then the overall efficiency of the power-to-gas process (from electricity to electricity) is about 30 %. The efficiency of the power-to-gas process can be increased by recovering the heat generated when the water is split. One potential application for this is fermentation in biogas plants. Since biogas plants need heat for fermentation and emit free CO_2 to the atmosphere, which can be reused to make methanate hydrogen, biogas can be viewed as complementary to the power-to-gas systems because it is a CO_2 neutral emission. Figure 5.19 depicts an example of a power-to-gas concept. The electrolyzers convert the surplus electricity generated by RES into hydrogen. The methanizers combine the hydrogen with the CO_2 emitted by biogas plants. The methane produced is then fed into the natural-gas network. The gas is used to generate either electricity (e.g., in gas–turbine power plants) or thermal power for heating or industrial purposes.

In contrast to the power-to-gas system's lower energy efficiency compared to other energy storage systems, its chief advantages are environmental and economic. A power-to-gas system burns hydrogen or methane in a carbon-free process when the gas is produced from renewable-energy sources. The primary economic advantage is the elimination of notable capital expenditure by utilizing the existing natural-gas infrastructure (e.g., pipelines, compressors, caverns). Over 200,000 km of natural-gas transmission pipelines and more than 200 caverns are in operation in Europe (see Fig. 5.20) They transmitted 5,058,000 GWh of energy in 2011. The American natural-gas system, considerably larger than the European natural-gas system, has some 490,000 km of high-pressure pipelines, 1400 compressors and 400 caverns (see Fig. 5.21). However, power to gas also has some limitations. Complications can occur in power-to-gas systems that store electricity as hydrogen when the latter is fed into the natural-gas network. The reasons are the components that typically make up the natural-gas network structure, such as pipelines, compressors, caverns, gas turbines and instrumentation. Originating from the potential problems caused by reactions between the materials, the greatest limitation is due to composing the pipeline medium. Opinions on the volume of hydrogen that natural-gas pipelines are able to transport vary in the literature and range between 10 and 50 %.

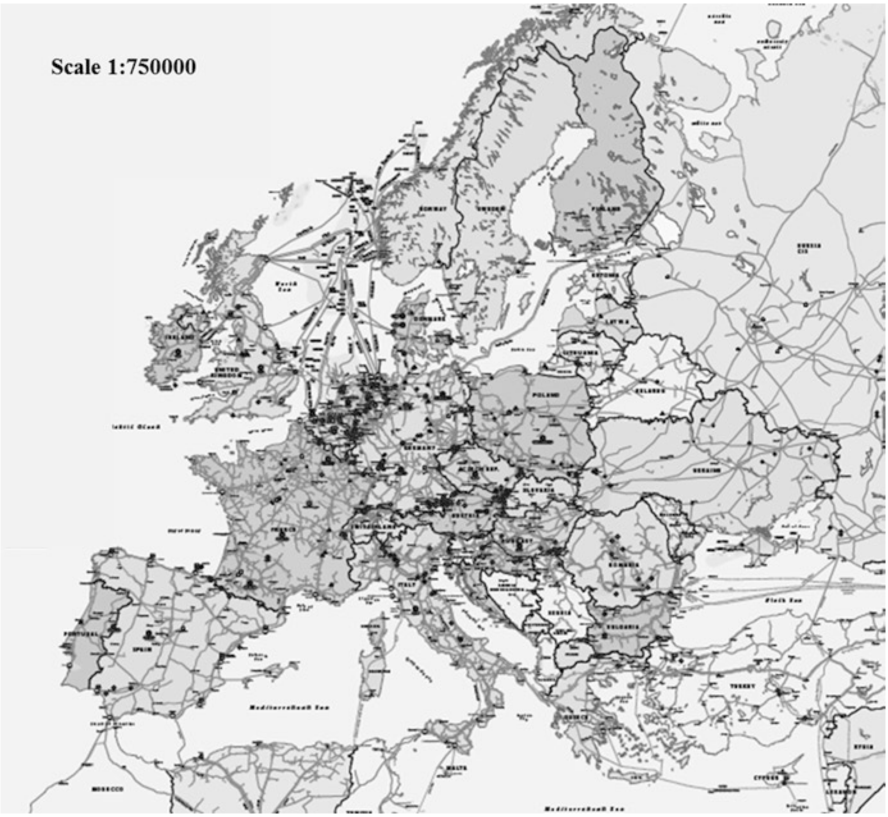


Fig. 5.20 The European natural-gas pipeline in 2014 [7]

Centrifugal compressors with a compression ratio of around 15 bars are normally used. They are driven by open-cycle gas turbines that burn natural gas taken from the natural- gas pipeline and require approximately 20–25 MW of power to drive the compressor. Compressor blade materials, the amount of energy required to compress the hydrogen-methane mixture and the boiler of the gas turbine impose limitations on compressors. The materials employed should enable the compressors actually used in the natural-gas network to compress a volume of up to 5 % hydrogen without any problem. The energy to compress the gas is calculated by Eq. (5.31), where γ is the ratio of the specific heat, p is the pressure, V is the volumetric density and the subscripts 0 and 1 indicate the initial and final compression.

$$W = \frac{\gamma}{\gamma - 1} p_0 V_0 \left[\left(\frac{p_1}{p_0} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \tag{5.31}$$

By considering the same compression ratio and the same mass flow rate, the energy to compress the hydrogen-methane mixture grows by increasing the volumetric percentage of hydrogen (Fig. 5.22). Approximately nine times as much energy

Fig. 5.21 The US network of natural-gas pipelines in 2009 [8]

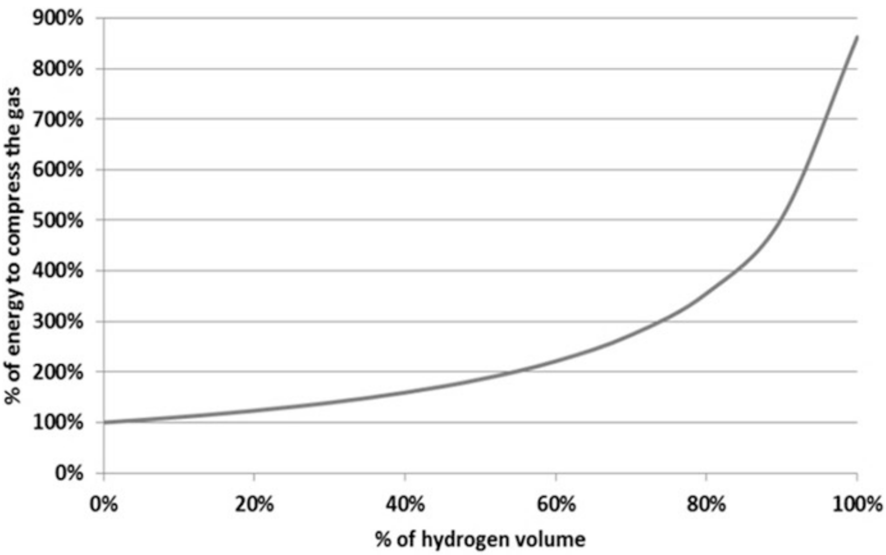


Fig. 5.22 The energy required to compress a hydrogen-methane mixture compared to the energy required to compress methane alone

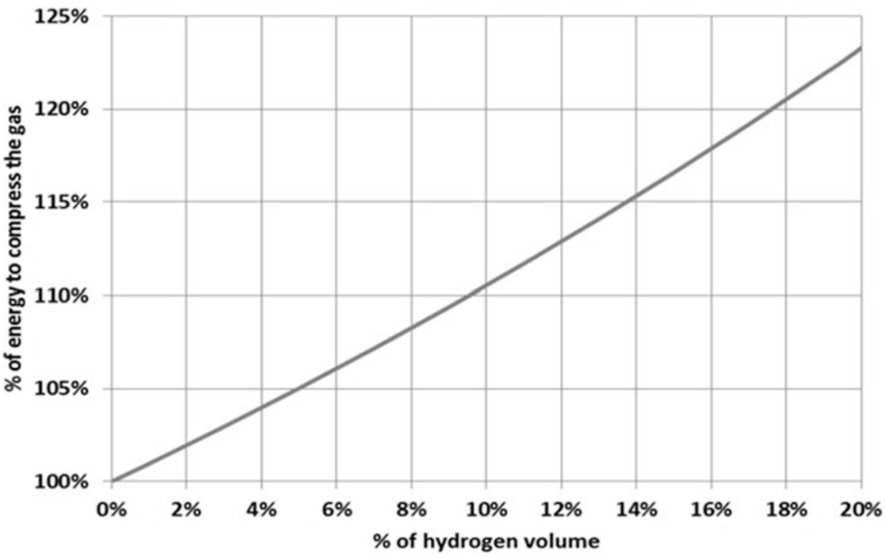


Fig. 5.23 The energy required to compress a hydrogen-methane mixture compared to the energy required to compress methane alone

is required to compress hydrogen alone than to compress methane alone. When the concentration of hydrogen is 10–15 % by volume, the power required to compress the mixture increases 10–17 % (Fig. 5.23). Since compressors are generally designed for (approximately 10–15 %) more power than nominal power, a mixture with as much as 14 % hydrogen-methane can be fed into the natural-gas network.

Gas-turbine boilers have different limitations. The main problems of burning a hydrogen-methane mixture are caused by the various burning velocities of the mixture (Table 5.4), which can destabilize the burning process and damage the boiler. Commercial gas turbines can burn a hydrogen-methane mixture of 0–8.5 % hydrogen. Some tests have demonstrated that boilers can be modified to burn a volume of up to 60 % hydrogen.

Table 5.4 Burning velocity of hydrogen and methane [5]

	Hydrogen	Methane
Burning velocity [cm/s]	306	33.8

Table 5.5 Maximum limits of hydrogen in a natural-gas network

Natural gas network components	Maximum limits [% of H_2 by volume]
Transport pipeline	50 %
Compressors	14 %
Caverns	55 %
Instrumentation	30 %
Gas turbine	1–3 %

Fewer limitations arise from the usage of the caverns. The experience of the past years about so-called town gas has shown that up to 55 % hydrogen by volume could be stored inside caverns. With reference to the measurement devices, different studies have shown that the devices actually used in the natural-gas network are able to work without any particular problem up to 10–30 %. Table 5.5 provides an overview of the maximum limits of hydrogen in a natural-gas network.

5.9 Compressed-Air Energy Storage

A CAES system can store electricity as mechanical energy alone (in a diabatic system) or as mechanical and thermal energy (in an adiabatic system). In both cases, the electricity is used to drive a compressor train that compresses and stores air in an underground space, such as an unlined cavern, and porous strata or a lined cavern and salt formation (see Fig. 5.24). During the discharge phase, the compressed air is heated before it expands in the turbine. The compressed air can be heated in burners (in a diabatic CAES) or in a thermal exchanger system (in an adiabatic CAES), which reuses the thermal energy recovered during compression. The CAES systems that are the most thermodynamically efficient continuously subtract heat during compression and continuously add heat during expansion, keeping the air at its ambient value, but, although the use of hydraulic air or water injection have been proposed, such isothermal processes are not easily achieved in practice. Since most compressors and turbines exchange a limited amount of heat with the atmosphere, their processes can be regarded as adiabatic. In reality, isothermal compression is replaced by sequences of adiabatic compressions with intermediate cooling, while isothermal expansion is replaced by adiabatic expansion with intermediate heating.

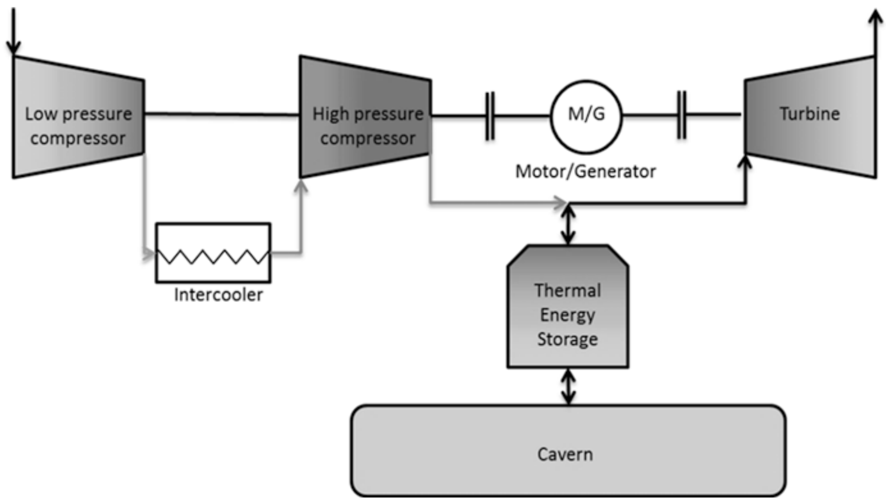


Fig. 5.24 Adiabatic compressed-air energy storage scheme [9]

Diabatic CAES systems are a hybrid of an energy storage system and a gas-turbine plant. Unlike conventional gas turbines, CAES systems precompress air in appropriate underground spaces and utilize it later by burning it in a burner together with a gaseous fuel, such as natural gas. In order to increase the overall efficiency, a recuperator may be used to preheat compressed air before it enters the combustion chamber. A recuperator recovers part of the energy from exhaust gases, thus reducing the need to burn fuel. The overall efficiency of diabatic CAES plants ranges between 54 and 42 %, depending on their configuration, i.e., whether or not they have a recuperator. There are currently two diabatic CAES plants in operation worldwide.

The heat generated during the compression of air (charging phase) in an adiabatic CAES system (A-CAES) is stored in a thermal-energy storage (TES) system. In some design projects, such as the ADELE project, the compressor train compresses air to as much as 50–70 bar. The compressed air heated to over 600–650 °C flows into the TES system. The heat-storage material inside the TES is then heated as the temperature of the compressed air drops. The cooled compressed air is conducted into an underground cavern at about 50 °C. During the discharge phase, the compressed air flows over the TES material once again, thus, raising its temperature. The heated compressed air flows inside the turbine which drives an electric generator. The round-trip efficiency is expected to reach a value of approximately 60–70 %.

The application domain of adiabatic CAES systems ranges from energy management to electrical-grid support. In the latter case, apart from local system services, such as short-circuit power and reactive power provision, A-CAES systems can, in principle, deliver primary, secondary and tertiary (minute reserve) controls. However, A-CAES systems can only supply these services for primary and secondary control under certain operational conditions, as is typical for any kind of thermal-power plant due to the material-related thermal-stress restrictions of the turbo machinery.

Test Questions Chap. 5

- What kinds of flexibility options in the power system can be replaced by energy storage?
- What are the main criteria used to classify energy-storage systems?
- What are the main components that limit the lifetime of redox-flow batteries?
- What is the maximal amount of hydrogen that should be fed into the natural gas network and why?
- List the differences between diabatic compressed-air storage systems and the adiabatic version.

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Chapter 6
Mobile Energy Storage Systems. Vehicle-for-Grid Options

6.1 Electric Vehicles

Electric vehicles, by definition vehicles powered by an electric motor and drawing power from a rechargeable traction battery or another portable energy storage system recharged by an external source, e.g. residential electrical systems or public electrical grids, are nothing new. Werner von Siemens developed and built his *Elektromote* in 1882 and Ferdinand Porsche his *Lohner-Porsche* in 1900, see Fig. 6.1.

In those days, electric vehicles reached ranges of up to 100 km and speeds of up to 105 km/h and employed the second most-used powertrain technology in vehicles after steam power. The advantage or rationale behind the high use of electric vehicles was the extremely advanced knowledge about electric motors and their reliability, as well as the presence of electricity systems in cities. Afterward, the development and refinement of internal combustion engines dealt electric vehicles a blow until they experienced a brief revival (1990s) because of various events (oil crises, government standards) and then a renaissance and renewed development from 2003 onward. Today, a typical electric car has a battery with nominal power between 8 and 30 kW and, in special cases such as the Tesla Model S, as much as 90 kW and a potential driving range, on one charge, between 100 and 220 km. This is very convenient and well-suited for city driving. Current reasons for the use and spread of electric today vehicles are generally the prospect of cutting fossil fuel use, boosting the efficiency of the entire energy chain (from production to consumption), cutting CO_2, and, in particular, optimizing the combination of two crucial infrastructures, namely, energy supply and vehicles, that are technically and economically on the basis of renewables.

A purely electric vehicle consists of a battery, a power inverter, an electric motor and a transmission, which collectively transmit the energy drawn from external connected energy sources or charging the infrastructure to the wheels. Depending on the components used, their features and designs, such as the type of electric motor, i.e., induction, synchronous or DC motor, it can achieve a total energy-conversion

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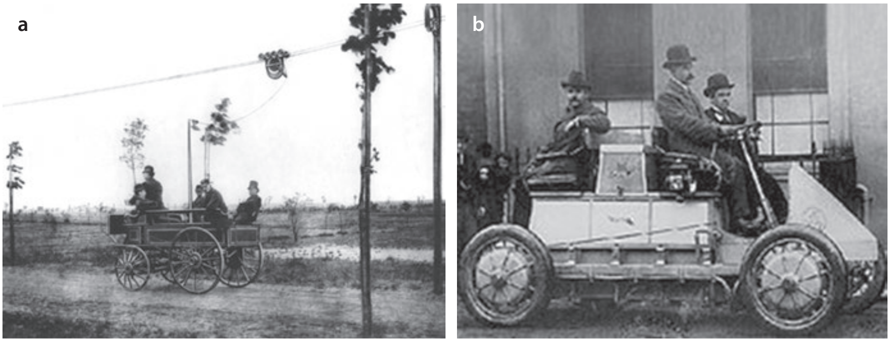

Fig. 6.1 The first electric vehicles: (**a**) Werner von Siemens [1] (**b**) Lohner-Porsche [2]

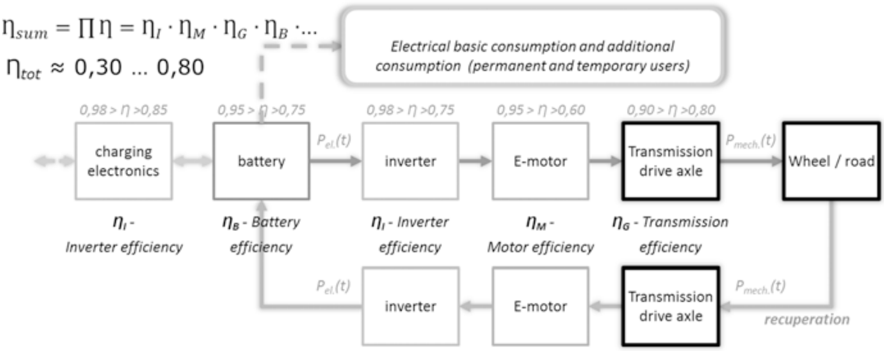

Fig. 6.2 Energy-conversion efficiency in the entire energy-conversion chain for electric vehicles [3]

efficiency of as much as 85 % in the energy conversion chain, constituting a highly efficient means of transportation (see Fig. 6.2).

