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Introduction

Batteries and other energy storage systems are options for the technical and economic optimization of an energy supply system and, in many cases, indispensable for ensuring the required functions. Very often, however, batteries are in competition with other technologies, which impact the development and market opportunities of batteries.

A comparison of batteries with other energy storage technologies is of little value without precise knowledge of the application and limitations of competing technologies.

All batteries are based on the same physical and chemical principles. Different electrochemically active materials and designs lead to major differences in properties, including the necessity of additional components required for safe and long-lasting operation.

Batteries are usually categorized according to their bridging time and application areas: portable, mobile, and stationary.

1.1 Energy Supply in General

Energy storage systems are an option for the technical and economic optimization of an energy supply system because they allow energy generation[1] to be quickly and efficiently adapted to energy consumption. Without energy storage systems that can both store and release energy, generation and consumption units would always have to adapt to each other with very high dynamics. Fast response times are often not possible or only possible at great expense. Energy storage systems also serve as an energy source for technical systems that do not have their own energy supply from primary energy sources, as well as for starting up systems that in most cases cannot be started without the provision of electrical energy from an energy storage system or the electrical grid.

1 The terms "energy production" and "energy consumption" correspond to common usage and are therefore used here. In the literal sense of the terms, of course, energy cannot be generated and consumed, but only converted.

Battery Technology: Fundamentals of Battery Electrochemistry, Systems and Applications,
First Edition. Alexander Börger and Heinz Wenzl.

Companion website: www.wiley.com/go/Börger/Battery_Technology

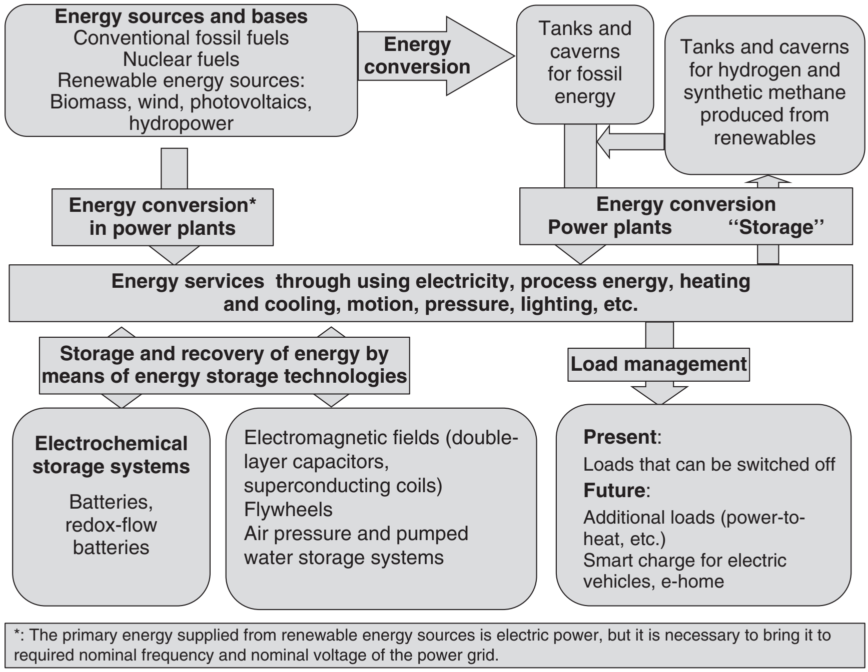

Figure 1.1 Electrochemical energy storage as part of the power supply system.

The use of batteries is indispensable in many cases to ensure the required functions. The following examples of electromobility and the electricity supply system will show that the overall technical and economic context must always be carefully considered when estimating and forecasting the future importance of batteries.

Figure 1.1 shows the integration of energy storage systems into the overall electrical energy supply system and illustrates in particular that energy storage[2] competes with many technical alternatives to ensure the required functions. In addition to highly dynamic generation units, which, unlike conventional thermal power plants, can adapt their power output very quickly to demand, alternatives for quickly balancing power generation and consumption are primarily load management systems and switchable loads, in particular heat generators (power-to-heat).