Figure 6.3 depicts the progressively broader stages of electrification, from conventional vehicles with internal combustion engines and partly electrified power systems, up through purely electric vehicle. Hybrid electric vehicles (HEV) can be classified as parallel, series-parallel and series hybrids based on their powertrain topology. They do not have any option for connection to the grid to charge their energy storage systems. The vehicle battery is charged solely by recovery (regenerative braking) or by means of the internal combustion engine through an electromechanical converter (electric machine). The two motors (electric motor and internal combustion engine) of parallel hybrids effect the powertrain, providing the capability of parallel or single operation. The advantage of stepping is that the two motors can be designed as light duty units, additionally cutting weight and thus costs.

Series-parallel hybrids are characterized by a (step-less) combination of series or parallel mode corresponding to the driving conditions and direct mechanical connection of the two motors. Series hybrids on the other hand are characterized by

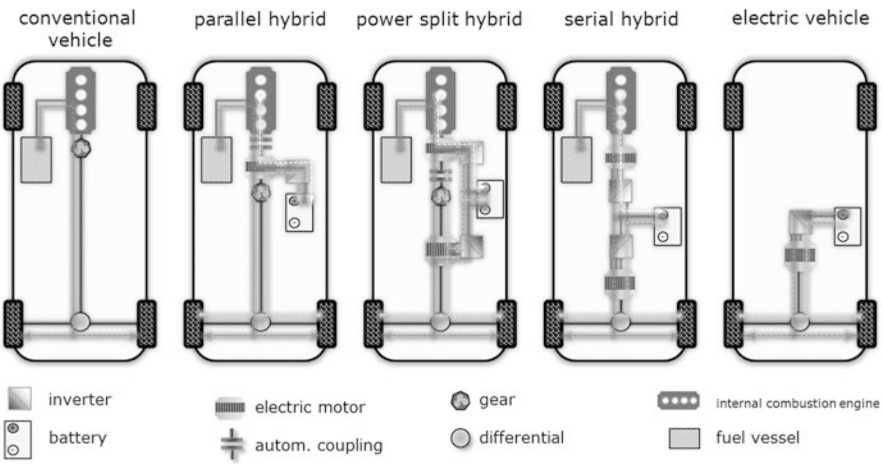

Fig. 6.3 Stages of electrification/powertrain topologies, of conventional through purely electric, vehicles [3]

repeated power conversion, the entire conversion chain thus attaining only moderate energy-conversion efficiency. Moreover, optimal operation is achieved by decoupling the combustion engine's rotational speed.

Vehicles with hybrid-powertrain technologies and an external grid connection are called plug-in hybrids.

The main component of an electric vehicle is its traction battery. Only chemical energy-storage systems are used in electric vehicles. This limited technology portfolio is defined by the uses of mobile traction batteries and their constraints, such as restricted weight, volume and safety criteria (transport). The conversion of electricity into chemical compounds constitutes one of the most widespread storage technologies, particularly for supplying power in the consumer sector (e.g., mobile devices) and for keeping the infrastructure running (e.g., telecommunications). Almost exclusively low-temperature and primarily lead-acid and lithium-ion batteries or high-temperature and primarily sodium-sulfur batteries, they are called internal storage systems since their energy level and output are interdependent.

External storage systems, on the other hand, have the advantage of independently sizable output and energy parameters. Both hydrogen/methane systems and redox flow batteries, which typically require more space, are representative of this group. The basic technical parameters of chemical storage systems are discussed in Sect. 5.6 and are compiled in Table 6.1 for mobile applications. Since they are generally connected to the grid by power electronics (now classified as rapid and reliable), this group of storage systems can cover a very wide range of use cases in electric vehicle and power-grid applications. Currently available energy storage systems and experiences have proven that lithium-ion systems are the preferred technology.

The various battery storage systems used in electric vehicles have characteristic charge curves dictated by technology or are powered by different charging processes, including constant current, constant voltage, negative pulse and so-called IU

Table 6.1 Technical parameters of chemical storage systems implemented in electric vehicles

Battery type	η %	Power density W/kg	Energy density Wh/kg	Self-discharge	P installation costs €/kW	E installation costs €/kW
Li-ion	to 95	100–185	120–200	5 %/month	150	180–600
Redox flow	to 5	N.A.	30–70	0.4 %/day	1500	150
NaS	to 75	250	200	10 %/day	200	150–600
H_2/methane	to 40	1000	580–33,300	<1 %/month	2000	6

charging. Based on the application and various strategies that control current and voltage, they achieve the goal of fully charging a battery within its operating limits.

Another component, the inverter, adjusts attributes of the grid parameter (voltage, current) and is responsible for converting them bi-directionally from AC voltage to DC voltage, i.e., for so-called charging and powertrain systems. This inverter is based on power electronic components that can have various circuit topologies depending on the requirements and type of electrification, see Fig. 6.4. The standards for such components that can be used in the automotive sector are very strict and have to be met all the time. These include:

- ambient air: –40–135 °C
- single circuit water cooling system: –40–105 °C (120 °C when power is reduced)
- overall life: 20 years
- service life: 10,000 h
- passive temperature cycles @ ΔT 100 k (15 years with two cold starts every day): 10,000 cycles

Each circuit topology has certain concrete advantages and disadvantages. A B6 full bridge with a bidirectional DC/DC converter and an HF transformer, for instance,

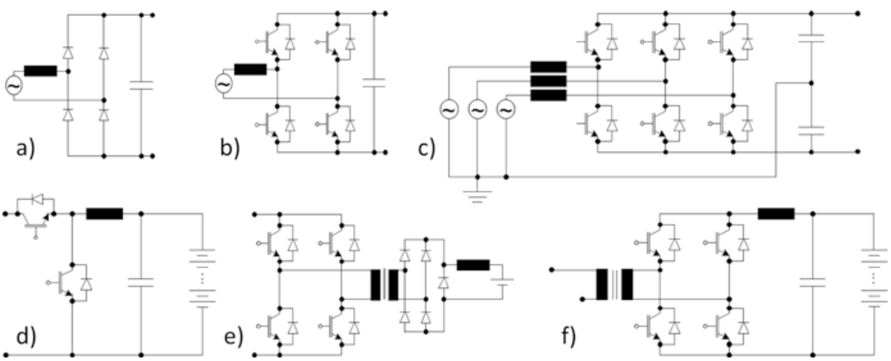

Fig. 6.4 Typical circuit topology of unidirectional and bidirectional chargers,(**a**) B2U input rectifier, (**b**) H bridge,(**c**) B6C full bridge,(**d**) bidirectional DC/DC converter, (**e**) DC/DC converter with an HF transformer,(**f**) bidirectional DC/DC converter with an HF transformer

Table 6.2 Comparison of the characteristics of electric motors used to power vehicles

	ASM	SM	GRM
Torque	0	+ +	0
Speed stability	+	0	+ +
Losses (driving cycle)	+	+	+
Costs	+	−	+ +
Reliability	+ +	+	+ +
Technology maturity	+ +	+	0

has comparably low energy conversion efficiency and high component complexity but advantageous galvanic isolation through the transformer and therefore always ought to be analyzed and assessed separately according to the design.

Electric motors, one of the links in the energy chain in electric vehicles, can be broken down into the following three groups:

- DC motor (DCM)
- synchronous motor (SM)
- induction motor (IM).

The motors in electric vehicle can be constructed as one central motor or as a distributed powertrain, e.g., a hub motor. DC motors have a simple control system that performs fast and simple operations but are extremely prone to wear caused by consumption of the carbon brushes installed. Permanent-magnet or brushless synchronous motors wear little but are expensive because of their magnetic materials/rare earths and therefore have to be evaluated from case-to-case/vehicle-to-vehicle. Induction motors are easily manufactured electric motors but are significantly larger than other motors. See the comparison of other features of electric motors in Table 6.2.

The transmission, the final link in the energy chain in electric vehicles, see Fig. 6.2, adjusts the speed between the motor and wheels and the torque between motor and wheels. It can be adapted to various different transmission models from manual to automatic, depending on the stage of vehicle electrification and powertrain function (electric driving, stop-start operation, efficient recovery, support function, unnoticed start of the internal combustion engine, electric all-wheel drive).

6.2 EV Standards and Technologies for Power and Transportation Systems

More than 300,000 electric vehicles were on the road worldwide in 2014. Assuming that the average battery capacity is 30 kW, this constitutes a flexible energy storage system capacity of 9 GW. Leaders are the USA (174,000 electric cars) and

Japan (68,000 electric cars), followed by China (45,000 electric cars) and Germany (17,500 electric cars). Diverse studies and analyses project a continual rise in the development of electric vehicles (see Fig. 6.5), thus multiplying the number of electric cars in the coming years and substantiating the tremendous potential to expand the flexible use of mobile storage systems [5].

Present-day electric vehicles are principally compacts, standard products with a range of up to 200 km and varying consumption per 100 km. Intended for short and medium-distance trips, their battery capacity ranges from a few to 80 kW, see Table 6.3.

These basically newly developed electric vehicles only recently became marketable and are increasingly being introduced on the road as standard products. They are an appropriate size since the average period of car use in Europe is around 60 minutes, around 80 minutes in Germany, and only 13 minutes in Latvia. The estimated average distance driven per trip is 33 km per person and day, 41 km in Finland and only 8.7 km in Latvia, and each country has to be considered as infrastructure-specific, see Table 6.4 and [23]. This reveals that electric vehicles' vast numbers and lower power ranges endow them with tremendous potential for use in energy supply systems and various use cases, either as small energy producers or storage systems. This property is reinforced by private ownership of mobile energy storage units/traction batteries and the fact that electric vehicles are parked most of the day and are not at those times used for transportation.

Making electric vehicles suitable and usable for the road (Motor Vehicle Code), as well as the electrical grid (grid connection, grid operation), necessitates modifying or upgrading various different standards and guidelines, which have to be defined both nationally and internationally, and would require a great deal of time.

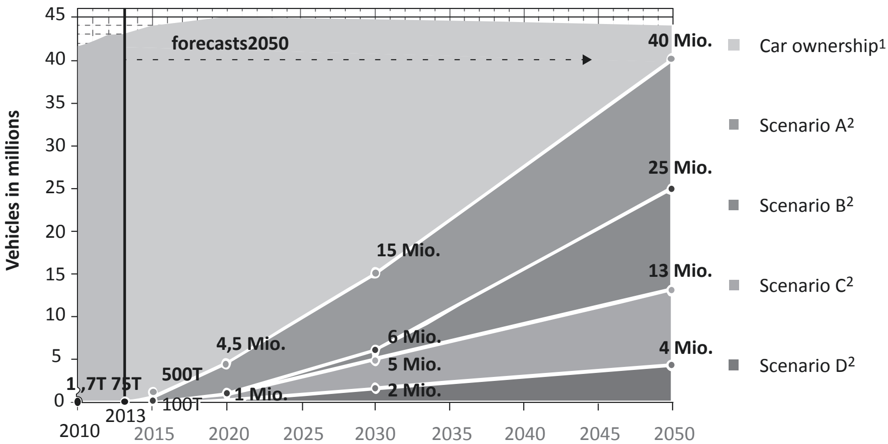

Fig. 6.5 Worldwide growth in the number of electric cars 2010–2050 [3]. Sources [1,2] Jan Richte, Ditmar Lindenberger (2010) EWI Institute of Energy Economics the University of Colonia[3]; Carolin Richter (2009) Electric mobility—opportunities, challenges and contribution. First German Electro Mobility Congress. Bonn 16–17 June 2009

Table 6.3 State-of-the-art electric vehicles

Vehicle	Picture	Range [km]	Consumption [kWh]
AUDI A3 e-tron	 [13]	50 km electric+890 km with range extender	11.4 kWh/100 km, 1.5 l/100 km combined
BMWi3	 [10]	190 km	12.9 kWh/100 km
Citroen Berlingo	 [11]	120 km	21.0 kWh/100 km
Citroen C-Zero	 [11]	150 km	12.6 kWh/100 km
Ford Focus Electric	 [12]	162 km	15.0 kWh/100 km
Kia Soul EV	 [12]	212 km	14.7 kWh/100 km
Mercedes B-Klasse Electric Drive	 [14]	200 km	16.6 kWh /100 km
Mitsubishi i-MiEV	 [15]	150 km	13.5 kW h/100 km
Nissan e-NV 200	 [16]	170 km	no information
Nissan Leaf (2012)	 [17]	175 km	17.3 kWh/100 km
Opel Ampera	 [18]	83 km electric + 420 km range extender	16.9 kWh/100 km, 1.2 l/100 km com bined
Peugeot iON	 [19]	150 km	12.6 kWh /100 km
Renault Kangoo Z.E.	 [20]	170 km	14.0 kWh /100 km

Table 6.3 (continued)

Vehicle	Picture	Range [km]	Consumption [kWh]
Renault ZOE (2013)	 [20]	210 km	14.6 kWh /100 km
Smart fortwo electric drive	 [21]	145 km	15.0 kWh /100 km
Tesla Model S 90D	 [22]	560 km	no information
Volkswagen e-Golf	 [9]	190 km	16.7 kWh/100 km
Volkswagen e-up!	 [9]	160 km	11.7 kWh /100 km

Table 6.4 European car parameters [8, 23]

Country	Average number of rides per person and day	Average kilometerage per person and day (in km)	Average driving time per person and day (in minutes)
BE	3.0	n/a.	n/a
CZ	n/a	21.9	n/a
DK	3.0	37.3	n/a
DE	3.3	36.9	80.0
EE	n/a	37.3	n/a
ES	1.8	n/a	44.4
FR	2.9	35.3	58.2
LV	1.9	8.7	13.0
NL	3.1	31.9	59.9
AT	3.0	28.1	68.8
FI	2.9	41.8	70.7
SE	2.7	44.1	62.6
UK	2.9	31.8	63.3
CH	3.6	37.1	84.5
NO	3.3	37.9	68.2

However, this book includes and describes only those aspects required to ensure their operation as mobile energy storage systems for electrical grids and the options to make them compliant for this purpose. Figure 6.6 defines the trends/scopes of standards/interfaces that apply to the actors and components used, such as [6]:

- Vehicle—charging infrastructure
- Vehicle—driver
- vehicle—energy market
- charging infrastructure—grid
- charging infrastructure—energy market
- charging infrastructure—charging infrastructure operator
- charging infrastructure operator—billing service
- driver—billing service
- driver—charging infrastructure (e.g., reservation of public charging stations)
- charging infrastructure operator—driver
- vehicle—service
- vehicle—billing service

The standards for reliable operation and the capability of flexible use of energy storage systems have to be derived from each of the interfaces/sub-processes. This book only examines the topic of vehicle-charging infrastructure interface and the

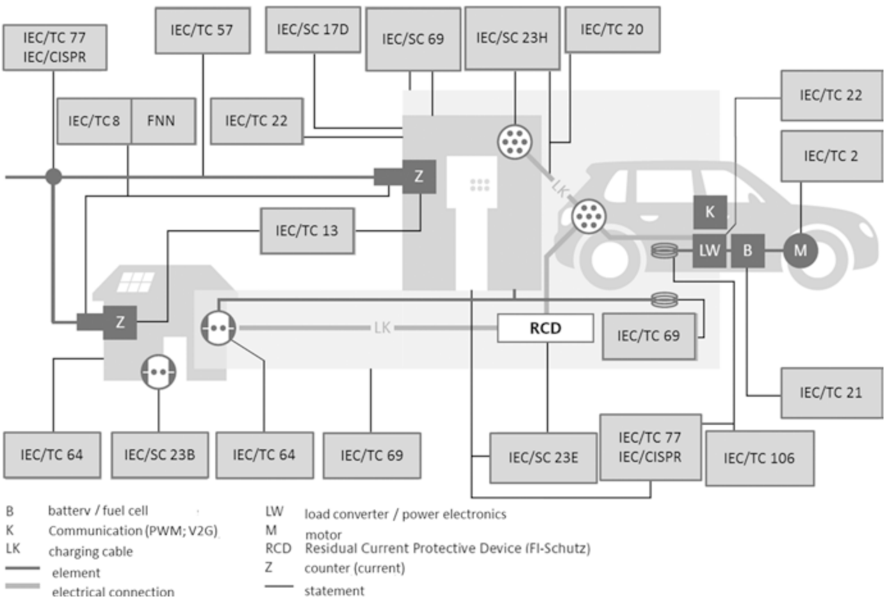

Fig. 6.6 DKE (German Commission for Electrical, Electronic and Information Technologies of DIN and VDE) and IEC (International Electrotechnical Commission) standards committees relevant to electric vehicles [6]

charging infrastructure more closely since it is essential to the flexible use of energy storage systems.

The form of energy and data exchange between charging stations and vehicles, as well as vehicles and charging stations (energy recovery), is contingent on the type of connection between these components, see Fig. 6.7 [4]. A distinction is usually made between classic plug-in and inductive (wireless) systems. Battery replacement systems, i.e., complete and fast battery- system replacement, can also be considered here. Plug-in systems establish a physical connection between a vehicle and a charging station, which can be differentiated by the type of voltage used. AC charging stations transmit power to a vehicle by AC voltage, which is inverted by a battery charger installed in the electric vehicle. The advantage of this system is generally the widespread use of low-voltage AC equipment, which is powered by "lower" voltage and thus also provides certain component savings (cost, weight), e.g., a rectifier does not have to be installed in the charging station. The disadvantage of AC charging technology is basically the capability of transmitting only limited power. Typical single-family household installations have a power supply of up to 16 A, providing a maximum of 11 kW of power for a three-phase connection. While it can be upgraded up to 63 A, i.e., 44 kW, this requires investing in the existing electrical infrastructure, and this is implemented as an extra option only in certain cases. DC charging technology generally has the advantage of the capability to transmit high power of >50 kW to very high power of 200 kW, e.g., Tesla S, and thus of charging a vehicle battery quickly, but this requires special components (i.e., a rectifier in the charging station and a DC-DC converter in the vehicle) including protective relays, which are quite expensive.

Inductive charging systems have a significant advantage over plug-in systems, namely, they do not need to have or use a cable or connector, and are therefore

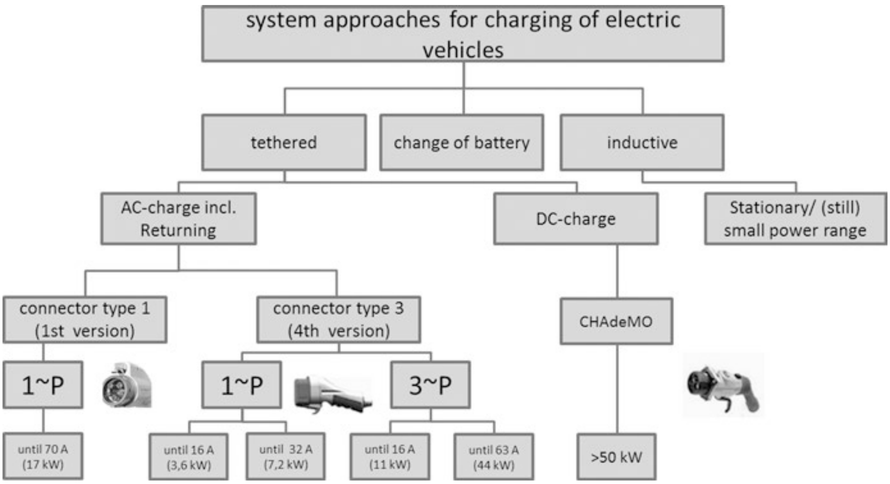

Fig. 6.7 Electric-vehicle charging systems [4]

primarily used in in the premium electric-vehicle class. The disadvantage of such systems is their inability to transmit more power than AC/DC charging technologies, i.e., up to 3.6 kW (technologically required by, among other things, potential spacing between coils and electromagnetic compatibility).

The alternative to fast charging technologies (high DC and AC power) is a battery replacement station. Batteries are preplaced to enable a procedure lasting a few minutes, the battery having been charged 100 % for use at this time. The disadvantage of this method is that it can frequently stress the mechanical contact of the battery terminals and thus reduce a battery's service life. These methods require tremendous charging power and capacity, which have to be provided at the replacement station. The issue of standardization is just as complex, e.g., questions about size and type of connection have to be answered.

Depending on the technology, diverse connector systems exist, which connect a charging cable and charging station with a vehicle. They have been proposed from the perspectives of various manufacturers' specifications and cannot yet be viewed as definitive standard systems, see Fig. 6.8. Experience with this, as well as their compact designs, has made the so-called Type 2 connector, or one and three-phase charging in compliance with the standard series IEC 62196, preferred for AC charging and the most widely established approach in Europe. Largely developed by Mennekes for AC charging and therefore also called a Mennekes plug, the Type 2 connector has three line contacts (L1, L2 and L3), a contact for the neutral conductor and a contact for the ground contact. It also has a proximity pilot (PP) contact, which detects the presence of the connector and defines the cable configuration/cable thickness by measuring resistance, and a so-called control pilot (CP), which ensures that charging signals and exchange control signals are sent between electric vehicle and charging station by so-called pulse-width modulation (PWM). Moreover, the Type 2 connector has two additional pins for fast DC charging and is classified as a so-called Combined Charging System (CCS) for European and American DC charging standards.

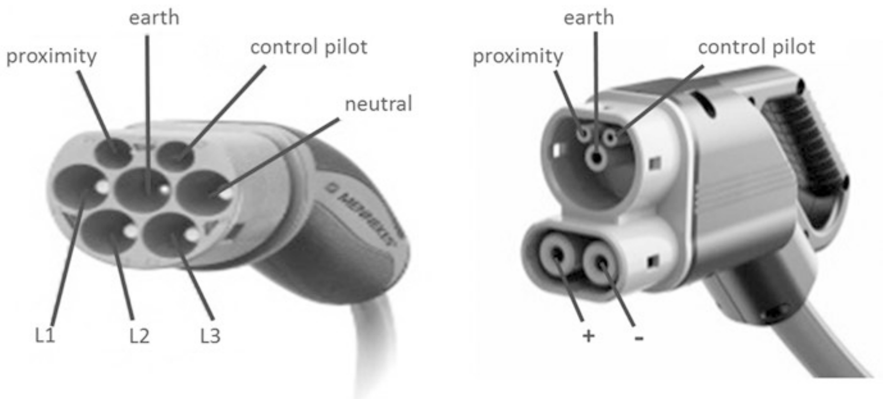

Fig. 6.8 Typical connector systems—AC charging (Type 2) and DC or AC and DC charging (CCS)

This connector's pilot contacts and the neutral conductor are used for safety and communication between a charging station and an electric vehicle during charging at fast DC-charging stations and are equivalent to the AC connector type. Only the bottom two thicker DC contacts are used for DC current. The DC extension for Type 1 and 2 connectors was jointly developed by the various committees in order to preclude different standards, as is the case with AC charging [4].

Regardless of the charging technology and use case, flexible use of mobile energy storage systems necessitates establishing interoperability among components such as vehicles and charging stations, as well as higher-level systems in order to exchange data on ongoing processes and components (e.g., vehicle condition, battery state of charge, temperature) and to execute commands/actions (controlled/dedicated charge/discharge curves) for the purpose of controlling technical and economic responsiveness. Attention must be paid to two standards relevant to the electric vehicle-charging station interface:

- IEC 61851
- IEC ISO 15118

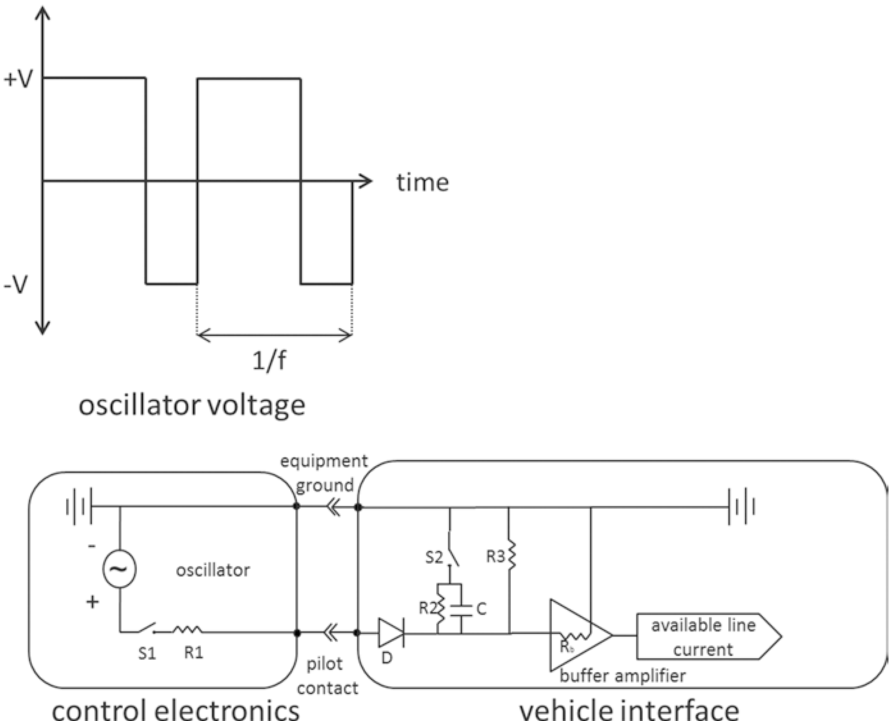

Fig. 6.9 Typical pilot circuit in an electric-vehicle system [24]

Part 1: Electric Vehicle Conductive Charging System—General Requirements of the standard IEC 61851 Electrical Equipment in electric road vehicles addresses general system standards and interfaces, protection against electrical shock, connection between power supply and electric vehicle and special requirements of vehicle launches and connector systems [24]. It defines basic charging modes, which, depending on their design, are essential to the implementation of electric vehicles as responsiveness option for smart grids:

- Charging mode 1: Connection of an electric vehicle (one or three-phase) by means of a standard socket-outlet for rated current up to 16 A
- Charging mode 2: Connection of an electric vehicle (one or three-phase) by means of a standard socket-outlet together with a control pilot between the electric vehicle and the plug or control unit and cable
- Charging mode 3: Direct connection of an electric vehicle to the AC grid employing a control pilot, which is always coupled with the system connected with the AC grid
- Charging mode 4: Indirect connection of an electric vehicle to the AC grid employing an external charger, the control pilot always coupled with the system connected with the AC grid

Regardless of the charging mode, with the exception of charging mode 1, the following functions and standards have to be met or ensured at all times:

- verification that the electric vehicle is properly connected (connection verification),
- continuous monitoring of the ground (by measuring the flow of current in the control pilot),
- activation and deactivation of the system (authorization for activation and safety for deactivation as a function of the status of the pilot circuit), and
- selection of the charge current (maximum power rating)

What is more, charging mode 1 does not involve any data communication. Charging modes 2 and 3 have freely selectable serial data communication. Such communication is mandatory for charging mode 4. In this standard, the pilot circuit in the plug-cable-socket system is the sole control system for use as a flexible mobile energy storage system, which is implementable in charging modes 2, 3 and 4 as soon as the pilot circuit has been designed properly (See the typical design in Fig. 6.9) [24].

The greatest continuous current supplied by the power supply system to an electric vehicle can be ascertained and controlled by an appropriate ratio of pulse-width modulation, thus making it possible to exchange power among components flexibly, too. Such so-called controlled charging/available line current is directly proportional to the duty cycle with a constant of 0.6 A/% of the duty cycle of 5–80 % (see Fig. 6.10) and can be used, to a certain extent, to control a mobile energy storage system/traction battery flexibly by external factors/functions, e.g., smart-grid use. This kind of controllability of a battery is quite complex and sensitive, however,

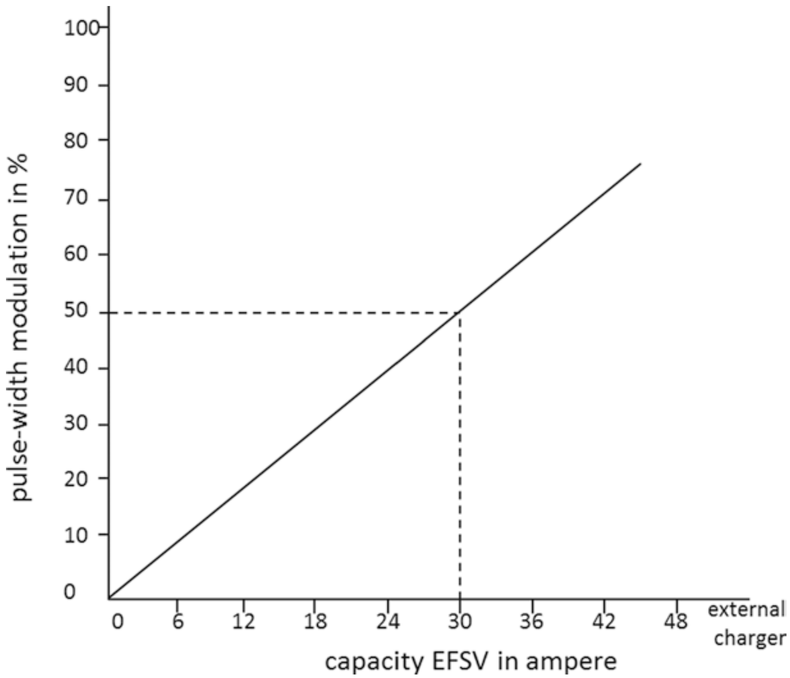

Fig. 6.10 Power supplied as a function of the pilot-circuit's duty cycle in compliance with IEC 61851 [24]

and a complete electric-vehicle system based on this does not permit other essential functions, e.g., personal identification or business logic such as dynamic price transmission and charging schedules or protective functions such as data encryption, or cannot meet their requirements such as speed, data performance and reliability.

For these reasons and because of the requirement to model systems among electric vehicle and external systems and their interactions and functions completely, ISO IEC 15118 Standard: Road vehicles—ehicle to grid communication interface was developed in 2013. ISO/IEC 15118 specifies the communication between electric vehicles (EV) and the electric vehicle supply equipment (EVSE) [25–27]. The communication components of this equipment are the electric-vehicle communication controller (EVCC) and the supply equipment communication controller (SECC). Communication is defined by two different concepts, namely, "basic signaling" and "high-level communication". ISO/IEC 15118-1 and ISO/IEC 15118-2 specify "high-level communication". The relations between these two concepts are specified in ISO/IEC 15118-3. The standard ISO/IEC 15118 specifies high-level communication between electric vehicles and charging stations [ISO/IEC 15118-2] and especially the types of messages, their particular format and, finally, the communication procedure in conformance with standards. Established systems are used to ensure the necessary generalization; a PLC modem provides an Ethernet connection for communication using the IP. The IP packets contain the messages specified by ISO/IEC 15118.

The standard's key points are condensed concretely in general requirements:

- High-level communication can be used to provide functions such as identification, payment and expanded additional services.
- Data communication between electric vehicles and other actuators/components must be treated confidentially, thus requiring such integrated mechanisms as security and safety functions (protection against monitoring, manipulation, replay attacks and hacking).
- Electricity supplied by the charge-spot operator must either be measured specifically in the EVSE or be part of overall energy consumption, and different billing options defined by the energy providers must be factored in or permitted.

The standard additionally defines the specific requirements of the various actors such as users, utilities and OEMs. The entire range of the standard's uses is elucidated by a description of the groups of actors, distinguishing between primary and secondary actors (see Fig. 6.11). Primary actors are directly involved in the charging process [25–27].

The information flow between an electric-vehicle communication controller and a supply-equipment communication controller is specified in keeping with all of the layers of the Open Systems Interconnection (OSI) reference model. The actors perform various functions, such as starting and stopping charging, identification, authentication and payment, as well as monitoring the system for faults, e.g., power cable faults.

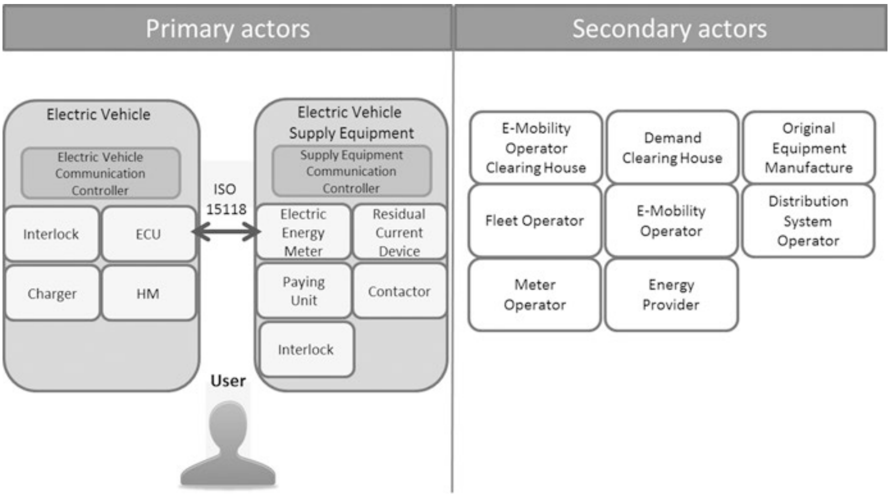

Fig. 6.11 Overview of primary and secondary actors according ISO IEC 15118 [25]

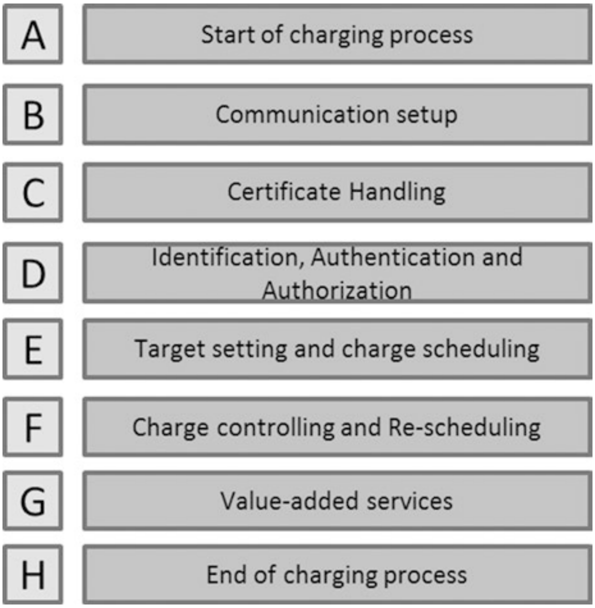

Fig. 6.12 ISO IEC 15118 use-case function groups [25]

ISO IEC 15118 breaks electric-vehicle system charging and discharging down into eight functional groups and resultant preliminary use cases (see Fig. 6.12): initialization of the process (i.e., verification of features such as the presence of PWM and high-level communication), communications setup (i.e., establishment of proper communication required between electric vehicles and charging stations), certificate handling, identification (authentication and authorization by RFID or credit card, for instance), charge-curve plotting, controlled charging and discharging and completion of charging. The actors involved and the procedures are specified for each of these scenarios. The potential combinations, i.e., the implementation of the standards in a vehicle and/or in a charging station, are differentiated. For instance, when ISO IEC 15118 has not been implemented in the charging station, but has been implemented in the vehicle, charging can only be done by following the standard IEC 61851, i.e., it is very rudimentary. On the one hand, the standard ISO IEC 15118 covers an extremely wide range of flexible uses for mobile energy storage systems, e.g., a vehicle-to-grid support use case (active power control, no allowance being made for reactive power control and frequency stabilization actions) and covers the complete range of services (e.g., authentication) and functions (agreement on charging criteria, encryption), thus making it indispensable for the flexible use of energy storage systems. On the other hand, it has not been implemented in all electric vehicles, and it is not yet widely in use since continued work on the standard and its parts is hindering its uniform use.

Charging Infrastructure and Electrical Grid Standards

Regardless of the charging technology, the charging station is an element essential to ensuring flexible energy and data exchange when servicing electric vehicles. It must meet interoperability standards for vehicle connection, as well as different standards resulting from such use cases as:

- private, semi-private, public or semi-public charge spots,
- outdoor, covered or indoor charge spots,
- fast charging on the road or charging at “relatives’ one-phase household sockets”, and
- analyzing and performing billing (individual billing, aggregate billing, direct payment), e.g., as defined in Germany’s so-called National Platform for Electric Mobility.

Generally, every charging station contains five function/component groups (component installation, communications components, components grid connection, vehicle connection components and user interface components) which, depending on the use case, can be combined in various ways, based on their complexity and potential services (see Fig. 6.13) [7]. A charging station consists of internal

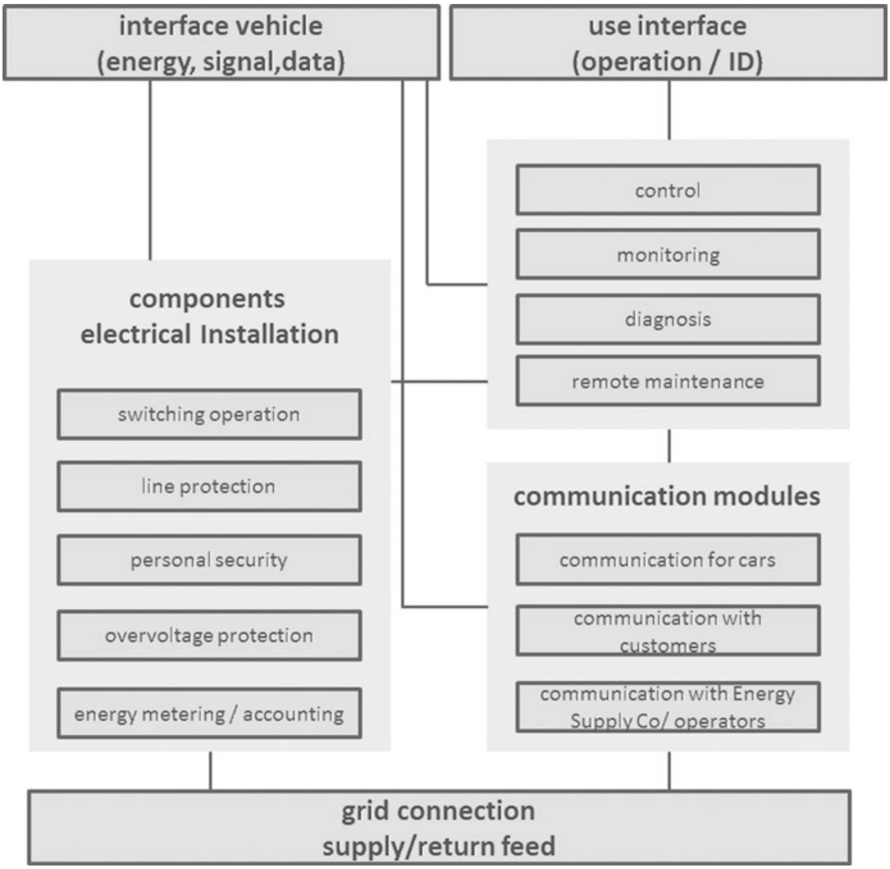

Fig. 6.13 Block diagram of a charging station [7]

components and external components, which exchange energy and data. Communication with electric vehicles has been described in the preceding section. Communication with the electrical grid and its standards is examined here and is dominated by the development and conversion of the energy supply system. The growing addition of renewables throughout various levels of the grid (the low-voltage level on which electric vehicles are connected, and the medium- and high-voltage levels) in many regions is resulting in bidirectional power flows and, under certain circumstances, can overload the electrical grid. Such new situations are making it necessary to equip even the lower levels of the grid, e.g., high-, medium- and low-voltage systems, in response to the attendant challenges since (metering and control) equipment has been lacking there in particular and new components, e.g., renewables as well as stationary and mobile energy storage systems, are being added there more than on the communication level of the grid.

Meeting these demands, continuing to maintain high system reliability with every component, and making new system services possible requires developing and establishing information and communications technologies (ICT) that are subject to technical and economic control mechanisms. This is the only way to coordinate and optimize operation of the energy-supply system with all of its facets, functions and components, e.g., electric vehicles, and based on, among other things, integrative data management. Since energy systems currently lack the ICT infrastructure necessary throughout all levels of the grid to perform various functions, either existing systems will have to be upgraded, especially in transmission systems, or new dedicated solutions will have to be developed, especially in medium- and low-voltage grids. A model of complete ICT architecture (see Fig. 6.14) is based on bidirectional data communication, thus enabling the system operator to analyze the system data, by monitoring data from meters and controllers online and to take appropriate action.

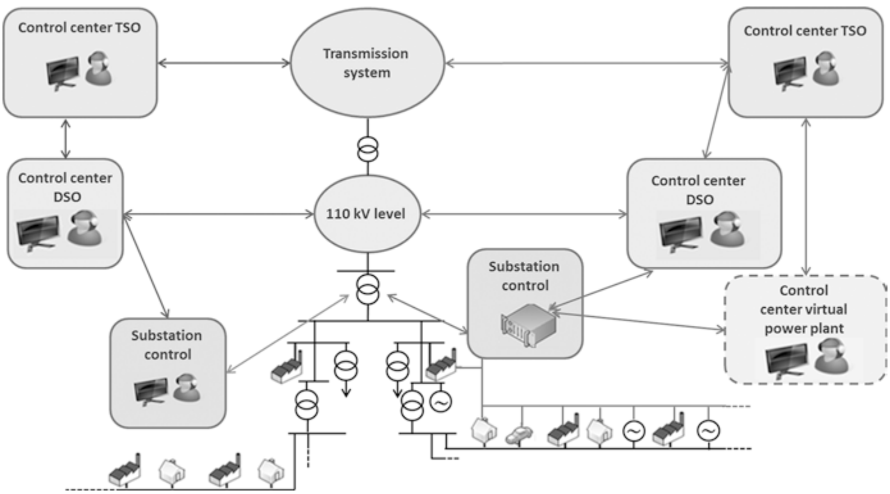

Fig. 6.14 Present and future ICT infrastructure for an energy-supply system [28]

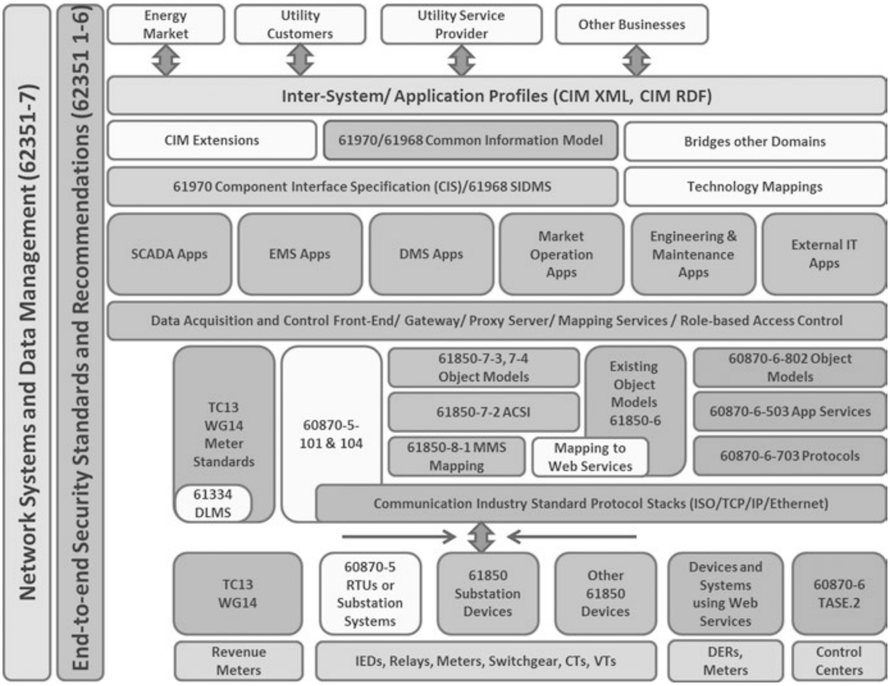

Fig. 6.15 Reference smart grid architecture [28]

Pertinent ICT standards for smart grids define the standards for interfaces and data models and additionally cover aspects of data and information security.

The IEC TC 57 (TC 57) committee has developed a complete standard architecture including communications standards (see Fig. 6.15). This architecture consists of standards assigned to each level of the system, from operations with limited quantities of data but fast communications (bottom of the graphic) through standards that address large quantities of data (top of the graphic). The three standards (i.e., IEC 61850, IEC 61970 and IEC 61968) in particular are indispensable to expedient implementation of, among other things, electric vehicles as responsiveness components.

IEC 61850 Substation Automation

This standard consists of several parts originally developed to standardize protective processes in automated substation systems. Since its modularity and transferability made the concept applicable not only to protection but also universally, it was enlarged for the entire power system and its components.

The individual parts of the standard specify the entire approach to digitizing automated processes and conformance tests, but they also focus on data exchange and services and standard configuration, as well as data mapping between various components and systems.

The advantage of uniform standards such as IEC 61850 over the standard IEC 60870 is its standard semantics, which, for instance, permit vendor-neutral data exchange (the individual interface fields having manufacturer-specific features). One distinctive feature of IEC 61850 is that standard mapping of services makes it possible to implement ready for use solutions. This is particularly relevant for mobile energy storage systems.

IEC 61968 and 61970, Common Information Model

Unlike the standard IEC 61850, the standards IEC 61968 and 61970 focus on the interfaces in energy-management systems. Both series of standards are intended not only to define the data models for the technical features and functions of energy-supply systems and their components, but also to make it possible to map business processes so that data systems can be connected with energy-market mechanisms, for instance. The standard IEC 61968 includes the distribution system. The basis for both standards is the Common Information Model (CIM), which employs object-oriented modeling of elements and processes and is based on Unified Modeling Language (UML). Certain classes, i.e., attributes, are defined and these classes are subsequently assigned to packets. What is more, CIM standards can be used to make upgrades independently. This is a very important aspect for new components and functions, in particular.

IEC 62351

The standard IEC62351 specifies the mechanisms that protect the ICT infrastructure in an energy-supply system from scheduled and unforeseeable events. It consists of a variety of parts but concentrates on data security, integrity, availability and detection, some parts of the standard still being in development. Since disruptions caused by ICT can compromise or cripple a system and its parts, and functions, this standard will play a major role in the future.

6.3 Electric-Vehicle Networks as Energy Storage Systems in the Power and Transportation System

Electric vehicle networks can only become established when they constitute a system capable of interconnecting all of the actors and components involved and the attendant electrical and transportation system infrastructures, through the information and communications infrastructure and of integrating the diverse infrastructure standards. It must evolve from a mobile energy storage system with limited controllability into a fully intelligent system that can be integrated in the energy system very flexibly and, for instance, respond to the volatility of renewable-energy production without curtailing transportation needs, see Fig. 6.16.

The respective infrastructure levels (electrical grid, transportation system and information and communications technologies) should not only perform the tasks of their own infrastructures but also facilitate value-added services for other levels. The electrical grid infrastructure is chiefly responsible for the security and

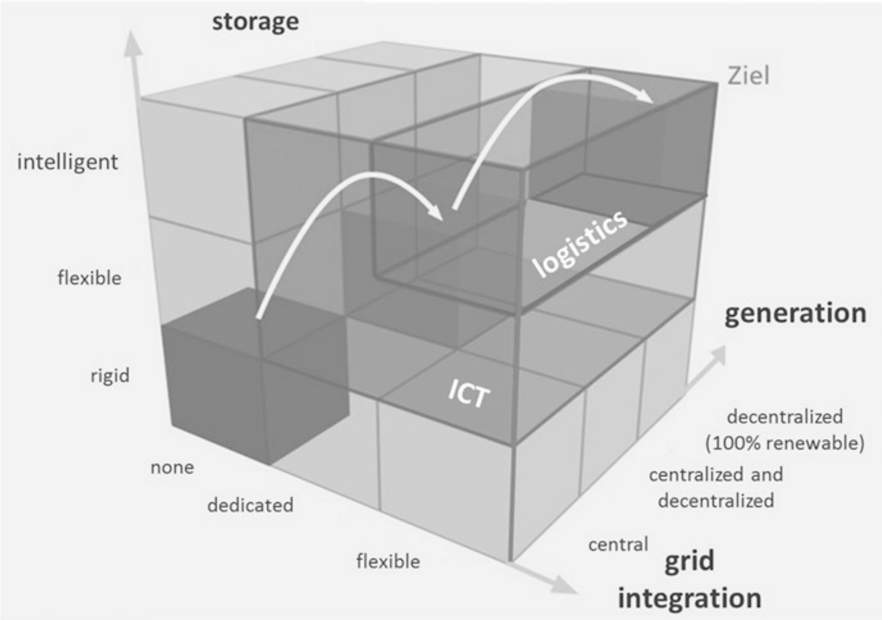

Fig. 6.16 Stages of development and infrastructures of an electric-vehicle network [29]

reliability of the energy supply, i.e., continuously balancing consumption and production while also factoring in the increasing and very flexible load/storage system (electric vehicle network). Primarily, connections with renewable-energy source are preferred, especially for the purpose of zero-emission electric-vehicle networks.

The controllable processes, integrated information and data exchange, and so-called controlled charging and discharging can be used to implement so-called vehicle-for-grid plans in which, on the one hand, electric vehicles can serve the electrical grid in vehicle-to-grid applications such as dedicated and selective active- and reactive-power supply and, on the other hand, electrical grids provide electric vehicles special services in grid-to-vehicle applications. Furthermore, forecasting of renewable-energy production and consumption (stationary and mobile), as well as the continuous supply of data (e.g., on the charging process, charge status) that is relevant to metering and processes in an electricity-supply infrastructure, deserves particular attention and plays an important role in the optimized implementation of electric-vehicle networks. The transportation infrastructure is fundamentally occupied with the typical tasks of ensuring transportation and with the definition siting and provision of appropriate charging stations to guarantee continuous and attractive electric transportation. Technical aspects, such as security and functions of charging stations contingent on the site of installation (public, semi-public, private), are taken into account and the consequences for unrestricted access to, and assurance of, electric transportation are factored in. From the perspective of electric vehicles, operation of a transportation infrastructure necessitates continuous communication of relevant information, such as vehicle SOC (state of charge) or power requirements,

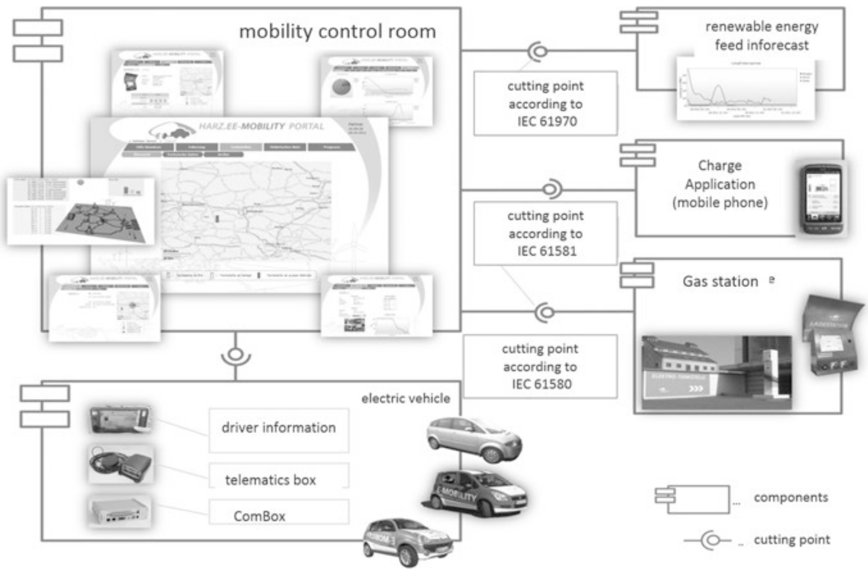

Fig. 6.17 Electric-vehicle network components and interfaces in the Harz. EE–mobility research project [29]

in order to meet customer demands and to be able to provide essential services (charging-station reservations, free charging-station searches). The information and communications infrastructure in an electric-vehicle network has the job of securely and reliably transmitting and providing all essential data and information from status information on existing communications connections to charging stations by user authentication, billing of charging, and parameters measured in the electrical grid and business processes. Moreover, every electric-vehicle network has a central data-management-and-decision tool, see Fig. 6.17, into which all information on the entire infrastructure flows continuously and out of which actions and control signals derived from it are sent to individual components. Depending on their role in the system, actors can retrieve and access data. Charge-point operators retrieve data related to charging in their charge-point network or transportation-service providers collect the electric-vehicle fleets' power requirements for the next 24 hours. End users, i.e., electric-vehicle drivers and owners, have other options such as driver-information systems and cell-phone apps at their disposal to monitor and interact with processes. A use-case description is usually prepared for every use case and contains other information, such as a brief description of the use case, the actors involved, trigger events, outcomes, input data, output data, preconditions and post conditions, general process descriptions and non-functional requirements. Based on the use cases, the systems architecture was broken down into systems components that are involved in the use cases and perform various jobs. This creates a complete electric-vehicle network architecture specifying all functions, their actors and options, which are used to define the standards.

Test Questions Chap. 6

- Why should we use e-mobility; what are the benefits and disadvantages?
- What components make up an electric-vehicle system?
- What are the various kinds of connectors between e-cars and charging stations?
- What types of information and communication technologies (ICT) and channels are needed to realize the e-mobility system?
- What kind of services can e-mobility provide in the power system?

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Chapter 7
Economics of Electric Energy Storage Systems

7.1 Electric-Energy Storage System Applications and Services

The flexibility that Electric-Energy Storage Systems (EES) will bring into the power system, as one of the key technologies which enables the widespread use of intermittent renewable energies and the decoupling of power generation from power consumption, can be used both in terms of power and energy. Such a capability will be beneficial to all the actors in the power system: the generation companies, the system operators (transmission and distribution) and the consumers (see Fig. 7.1). Generally, the benefits of EES from the points of view of utilities, consumers and generation are introduced in Sect. 1.1.2. In this chapter, the economic benefits from the point of view of the market participants will be specified in detail.

The benefits that the EES offer differ very much from operator to operator. For the generation companies, mainly those operating fossil-based power plants, for example, the use of EES will allow them to enlarge their trading activities both in the wholesale and the ancillary-services markets. The economic benefits offered by the EES to the fossil-based power-plant operators are summarized in Table 7.1. It is a different case for the generation companies operating power plants based on renewable energy sources (RES). For those companies, the use of EES presents the possibility of reducing the issues due to the power-forecast error and the intermittent power generation (see Table 7.2).

By considering the large consumers, the use of EES will both ensure a higher level of power quality and offer more flexibility options, which could be sold as services to the grid operators. However, these services can only be obtained if the EES are installed behind the meter of the consumers. The bill for the consumption of electricity (C_{el}) for the small consumers (residential) depends generally on the electricity price (α) and on the amount of electricity consumed (E_{el}) (see Eq. (7.1)). The use of EES may be beneficial only for those consumers who also generate electricity by RES (i.e., through photovoltaic panels or micro-wind turbines). Such a new category of consumer is also called a prosumer, because they are both a producer and a

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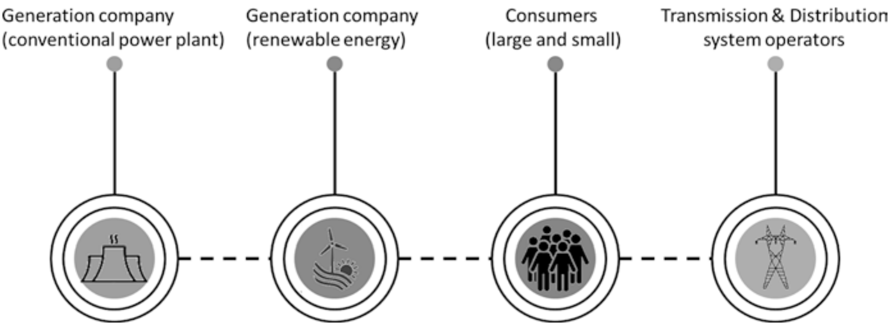

Fig. 7.1 Actors operating in the electricity sector

Table 7.1 The benefits of energy storage systems (ESS) for fossil-based generation companies

Services	Definition
Black start	In the case of a grid outage, black start generation assets are needed to bring larger power plants back into operation.
Voltage support	The voltage in the transmission and distribution system has got to be maintained within an acceptable range to ensure that the active and reactive power production is matched with the demand.
Spinning/ Non-spinning reserves	The spinning reserve is the generation capacity which is online and can serve the load immediately in case of unexpected contingency events (i.e., unplanned outage of a power plant). Non-spinning reserve is the generation capacity which is not available instantaneously but can respond to unexpected contingency events within ten seconds
Frequency regulation	Frequency regulation is required by the system operators to ensure that the system generation is perfectly matched with the system load on a moment-by-moment basis to avoid grid instability.
Energy arbitrage	Energy arbitrage involves purchasing electricity on the wholesale market when the market price is low (typically during the night-time hours) and selling it back to the wholesale market when the electricity price is high (typically at midday and in the late afternoon).

Table 7.2 ESS benefits for renewable energy-based power plants

Services	Definition
Firming capacity	RES, such as wind and solar, generate power in an intermittent way, which can create grid instability. The ESS can smooth the intermittent output of RES and control the ramp rate (MW/min) of power generation.
Renewable-energy time-shift	RES, such as wind and solar, generate power when specific weather conditions exist, which do not always match the power demanded. ESS can capture the excess of RES during low-demand times and dispatch it during high-demand times.
Intermittent RES integration	Conventional power plants are often re-dispatched and do not efficiently operate when integrating a high amount of intermittent RES into the electric grid. ESS can reduce the need to use conventional power plants.

consumer. The use of EES may generate savings for the prosumer because the latter might both increase their energetic autarchy and minimize their electricity bill.

$$C_{el}[€] = \alpha \cdot E_{el} \quad (7.1)$$

The electricity bill of large consumers (mostly industrial operators) is different from that of small consumers. The large consumers are charged both for the electricity they consume and for the power (P_{el}) they withdraw from the network. The electric power withdrawn is charged by the so-called power price (β), as depicted in Eq. (7.2).

$$C_{el}[€] = \alpha \cdot E_{el} + \beta \cdot P_{el} \quad (7.2)$$

Therefore, the large consumers may benefit from using ESS by the reduction of the electric power withdrawn, by shifting the load from peak time to off-peak time (generally during the night) and offering backup power to the system operators. Table 7.3 summarizes the main characteristics of the services offered by ESS.

The benefits offered by EES to the system operators (transmission and distribution) are oriented principally to the deferral of large investment both in upgrading the system infrastructures and in the offering of services for congestion management. The upgrade of the infrastructure for the distribution system operators is driven mainly by the peak demand events, which generally occur on a few fairly predictable occasions each year (see Fig. 7.2). Two main benefits can be obtained by using EES to cover such peak events: On the one hand, they may defer large investment and free up capital which could be used elsewhere; on the other hand, they avoid the oversizing of some elements. This is mostly evident in the distribution systems.

Table 7.3 ESS benefits for small and large consumers

Services	Definition
Backup power	In the case of grid outages, the ESS can provide backup power at multiple scales, ranging from second-to-second power-quality maintenance for the large consumers to daily backup for small consumers.
Increase of energetic autarky	The prosumers (consumers which also generate electric power) can use ESS to charge the electric power generated during the internal low-demand time and discharge it during the high-demand time. Consequently, their energetic autarky increases and the electricity bill decreases.
Demand-charge reduction	The electricity bill for large consumers is the sum of the energy consumed and the power absorbed. Discharging the ESS when the power load is high contributes to decreasing their electricity bill.
Dynamic tariff management	Using dynamic tariffs, the consumers can increase their power purchase during the time of low prices by charging their ESS, and decrease their power purchase during the time of high prices by discharging their ESS.

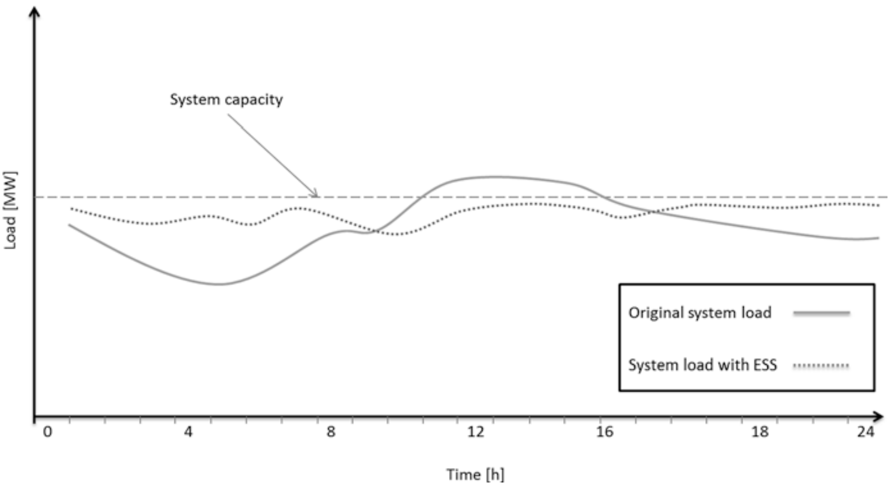

Fig. 7.2 Load profile before and after the use of ESS for deferring the an upgrade of a generic distribution system

Table 7.4 ESS benefits for transmission and distribution-system operators

Services	Definition
Transmission congestion management	The system operators formerly charged the utilities when they used congested transmission corridors during certain times of the day. During congested periods, the ESS, which are installed on the downstream of the congested transmission corridors, can discharge power and minimize the congestion of the transmission system.
Transmission and distribution deferral	The ESS can contribute to delaying investment in upgrades or oversizing the system, freeing up money for other purposes.

It is different in the transmission systems, where the upgrade of the infrastructure is driven mainly to manage the congestions or to enlarge the interconnections (see Table 7.4).

7.2 Electric-Energy Storage Economics

7.2.1 Cost Analysis

Two different type of costs have got to be considered in the evaluation of the EES:

- the total capital costs (TCC) and
- the life cycle costs (LCC).

The TCC cover the costs due to the purchase of the EES, their installation and their delivery. They include the costs of the power-conversion system (PCS) and those for the overheads. The PCS costs are usually explained as the costs related to the power capacity [€/kW], which are different from the costs related to the energy capacity [€/kWh]. The overhead costs can be expressed as costs related to the power capacity, as those related to the energy capacity, or as the sum of the costs for power and energy capacity. They include the costs of project and construction engineering, grid connection and integration facilities (e.g., transformers). A summary of the main items for evaluating the TCC is given in Table 7.5.

The TCC can be calculated either per unit of power (see Eq. (7.3)) or per unit of energy (see Eq. (7.4)):

$$C_{cap} = C_{PSC} + C_{OH} + C_{sto} \cdot h \tag{7.3}$$

$$C_{cap} = \frac{C_{PSC}}{h} + \frac{C_{OH}}{h} + C_{sto} \tag{7.4}$$

where C_{cap}, C_{PSC}, C_{OH} and C_{sto} depict the TCC, the costs for the PCS, the costs for the overhead and those for the energy capacity respectively, while h represents the storage capacity (at nominal power rate) expressed in hours.

In addition to the TCC, the LCC consider all the expenses related to:

- fixed operation and maintenance $(O\&M)_{fix,}$
- variable operation and maintenance $(O\&M)_{var,}$
- replacement (CR), and
- disposal and recycling (CDR).

The LCC can be represented both as levelized annual costs (LAC), which depict the yearly costs that the operator of the ESS has got to cover for suppling the EES

Table 7.5 Main items for calculating the total capital costs (TCC) [based on [1]

TCC element	Cost element	Example
Costs related to the power rate	Power interconnection, cabling and piping	Converter, rectifier, turbine/ pump (for hydro-pump stations)
Costs related to the energy capacity	Containment vessels, construction and excavation	Battery banks, air tanks (for the compressed-air storage systems: CAES), caverns, reservoirs, electrolyte (for the flow batteries)
Overhead costs	Project engineering, grid connection and system integration, protection and isolation devices, construction management, land and access, buildings and foundation, monitoring and control system, shipment and installation	Switches, DC brakes and fuses

services, as well as the levelized cost of electricity (LCOE) supplied by the ESS. The LAC are expressed per unit of power (i.e., €/kW), while the LCOE are calculated per unit of energy (i.e., €/kWh).

In order to estimate the LCC, the annualized capital costs (*Ccap,a*) of the TCC have to be calculated firstly through the capital-recovery factor (*CRF*) (see Eq. (7.5)). The capital- recovery factor is calculated according to Eq. (7.6), whereby (i) depicts the interest rate during the lifetime of (T):

$$C_{cap,a} = TCC \cdot CRF \tag{7.5}$$

$$CRF = \frac{i \cdot (1+i)^T}{(1+i)^T - 1} \tag{7.6}$$

The total annual operation and maintenance costs ($C_{O\&M,a}$) are estimated by summing the annual fixed operation and maintenance costs ($C_{O\&M,f}$) with the annual variable operation and maintenance costs ($C_{O\&Mv}$) (see Eq. (7.7)). These last two are calculated by multiplying the operation and maintenance costs by the yearly full-operating hours (h). The price of electricity or of the natural gas (in the case of diabatic CAES) could either be included in the variable operation and maintenance costs or be calculated alone.

$$C_{O\&M,a} = C_{O\&M,f} + C_{O\&M,v} \cdot h \tag{7.7}$$

The future costs of the ESS (C_R) should be considered first to estimate the annual costs to replace the EES (see Eq. (7.8)). These costs have got to be expressed in terms of energy (i.e., €/kWh). In addition, the capacity of the ESS, which is expressed as charging/discharging time (h), the replacement period (t), the efficiency of the future ESS (η_{sys}) and the number of replacements (r) during the lifetime considered have got to be known.

$$C_{R,a} = CRF \cdot \sum_{k=1}^{r} (1+i)^{-kt} \cdot \left(\frac{C_R \cdot h}{\eta_{sys}} \right) \tag{7.8}$$

The annualized disposal and recycling costs ($C_{DR,a}$) can be calculated according to Eq. (7.9), by considering the interest rate (i) and the lifetime of the EES (T):

$$C_{LCC,a} = C_{cap,a} + C_{O\&M,a} + C_{R,a} + C_{DR,a}. \tag{7.9}$$

The costs of the electricity discharged are calculated through the LCOE (see Eq. (7.10)). In order to calculate the LCOE, the $C_{LCC,a}$ have to be divided by the full annual operating hours (h) of the EES, so:

$$C_{LCOE} = \frac{C_{LCC,a}}{h}. \tag{7.10}$$

The net levelized cost of the electricity discharged (C_{NLCOE}) is calculated by subtracting the costs of charging electricity from the LCOE (see Eq. (7.11)):

$$C_{NLCOE} = \frac{C_{LCC,a}}{h} - \frac{price\,of\;electricity}{\eta_{sys}}. \tag{7.11}$$

7.2.2 Investment and Operation Costs Analysis of EES

The capital costs for the EES depend on the technology, on its grade of maturity and on the site where it is built. The pumped-hydro storage systems, for example, which are the most diffuse EES worldwide, are a capital-intensive technology with a high degree of maturity. Such a technology can store electricity with an overall efficiency of about 80 %. No high reduction costs for the PCS (both for the pump and for the turbine) are forecast in the next few decades. The PCS costs have a wide range: On average, the costs are about 500 €/kW. The costs for the reservoir depend mostly on the site and on the plant size for which it should be realized; they also have a wide range. A kWh of reservoir can cost between 8 and 126 €. The fixed operation and maintenance costs, which range between 1 and 9.2 €/kWh per year, are low. The variable operation and maintenance costs are even lower: They range between 0.19 and 0.84 €/MWh. Table 7.6 summarizes the main cost components for the capital costs analysis of pumped-hydro systems.

The PCS costs for the diabatic CAES can be compared to those of gas-turbine plants. Since the gas-turbine plant is a highly mature technology, no large reduction costs are expected for the PCS during the next few decades. An increase of the PCS costs of 30–40 % for the adiabatic CAES (A-CAES) is estimated if compared with the diabatic one. This is due mainly to the designs of the compressor and turbine, which will be stressed with higher pressures. However, the overall efficiency of the A-CAES is estimated to be 26–38 % higher than the diabatic version. The costs related to the compressed-air reservoir do not depend on the storage version (diabatic or adiabatic) and may be very low if existing caverns are used. In the case that

Table 7.6 Main cost components for pumped hydro storage systems (based on [1, 2])

Item	Average	Range
Power conversion system (PCS) costs [€/kW]	512	373–941
Overhead costs [€/kW]	15	3–28
Storage costs [€/kWh]	68	8–126
Yearly fixed operation and maintenance costs [€/kW]	4.6	2.0–9.2
Variable operation and maintenance costs [€/MWh]	0.22	0.19–0.84
Lifetime [years]	>50	–

Table 7.7 Reservoir costs for compressed-air storage systems (CAES) (based on [1])

Cavern formation type	Storage costs [€/kWh]
Natural porous rock formations from depleted gas or oil sites	0.10
Solution-mined salt caverns	1.01
Dry-mined salt caverns	9.71
Abandoned limestone or coal mines	9.71
Rock caverns from excavation of impervious rock formations	29.55

an ex novo underground reservoir is created, then the costs depend on the geology of the site. Table 7.7 summarizes the cost of creating a cavern for various geological formations. Underground reservoirs are preferable if the discharge time is higher than 8 h. For smaller CAES (3–15 MW; 2–4 h discharge time), the use of an aboveground reservoir is also possible (typically a pressure vessel). However, even if the project engineering may be easier than the underground solution, the overall costs are higher. The A-CAES, compared to the diabatic one, uses a heat storage whose costs are not easy to estimate since there are no extant industrial examples. Table 7.8 shows the main cost components of diabatic CAES and A-CAES.

Flywheels are a mature storage technology similar to the pumped hydro and CAES. They are used mostly for power applications and have a high overall efficiency (>85 %) and a long lifetime (>15 years). Due to the various types of materials used, the high-speed flywheels are up to five times more expensive than the low-speed version. Table 7.9 depicts the main cost components for the flywheel technology.

High-temperature sodium-sulfur (NaS) batteries are one of the most diffuse electrochemical storage technologies. They have an overall efficiency of about 75–85 %

Table 7.8 Main cost components for CAES (based on [1, 3])

Item	Type of reservoir	Average	Range
PCS costs [€/kW]	Aboveground Underground	846 843	804–887 549–1014
Storage costs [€/kWh]	Aboveground Underground	109 40	86–131 4–64
Yearly fixed operation and maintenance costs [€/kW]	Aboveground Underground	2.2 3.9	2.2–3.7 2.0–4.2
Variable operation and maintenance costs [€/MWh]*	Aboveground Underground	2.2 3.1	2.2–2.5
Lifetime	→ 40		

*These costs refer only to the diabatic version. The fuel costs range 8–20 €/MWh and the emission costs 18–22 €/MWh.

Table 7.9 Main cost components for flywheels (based on [1])

Item	Average	Range
PCS costs [€/kW]*	287	263–470
Storage costs [€/kWh]	2815	865–47764
Yearly fixed operation and maintenance costs [€/kW]	5.2	4.3–6.0
Variable operation and maintenance costs [€/MWh]*	2.0	0.2–3.8
Lifetime [years]	>15	

*Includes the overhead costs.

and an expected lifetime ranging between 2500 and 4500 cycles. The investment costs for a unit of power range between 241 and 865 €/kW, while those per unit of energy range between 184 and 847 €/kWh. The fixed operation and maintenance costs range between 2 and 17 €/kW yearly, while variable costs range between 0.2 and 5.6 €/MWh. Table 7.10 summarizes the main cost components for the high-temperature NaS batteries.

Lithium-ion batteries have an overall efficiency comparable with the high-temperature NaS batteries. Lithium-ion batteries have a record of use of more than 25 years both in power electronics and in grid-scale applications. The lifetime can also exceed 10,000 cycles. The PCS costs range between 165 and 581 €/kW. The energy storage costs are more expensive and range between 470 and 1249 €/kWh. The overhead costs can be estimated, on average, at 80 €/kW. The fixed operation and maintenance costs are estimated, on average, at 6.9 €/kW per year. The variable maintenance and operation costs are very low and range between 0.4 and 5.6 €/MWh. Table 7.11 shows the main cost components for lithium-ion batteries.

Regarding flow batteries, there is no relationship between the costs for the power capacity and those for energy capacity. The energy capacity depends on the amount of the electrolyte solution, while the power capacity depends on the active surface of the cell. Currently, many electrolyte solutions have been tested for flow batteries,

Table 7.10 Main cost components for high-temperature NaS batteries (based on [1, 4])

Item	Average	Range
PCS costs [€/kW]	366	241–865
Overhead costs [€/kW]	80	–
Storage costs [€/kWh]	298	180–563
Yearly fixed operation and maintenance costs [€/kW]	3.6	2.0–17.3
Variable operation and maintenance costs [€/MWh]	1.8	0.3–5.6
Replacement costs [€/kW]	180	180–443
Lifetime [years]	<15	

Table 7.11 Main cost components for lithium-ion batteries (based on [1, 4])

Item	Average	Range
PCS costs [€/kW]	463	165–581
Overhead costs [€/kW]	80	
Storage costs [€/kWh]	795	470–1249
Yearly fixed operation and maintenance costs [€/kW]	6.9	2.0–13.7
Variable operation and maintenance costs [€/MWh]	2.1	0.4–5.6
Replacement costs [€/kW]	369	187–543
Lifetime [cycles]	>15,000	

Table 7.12 Main cost components for flow batteries (based on [1, 4])

Item	Average	Range
PCS costs [€/kW]	490	472–527
Storage costs [€/kWh]	467	433–640
Yearly fixed operation and maintenance costs [€/kW]	8.5	3.4–17.3
Variable operation and maintenance costs [€/MWh]	0.9	0.2–2.8
Replacement costs [€/kW]	130	11–192
Lifetime [cycles]	>10,000	

but the vanadium type is used most often. In comparison with the other battery technologies, the overall efficiency of flow batteries is approximately 60–65 %. However, the electrolyte solution has an unlimited lifetime, even if the circulating pumps need to be changed every 10,000 cycles. The PCS costs range between 472 and 527 €/kW. The costs for the energy capacity range between 433 and 640 €/kWh. The yearly fixed operation and maintenance costs are, on average, 8.5 €/kW, while the variable operation and maintenance costs range between 0.2 and 2.8 €/MWh. Table 7.12 summarizes the main component costs for flow batteries.

Superconducting magnetic ESS have a very high efficiency (about 97 %) and an extremely long lifetime (>100,000 cycles). They are used mostly for power-quality applications. The PCS costs range between 212 and 568 €/kW. The costs for the energy capacity are much higher and range between 5310 and 6870 €/kWh (see Table 7.13). The fixed and variable costs for operation and maintenance can be neglected.

The power-to-gas solution (both hydrogen and methane) is very different from the other energy storage technologies. Such a solution enables the storage of a very high amount of energy for a long time, and it could be considered as a seasonal solution. Even if the overall efficiency is the lowest among the energy storage solutions (about 35–45 % considering AC-AC), the main advantage of the power-to-gas

Table 7.13 Main cost components for superconducting magnetic energy storage (based on [1, 4])

Item	Average	Range
PCS costs [€/kW]	212	218–568
Storage costs [€/kWh]	5310	6090–6870
Lifetime [cycles]	>100,000	

solution is the use of the natural gas infrastructure. Therefore, the costs of the gas pipeline and of the compression stations will not be considered. The PCS costs for the electrolysis are related strictly to the technology used. They range between 590 €/kW for the solid-oxide electrolysis with an efficiency of 83 % (power to hydrogen) to 1400 €/kW for the alkaline electrolysis with an efficiency of 43–66 % (power to hydrogen). The cost of the methanizer (hydrogen to methane) is about 1000 €/kW. The overall capital costs for power also depend on the conversion technology used for the gas to power. Considering the fuel cells (hydrogen to power), then the overall PCS costs range between 1383 and 4653 €/kW, while the costs vary between 1102 and 3362 €/kW when using the gas turbine (hydrogen to power). The overhead costs can be estimated at 25 €/kW. Considering only the construction of the gas reservoir (aboveground or underground), the cost of energy ranges between 0.002 and 134 €/kWh for the underground and aboveground solution, respectively. Table 7.14 summarizes the main cost components for the power-to-gas solution, while Table 7.15 shows the costs of storing hydrogen in various geological formations. A summary of the power-capacity and energy-capacity costs for various kinds of ESS is given in Fig. 7 3.

A summary of the power-capacity and energy-capacity costs for different kinds of ESS is given in Fig. 7.3.

The TCC for each energy storage technology have been calculated according to Eqs. (7.36) and (7.37). Figure 7.4 summarizes the TCC related both to the installed power capacity and the installed energy capacity. Typical energy capacity values have been considered to estimate the TCC.

Table 7.14 Main cost components for the power to gas storage system (based on [1, 5])

Item	Average	Range
PCS costs [€/kW]	2465* 1570**	1383–4453* 1102–3362**
Storage costs [€/kWh]	Aboveground: 130 Underground: 3.7	Aboveground: 125–134 Underground: 0.02–12.4
Yearly fixed operation and maintenance costs [€/kW]	25* 26**	16–44* 23–48**

*With fuel-cell technology (hydrogen to power).
**With gas turbine (hydrogen to power).

Table 7.15 Main cost components for hydrogen-storage systems (based on [1])

Cavern formation type	Storage costs [€/kWh]
Natural porous rock formations from depleted gas or oil sites	0.002
Solution-mined salt caverns	0.02
Dry-mined salt caverns	0.14
Abandoned limestone or coal mines	0.14
Rock caverns from excavation of impervious rock formations	0.41
Geologic storage of hydrogen	0.25

The LCC have been estimated according to Eq. (7.42). The annual costs for the replacement of the ESS have been not considered in the estimation. Some parameters, such as the fixed and variable operation and maintenance costs, of some energy-storage technologies were not taken into consideration regarding the leak of information in literature. The variable operation and maintenance costs do not consider the costs of electricity for charging the ESS, while they consider the fuel costs (only for the diabatic CAES). An interest rate of 8 % has been assumed. A value of 800 h per year has been considered for the full–load-hours parameter. This value might be lower than the real one for many applications, for example, those for power quality. A summary of the LCC for various kinds of energy storage technology is depicted in Table 7.16.

The levelized costs of discharged electricity are calculated according to Eq. (7.43). An electricity price of 50 €/MWh for charging the ESS was assumed. The influence of the full-load hours on the levelized costs of discharged electricity is shown in Fig. 7.5.

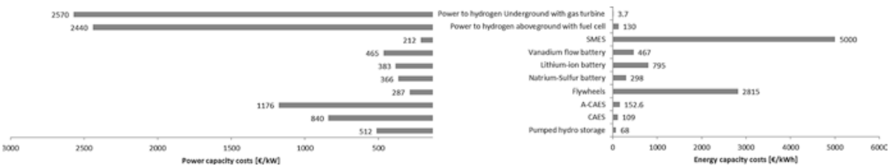

Fig. 7.3 Summary of power- and energy-capacity costs for various energy storage systems (ESS)

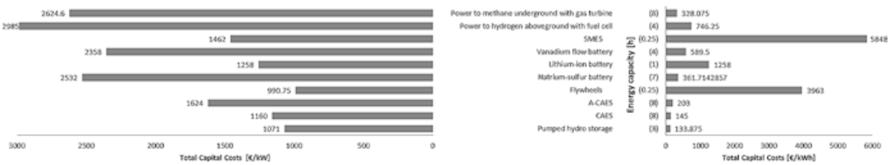

Fig. 7.4 Total capital costs for various kinds of ESS

Table 7.16 Summary of the life-cycle cost analysis for various kinds of ESS

	TCC [€/kW]	C_{FOM} [€/kW]	C_{VOM} [€/kWh]	Lifetime [years]	Full load hours [h/year]	C_{FR}	C_{cap} [€/kW]	C_{LCC} [€/kW]
Pumped-hydro storage	1071	4.6	0.00022	20	800	0.1018	109	113
CAES	1160	3.9	0.0031	20	800	0.1018	118	124
A-CAES	1624	3.9	–	20	800	0.1018	165	165
Flywheels	990	5.2	0.002	10	800	0.1490	147	154
Natrium-sulfur battery	2532	3.6	0.0018	20	800	0.1018	257	262
Lithium-ion battery	1,258	6.9	0.0021	15	800	0.1168	146	155
Vanadium flow battery	2,358	8.5	0.0009	15	800	0.1168	275	284
SMES	1462	–	–	10	800	0.1490	217	217
Power to hydrogen aboveground with fuel cell	2985	25	–	15	800	0.1168	348	373
Power to hydrogen underground with gas turbine	2624	26	–	15	800	0.1168	306	332

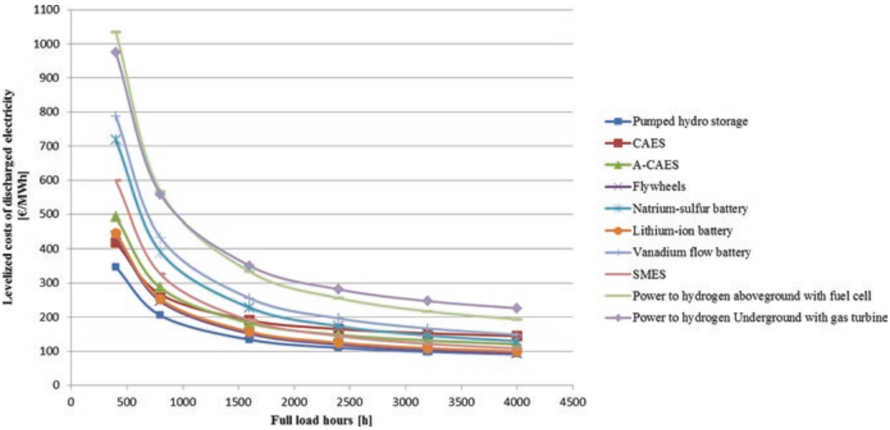

Fig. 7.5 Levelized costs of discharged electricity for various full-load hours and various ESS

Test Questions Chap. 7

- What are the main criteria used to classify energy-storage systems?
- Which cost-calculation methods are useful for the determination of the storage economic benefits of storage?
- What is the capital-recovery factor?
- Which are the values of the lifetime factors for various storage technologies?
- Which storage technology today is cheapest and which is most expensive?

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Chapter 8
Reliability in Smart Grids with Energy Storage Systems

8.1 Reliability in Power-Energy Systems

A reliable supply of electricity with the requisite high quality to industrial consumers, in particular, is essential for society's continued development and welfare. The standard DIN 40 041 defines reliability as an entity's quality in terms of being able to meet the demand for reliability during or after specified time intervals and under specified conditions of use. The electricity supply is considered to be reliable when it continuously meets customer demand (just-in-time), and this must be so while the complete system of primary-energy production, conversion, transport and distribution are always necessarily factored in. Various malfunctions or events characterized by their intensity (insufficient energy) and duration also affect the security of supply in various ways, e.g. affecting varying numbers of consumers. Causes of malfunctions are external, e.g., storms and lightning strikes, terrorism or solar winds, or internal, e.g., planning and design errors or operational errors such as overloaded system components, short circuits caused by incorrect operation, switching surges, and have various points of origin. Statistical data on this are plotted in unavailability graphs, see, e.g., Fig. 8.1. Malfunctions that go undetected or cannot be assigned to any of the predefined groups/criteria are placed under the category "no identifiable cause" [1].

The acceptable limit for permissible durations of a malfunction (as a function of the unavailable quantity of power) is presented in Fig. 8.2. Smaller malfunctions (of only kilowatts of power unavailable because of a malfunction) have a longer acceptable interruption time, even up to hours. Major malfunctions may not exceed the acceptable interruption time, normally of just seconds.

The quality of the power supply is specified by a variety of factors including:

- service quality,
- voltage quality, and
- supply reliability.

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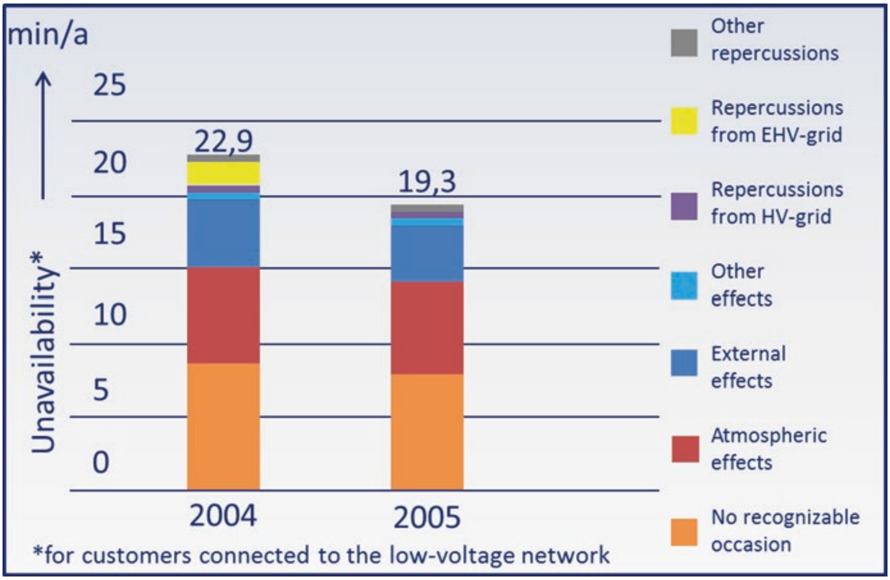

Fig. 8.1 Trend of energy unavailability in Germany 2004–2005

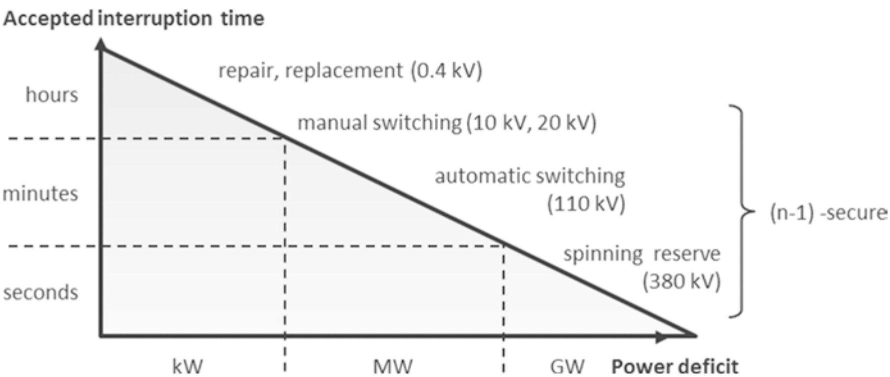

Fig. 8.2 Acceptable interruption duration as a function of supply interruption (power unavailability) based on a Zollenkopf curve [2]

Service quality is the quality of services provided by an energy supplier to consumers before and during an existing contractual relationship. Quality of voltage is defined by national and international standards such as EN50160 (medium and low voltage) and the grid code (high and ultra-high voltage). They define grid-parameter features such as acceptable voltage range, which may not exceed ±10 % of the nominal voltage. Predefined frequency conditions also apply to synchronous systems so that a range of 49.5 Hz ≤ f ≤ 50.5 Hz is guaranteed for 99.5 % of the time and 47 Hz ≤ f ≤ 52 Hz for 100 % of the time. Supply reliability is expressed as

Table 8.1 Supply reliability parameters [3].

Parameter	Symbol	Unit	Values for Germany in 2012
Interruption frequency (number of interruptions per customer per year)	H_U	[1/a]	0.28
Interruption duration (average duration of a supply interruption)	T_U	[min]	15.9
Unavailability (average total length of all supply interruptions per customer per year)	Q_U	[min/a]	4.45

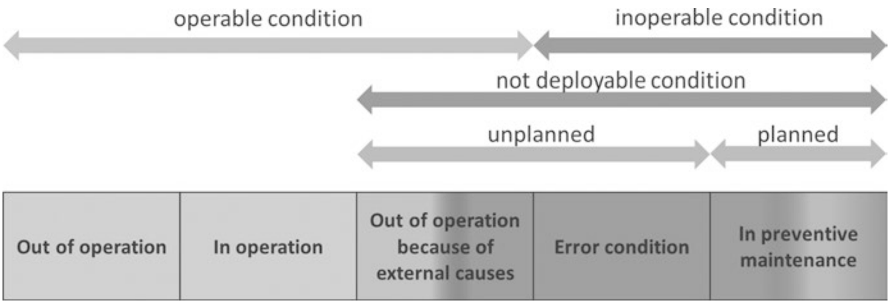

Fig. 8.3 Operating state classification

a measure of an electric-power system's capacity to supply customers sufficiently. Supply reliability identifies the number and duration of supply interruptions, the main parameters being operability, maintainability and maintenance support, see Table 8.1.

All of the system components (equipment) and their states are specified and defined. There are two states: operating or not operating, which occur either as scheduled (servicing) or unscheduled (malfunction), see Fig. 8.3.

The transparent variable of supply reliability is expressed by the supply-interruption duration/energy unavailability (in minutes) per calendar year and analyzed statistically. As Fig. 8.4 [1] shows, European countries have a range of supply-reliability indices. Power was unavailable for 14.9 minutes in Germany in 2010 and more than ten times longer (193 minutes) in Finland. The differences are generally due to different grid structures, equipment, components and systems and operating modes.

8.2 Grid-Reliability Calculations

Reliability is the capability of a component or system to perform its required function without failure—under given conditions for a given time interval [3]. Reliability is relevant to highly complex systems consisting of numerous components. The

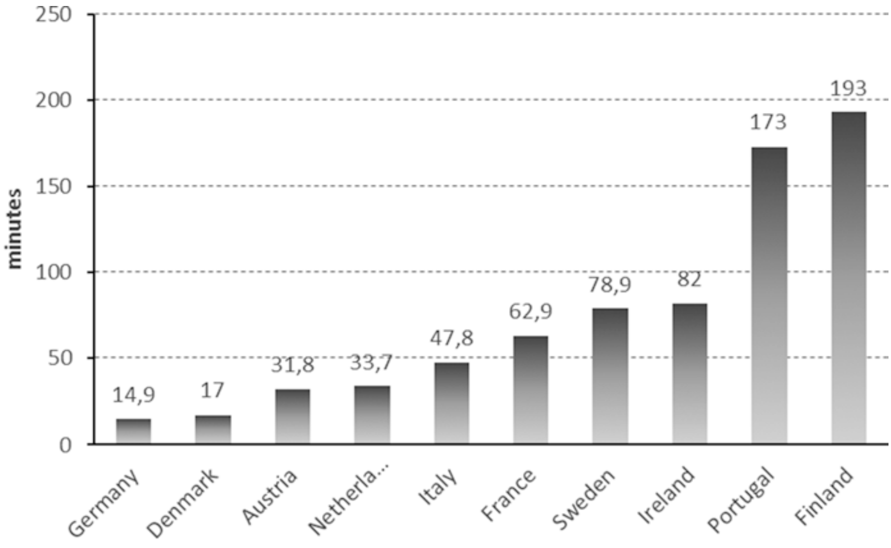

Fig. 8.4 Supply interruptions in European nations in 2010 [4]

reliability of a complete system is contingent on the reliability of the individual system components and equipment, as well as their interconnections. Stochastic processes are used to model each system component, i.e., its state, in time domains. Only one state (operating or not operating) is possible at any time, see Fig. 8.5.

Components have other specific parameters defined on the basis of manufacturers' experiences with tests and real operation over a specified time. These include:

- mean time to failure (MTTF), the expected time of failure measured from the time of a completed repair,
- mean time to repair (MTTR), the expected time needed to repair an element measured from the time of failure until its repair,

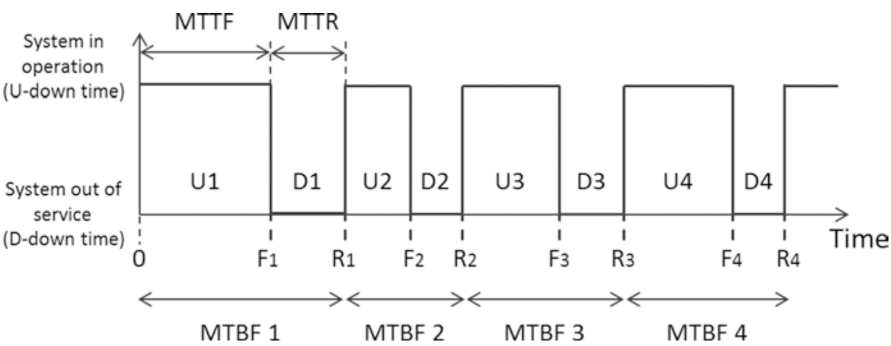

Fig. 8.5 Operating states of elements over time

- mean time between failures (MTBF), the average time between successive failures expressed as the total of MTTF and MTTR in Eq. (8.1):

$$MTBF = MTTR + MTTF \tag{8.1}$$

- expected failure rate λ and expected repair rate μ related to the MTTF and MTTR as in Eqs. (8.2) and (8.3), respectively, indicating the number of failures $n_{f|T}$ and repairs $n_{r|T}$ in the given period of observation T, where t_{TFi} is the time to ith-failure and t_{TRi} is the time to ith-repair

$$\lambda = \frac{1}{MTTF} = \frac{n_{f|T}}{\sum_{i=1}^{n_{f|T}} t_{TFi}} \tag{8.2}$$

$$\mu = \frac{1}{MTTR} = \frac{n_{r|T}}{\sum_{i=1}^{n_{r|T}} t_{TRi}} \tag{8.3}$$

These standard parameters furnish the basis for calculating the two basic parameters of availability A and unavailability U, which are the starting point for creating the base model of components. These parameters can be calculated by observing the operating waveform where t_{up} indicates all interval durations of element operation and t_{down} its outage or failure or by using the aforementioned parameters, see Eqs. (8.4) and (8.5):

$$A = \frac{\sum t_{up}}{\sum t_{up} + \sum t_{down}} = \frac{MTTF}{MTTF + MTTR} = \frac{\mu}{\mu + \lambda} \tag{8.4}$$

$$U = \frac{\sum t_{down}}{\sum t_{up} + \sum t_{down}} = \frac{MTTR}{MTTF + MTTR} = \frac{\lambda}{\mu + \lambda} \tag{8.5}$$

Distribution Functions and Parameters

Since reliability parameters normally represent average rather than current values, they are normally defined by random numbers, which, in turn, are specified by probability-distribution functions. Typical distribution functions are:

- probability distribution,
- exponential distribution, and
- Weibull distribution.

Probability Distribution Functions

A probability distribution function f(x) has a related probability density function f(t) that represents the probability of random variable x having a specific value. This f(t) function specifies a component's probability of failure after the time t has passed. Depending on the type of component, the f(t) function can represent various expressions, but it always returns a value between 0 and 1. The integral of the probability-distribution function over all possible results is equal to 1, because each random occurrence has one actual outcome, which is presented in Eq. (8.6):

$$\int_{-\infty}^{\infty} f(x)dx = 1. \tag{8.6}$$

The component cumulative distribution function F(t) describes the probability that an element will have failed once the time t has passed. This is expressed by Eq. (8.7):

$$\boldsymbol{F(t) = P(T_f \leq t) = \int_0^t f(x)dx; \quad t > 0,} \tag{8.7}$$

where F(t) is the cumulative distribution function and T_f is the element's time to failure.

The probability that time values in the reliability calculation are negative is 0, and the probability that the duration is less than infinity is equal to 1, as presented in Eq. (8.8):

$$\mathrm{F}(0) = 0; \qquad \mathrm{F}(\infty) = 1. \tag{8.8}$$

The hazard function λ(t) is closely related to the probability-density function and the cumulative distribution function. The hazard function represents the probability of an element's failure if it has not already failed. Since the density function represents the probability that an element will fail and the cumulative distribution function represents the probability that an element has failed already, the hazard function is expressed by Eq. (8.9). An example of the hazard function is the bathtub curve that describes changes in an aging component's failure rate. Hazard functions are therefore identical to failure rate functions [1].

$$\lambda(\boldsymbol{t}) = \frac{\boldsymbol{f(t)}}{1 - \boldsymbol{F(t)}} \tag{8.9}$$

The reliability function R(t) expresses the probability that a component will function until a specific time and is represented by Eq. (8.10) [DISS BA]:

$$\boldsymbol{R(t) = 1 - F(t) = P(T > t).} \tag{8.10}$$

Probability distribution functions are characterized by the statistical metrics of mean values, variances and standard deviations. The value obtained is the geometric mean of the function and can be calculated with Eq. (8.11). Variance measures the function's variation around the mean, as in Eq. (8.12). The square root of the variance is the standard deviation specified in Eq. (8.13) [1].

$$\boldsymbol{\mathit{Expected\ value} = \bar{x} = \int_{-\infty}^{\infty} xf(x)dx} \tag{8.11}$$

$$\boldsymbol{Variance} = \boldsymbol{\sigma}^2 = \int_{-\infty}^{\infty} \left[\boldsymbol{f}(\boldsymbol{x}) - \bar{\boldsymbol{x}} \right]^2 \boldsymbol{dx} \tag{8.12}$$

$$\boldsymbol{Standard\ deviation} = \boldsymbol{\sigma} = \sqrt{\boldsymbol{Variance}} \tag{8.13}$$

Exponential Distribution

Exponential distribution has a constant hazard function and is therefore commonly used in reliability analysis. The hazard function represents an electrical component during its useful life. Exponential distribution is denoted by a single parameter of the failure rate λ. Examples of exponential distributions of reliability and failure rate over time are presented in Fig. 8.6. Exponential distribution can be calculated with Eqs. (8.14–8.18):

$$\boldsymbol{f}(\boldsymbol{t}) = \lambda \boldsymbol{e}^{-\lambda t}; \quad \boldsymbol{t} \geq 0 \tag{8.14}$$

$$\boldsymbol{F}(\boldsymbol{t}) = 1 - \boldsymbol{e}^{-\lambda t} \tag{8.15}$$

$$\lambda(\boldsymbol{t}) = \lambda \tag{8.16}$$

When additionally are:

$$Expected\ value = \bar{\boldsymbol{x}} = \frac{\mathbf{1}}{\lambda} \tag{8.17}$$

and

$$Variance = \boldsymbol{\sigma}^2 = \frac{\mathbf{1}}{\lambda^2} \tag{8.18}$$

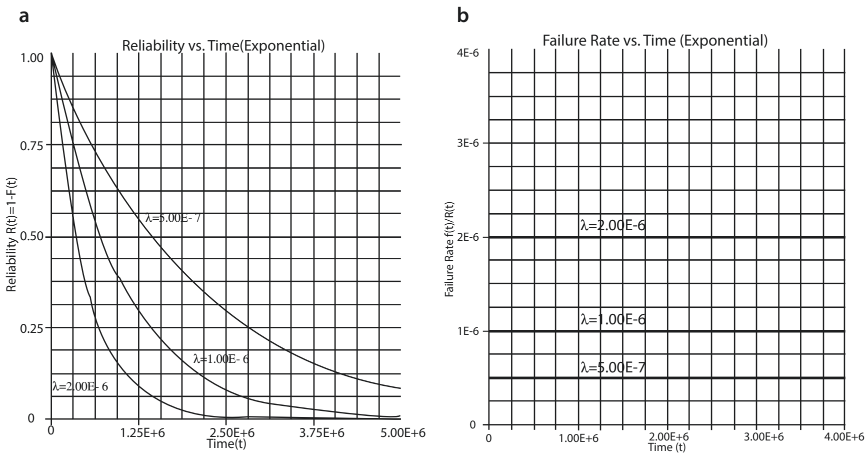

Fig. 8.6 Exponential distribution of (**a**) reliability over time; (**b**) failure rate over time [5]

Weibull Distribution

A Weibull distribution has two parameters, a scale parameter α and a shape parameter β that take on various forms in response to different data sets. A Weibull distribution is used to represent the early normal operation and wear-out period of a component's life cycle, as presented in Fig. 8.7 [5]. A Weibull distribution is defined by the formulas in Eqs. (8.19–8.21) [5]:

$$f(t) = \frac{\beta t^{\beta-1}}{\alpha^{\beta}} e^{\left(-\left(\frac{t}{\alpha}\right)^{\beta}\right)}; \quad t \geq 0 \tag{8.19}$$

$$F(t) = 1 - e^{\left(-\left(\frac{t}{\alpha}\right)^{\beta}\right)} \tag{8.20}$$

$$\lambda(t) = \frac{\beta t^{\beta-1}}{\alpha^{\beta}} \tag{8.21}$$

where α is the scaling factor and β is the shape parameter [1].

Methods

Analysis and simulation methods have long been employed to calculate reliability, see Fig. 8.8. Selection of the right method depends on various factors. Factors such as the size of the electric power system analyzed (number of nodes, topology), its dependence on connected components (every component being dependent on another) and the number of use cases (larger systems having more use cases) play a major role.

The analysis methods are either state-space methods or network methods. State-space methods are, in turn, either combinatorial methods or Markov processes and consider every possible grid state. A system can be in only one state at any given

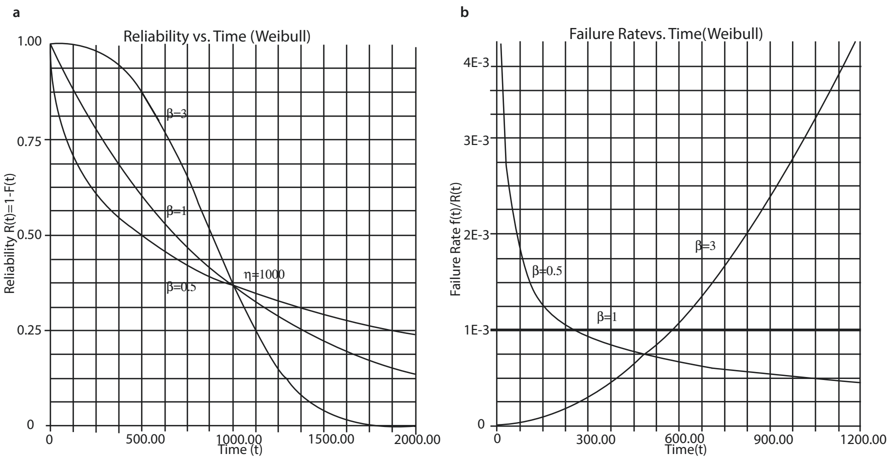

Fig. 8.7 Weibull distribution of (**a**) reliability over time; (**b**) failure rate over time [5]

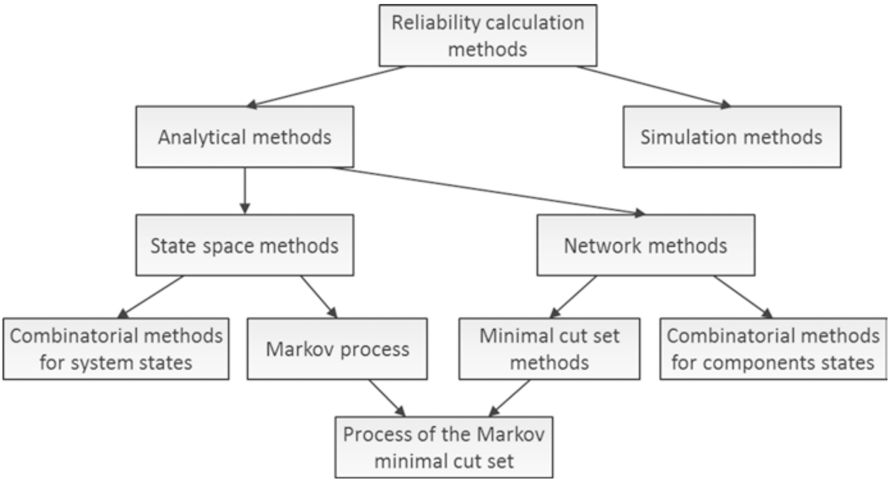

Fig. 8.8 Methods for reliability calculation [6]

time. Stochastic processes are used to model and calculate the transitions between every state. The combinatorial method uses the probabilistic relationships between elements of systems to ascertain all possible system states. In Markov processes, a system's state in time is solely a function of its preceding state. An element is characterized by one of two states, "operating" or "not operating". The transition probabilities from one state to another are the failure rate λ and the repair rate μ, which are the reciprocals of the analyzed component's MTTF and MTTR, respectively. Some elements can have more than two states. Estimating future probabilities for every state requires specifying the state-transition probabilities from every state Zj to one state Zm, starting with the initial state. The transition probability is treated as a matrix [P(t)] and represented by Eq. (8.22):

$$P(t + \Delta t) = [P(t)] \cdot P(t) \tag{8.22}$$

where [P(t)] is the matrix of transition probabilities from t to t+Δt, and P(t) is a vector of state probabilities at the time t.

Network methods are well-suited for modeling complex power systems with multiple components. Every element is represented as operating or not operating. Network methods subsume combinatorial methods for system states and minimal cut-set methods. Simulation methods are dominated by Monte Carlo methods, which can be completed sequentially or non-sequentially. They assess reliability by simulating a process and random system performance factoring in various variables in each simulation step. These include the number of failures, time between failures and various resupply times. Random numbers converted by a distribution function reproduce the performance of individual components. The quality of the results is contingent on the simulation cases. The larger the number of simulation cases, the better the results can be expected to be.

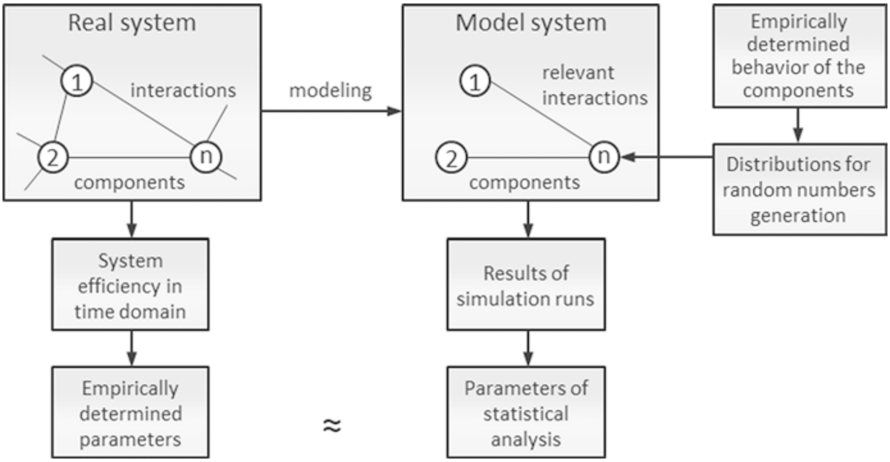

Fig. 8.9 Principle of a Monte Carlo simulation of electric power systems [6]

The principle of the Monte Carlo simulation is illustrated in Fig. 8.9. First, a stochastic model is developed based on the real system model (components and the interactions and interrelationships). Then, random variables are generated, which are used in multiple simulations of random processes. Statistical analysis of the simulated processes ultimately delivers the results. The Monte Carlo method has two fundamental advantages. Running a simulation with the same input data several times will not necessarily deliver the same results. Repeating the simulation can generate the distribution functions of the results, which make it possible to observe deployment of the reliability indices. Moreover, Monte Carlo methods can be used to assess the influence that the time required for necessary repairs of malfunctioning components has on the reliability of the overall system.

The optimal method for a particular system is ascertained by analyzing the parameters and criteria case by case. The aforementioned methods are compared in Table 8.2. Monte Carlo simulation requires more computation than analysis methods. This is reflected in the computation time. Moreover, the Monte Carlo method analyzes every possible state, while other methods do not.

Table 8.2 Comparison of reliability-modeling methods

	Monte Carlo simulation	Analysis methods
Computation time	Long simulation times	Dependent on simplification
Result	Dependent on simulation steps and random number generator Complete probability distribution of reliability indices	Constant expected value
System simulation	Every state is analyzed	Only significant states are analyzed

Table 8.3 Select reliability indices

Customer-based indices	
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
CAIDI	Customer Average Interruption Duration Index
ASAI	Average Service Availability Index
ASUI	Average Service Unavailability Index
EENS	Expected Energy Not Supplied
CAIFI	Customer Average Interruption Frequency Index
CTAIDI	Customer Total Average Interruption Duration Index
$CEMI_n$	Customers Experiencing Multiple Interruptions
MAIFI	Momentary Average Interruption Frequency Index
Load-based indices	
ASIFI	Average System Interruption Frequency Index
ASIDI	Average System Interruption Duration Index
Power quality indices	
$SIARFI_x$	System Instantaneous Average RMS Variation Frequency Index
$SMARFI_x$	System Momentary Average RMS Variation Frequency Index
$STARFI_x$	System Temporary Average RMS Variation Frequency Index

Reliability Indices and Criteria

Various indices, which have been developed by diverse standards' bodies and are sometimes applied and defined nationally, are used to assess power-supply system reliability. The most commonly used indices (see Table 8.3) fall into one of three categories: customer based, load-based or power quality. Customer-based indices include system and customer criteria generally specified by interruption duration and interruption frequency. The load based indices of Average System Interruption Frequency Index and Average System Interruption Duration Index only apply to a system. Power-quality indices are used for system-based assessment of grid quality represented by an RMS.

8.3 Storage-System Reliability

8.3.1 Case Study: Calculation of Storage-System Reliability

Critical power-supply infrastructures and their components/equipment must be planned for the long term and operated with constant efficiency to ensure that security of supply is technically reliable and cost-effective. Reliability modeling plays a crucial role in the verification of the technical feasibility of components such as storage systems, as well as in investment-decision support and risk assessments of the aforementioned factors.

This 9-Bus IEEE benchmark network represents a portion of the Western System Coordinating Council (WSCC) [7]. A power infrastructure contains three generators, three transformers, three load points, nine electric nodes, six lines and three branches. The base KV levels are 13.8 kV, 16.5 kV, 18 kV and 230 kV. The line-complex powers are approximately hundreds of MVA each. As a test case, the WSCC 9-bus case is easy to control and additional devices have been added such as energy storage and a renewable source of energy, see Fig. 8.10. The configuration parameters of the system are given in Tables 8.4 and 8.5 and they are used as input data for simulation. The electrical components from the graphical representation can be identified in the table by their location between beginning node (n_b) and ending node (n_e) with assigned reliability parameters. Furthermore, the number of customers connected to a particular node and power available at that specific node are given. The WSCC 9-bus case has been extended through the integration of energy storage in bus 6 and an additional renewable-power source from wind turbines.

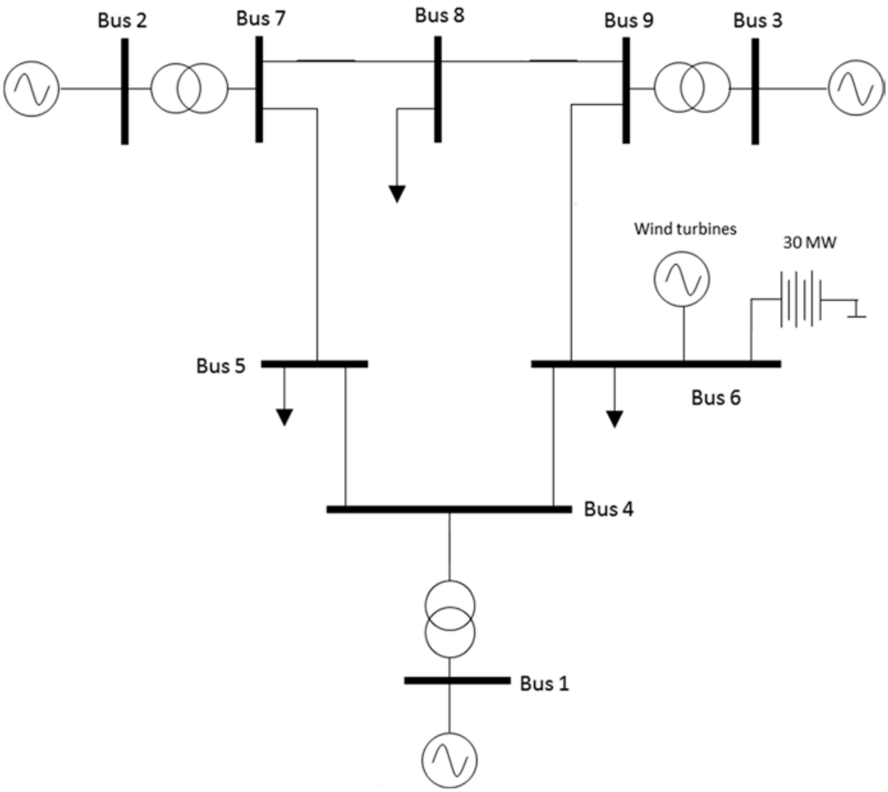

Fig. 8.10 9-Bus test system configuration

Table 8.4 Parameters used for 9-Bus test system—reliability indices

Reliability parameters					
Beginning node	Ending node	Failure rate of component	Time to repair without storage [h]	Time to repair with storage [h]	Failure rate of storage system
1	4	0.08	50	30	0.05
4	5	0.25	20	7	
4	6	0.25	20	7	
2	7	0.08	50	30	
7	5	0.25	20	7	
7	8	0.25	20	7	
3	9	0.08	50	30	
9	8	0.25	20	7	
9	6	0.25	20	7	

Table 8.5 Parameters used for 9-Bus test system—components configuration

Number of the node	Power available at particular node [MW]	The power of connected customers [MW]	Number of customers connected to node
1	72	0	0
2	163	0	0
3	85	0	0
4	0	0	0
5	0	125	90,000
6	15 wind, 30 storage	90	60,000
7	0	0	0
8	0	100	70,000
9	0	0	0

The modeling of connected electrical systems and storage installations based on complex network theory was carried out on the example of a 9-Bus power system. In order to estimate the indices reliability of the power system, the simulation approach based on the Monte Carlo method was implemented. The Monte Carlo simulations have been performed for the total sample of N = 100 years with a simulation time in sequence T = 1 year = 8760 hours. The algorithm generates a random loss of element in a power system. On that basis, the time to repair an element in every year is calculated. The calculations are carried out for a period of 100 years and, based on these calculations, a histogram can be created. The energy storage can be used as additional component of grid that improves the reliability of the electrical system. In case the line is inoperative, the energy storage can partly cover the energy demand, depending on the grid situation and structure. The customers are still being supplied with electricity, and the reliability indices are better than without the storage system. In order to determine the reliability of the grid, the power flow was not carried out. The simulation based on the history of grid's condition and number of failures of each component of the power system. Therefore, the size of the energy storage will affect the value of the reliability indices. In the example, the storage with installed power of 30 MW was used. The installation can provide 30 MW of power for one hour (30 MWh) during the failure of the power system. Availability of power from energy storage and its respond time are closely affiliated with the technology of integrated energy storage. In the case of simulation, the technology of energy storage is based on the lithium-ion battery. Since lithium-ion technology is characterized by a time of respond, which is very short for this kind of technology, this allows for a quick response in case of failure, and the rate of changes in the system is reduced [3]. Other solutions such as hydro-power pump and CAES have larger capacities of power and longer charging times, but the time to respond to failure is much longer than in lithium-ion energy storage [8].

In modeling the both the electrical and the storage system, some assumptions were made. Since the method is probabilistic and power flow is not calculated, the parameters of electrical components such as transformers, lines and generators are reduced to checking their operational availability. Failure rates of these elements were selected in accordance with recognized values for their type and voltage-level operation. Repair times also depend on many factors like type of failure, maintenance resources of the operator and weather conditions.

The reliability indices are graphically presented as histograms demonstrating the distributions of data. The adjacent bars on the histogram determine intervals of values, and their length quantifies the frequency of the observations in the interval. For the representation of obtained results, each bar includes a range of values from several sequences of simulation.

The distributions of indices are the most valuable means to evaluate the system with regard to the assessment of system reliability. Based on input data and configuration of the electrical power system (EPS), the reliability indices achieved very high values, which prove that the system is very reliable. Regarding EPS with storage system, the reliability indices are even greater, which demonstrates that the storage contributes to improving the reliability of the electric network.

The distributions of reliability indices for the 9-Bus system are presented in Fig. 8.11. The reliabilities for electrical power systems (EPS) without storage systems are represented with grey bars, and blue bars indicate results for the electrical power system with storage system. It can be noticed that the obtained results for the system supported by energy storage possess better reliability indices than that of the electrical system without storage installation (SI). SAIDI index for SI at point 0.0 has a height of 72, which mean that in 72 out of 100 years, the system average interruption duration was 0 hours. The value for EPS at the same point is 66 years without interruption. Also there are more blue SI bars close to zero-interruption hours a year than the grey bars of the EPS system which indicates fewer number of hours when customers are not supplied.

SAIDI is the **System Average Interruption Duration Index**, and it measures the total duration of an interruption for the average customer during a given time period. It is normally calculated for the period of one year and results in the number of customer minutes or hours of interruption. According to Fig. 8.11, the SAIDI index produces higher values when storage system is connected to the electric network. This effect is caused by energy-storage properties. When there is a loss of voltage, storage can temporarily supply customers, which causes increase reliability for the whole system. So a SAIDI index for a system connected with storage system (blue bars) is higher than a SAIDI index representing for a system without energy storage (gray bars). The reliability of a system and the height of the bars depends on the energy storage that is used.

SAIFI is the **System Average Interruption Frequency Index**, which provides the average number of interruptions in the system that a customer experiences during the observation period, normally calculated for 1 year. The SAIFI index results remain nearly the same for both systems, since only the duration of failure has been changed, while the number of failures remains the same.

CAIDI, the **Customer Average Interruption Duration Index,** represents the average time required to restore service after an outage occurs, which indicates how long an average interruption lasts. It measures the duration of time that the customer is de-energized per interruption. Assuming that energy storage exists in the system,

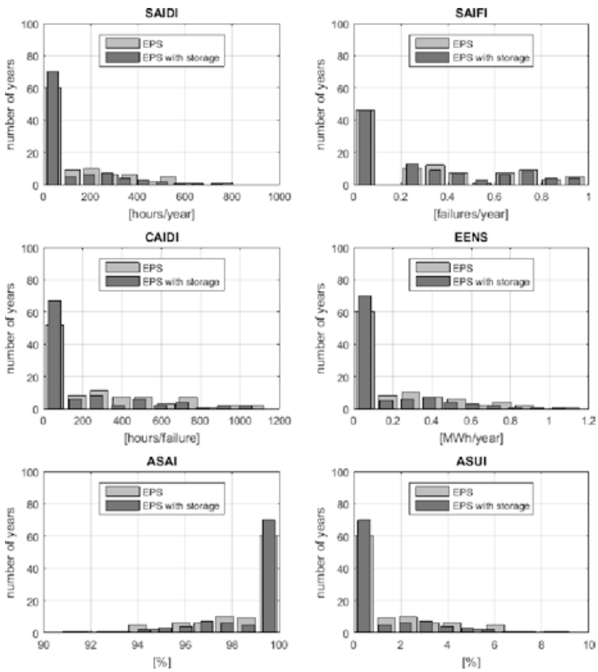

Fig. 8.11 Reliability indices distributions of the 9-Bus test system

the reaction to occurring faults is faster and, thus, the durations of customer interruptions are shorter, which is reflected in the CAIDI index. Therefore, an EPS with energy storage yields better results.

ASAI is the **Average Service Availability Index,** which is the ratio of total time in which a customer was energized during the observation period to the total time of customer service demanded. The average service availability index ASAI is expressed as a percentage so, where the distribution bars are concentrated close to 100 %, this means that the overall reliability of the system is very high.

ASUI, the **Average Service Unavailability Index,** represents the fraction of time that service was not available for the customer of the total customer hours demanded. The ASUI index clusters close to zero for cases in which the system is mostly unavailable.

EENS, the **Expected Energy Not Supplied** indicates the amount of unsupplied energy to the customer in the system due to power interruptions. According to EENS index value, the energy not supplied to the customers is close to zero, but the EPS is normally more reliable with additional source of energy in this cas EES., and for indicate with energy storage the value is higher, it means. The dependence on EES is clearly reflected in the EENS index.

In order to present the histograms of the system-reliability indices, which refer to the values of the failure rates of the components, the values were assumed to be much worse that those in reality. The duration of the system failure and repair time have also been extended. For the purpose of simulation, the average time of failure

Table 8.6 Reliability-related parameters vs storage technologies

Storage technologies	Supply reliability		Voltage quality		Service quality
	Short-term phenomena (interruptions)	Long-term phenomena	Short-term phenomena (e.g., flicker, harmonics)	Long-term phenomena's (e.g., voltage profile)	
Chemical storage systems (e.g., batteries)	+	+/−	+	+/−	+
Electrical storage systems (e.g., super caps)	+	−	+	−	+
Mechanical storage systems (e.g., pump storage)	+/−	+	−	+	+
Thermal-storage systems	−	+	−	+	+

per customer is expressed in hours (1–10 h). In fact, in European countries, these times are given in minutes, and it ranges between 15–500 min/year/customer.

Based on this simulation case, it can be summarized that energy storage supports the power system in order to maintain the reliability of the power flow in the network. Customers may be exposed to disruptions during the occurrence of a failure of the power system. When the failure appears, power systems will be not able to supply some customers. To reduce the amount of customers that are affected by disruption of electrical grid component, the system can be equipped with devices such as storage energy to supply recipients. Thus, the additional sources will increase the reliability of the system and cause fewer customers to be exposed to disruptions. The energy storage contributes to the improvement of reliability of the system. Type of storage, technology and costs depends on many factors. In order to select the appropriate energy storage, proper analysis must be carried out because, e.g., not all storage-system technologies have the technical properties to fulfil the requirements defined by the relevant use case, see Table. 8.6.

Test Questions Chap. 8

- What is meant by the phrase "power-system reliability"?
- What kind of criteria describe reliability?
- What is the level of reliability of power systems in European countries today?
- What are the kinds of reliability-calculation methods?
- What kind of storage parameters should be taken into account when calculating power system reliability?

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