Electricity from a photovoltaic system that is not consumed immediately at the site of installation can be used locally or, for example, it is to be

- stored in a battery,
- used as thermal energy for space heating or hot water supply via an electrically operated heating cartridge,

2 In Figure 1.1, it should be noted that storage facilities for materials (tanks for processed energy sources) are only referred to as energy storage facilities if they are produced using electricity that is not used directly for energy services. Without this conceptual differentiation, crude oil, heating oil, or gasoline tanks and underground salt caverns for fossil fuels would otherwise also have to be referred to as energy storage facilities.

- used by switching on household loads such as washing machines or refrigerators depending on the supply, or
- made available to the electrical grid for loads elsewhere.

From a system perspective, these alternatives are equivalent and therefore are often referred to as storage-equivalent systems or functional storage systems.

Electrochemical energy storage systems are also in technical and economic competition with other energy storage technologies, see Ref. [1].

1.2 Electrochemical and Non-electrochemical Energy Technologies

In principle, energy can be stored in very different ways, that is, in different forms of energy, namely

a) mechanically, for example, in the form of potential energy in pumped storage power plants or in the form of rotational energy in flywheels,
b) magnetically, for example, in the magnetic field of a superconducting coil,
c) electrically, for example, in the electric field of double-layer capacitors,
d) chemically, for example, by conversion to hydrogen,
e) thermally, for example, in the form of hot water storage tanks or in steam boilers, and
f) electrochemically, that is, by converting electrical energy into chemical energy.

Table 1.1 provides a short summary of these technologies and the basic physical formulas.

Table 1.1 Comparison of different energy storage technologies.

Energy type	Principle	Examples
Potential energy	$E = mg\Delta h$	Pumped storage power plants
Gas pressure	$E = p\Delta V$	Compressed air storage
Rotational energy	$E = 0.5J\omega^2$	Flywheels
Magnetic energy	$E = 0.5LI^2$	Loss-free direct current flowing in a superconducting coil (so-called SMES)
Electrical energy	$E = 0.5CU^2$	Double-layer capacitors (ultracapacitors, electrolytic capacitors, etc.)
Chemical energy	$E = n\Delta_r G$	Hydrogen storage
Thermal energy	$E = C_i\Delta T$	Hot water tank
Electrochemical energy	$E = \int UI\mathrm{d}t$	Batteries

Explanation of symbols: m: mass, g: gravity constant, h: height, p: pressure, V: volume, J: moment of inertia, ω: rotational speed, L: inductance, I: current, C: capacitance (in Farad), U: voltage, n: amount of substance, $\Delta_r G$: free enthalpy of reaction, C_i: heat capacity of substance i, ΔT: temperature difference, t: discharge time.

With some energy storage technologies, particularly thermal storage, the stored energy cannot be made available to the overall system as electrical energy or only at great cost. Despite various limitations, different energy storage systems compete with each other in certain applications. Before discussing electrochemical energy storage systems in detail in the following chapters, here are some comments on non-electrochemical energy storage systems.

1.2.1 Capacitors and Ultracapacitors

The energy content of capacitors is very low, even for the group of so-called ultracapacitors or supercapacitors[3] (ultracaps) with very high capacitances (unit Farad: 1 F = 1 As/V). At a nominal voltage of 2.5 V and a capacity of 3000 F, for example, the energy content is only approx. 2.6 Wh, of which normally only 75% can be technically extracted, compared to approx. 9 Wh for a small 2.5 Ah lithium-ion cell, which is significantly more compact, lighter, and cheaper. In terms of specific power (W/kg), however, ultracapacitors can deliver significantly higher electrical power and are therefore used in special applications.

Ultracapacitors have a high self-discharge rate (they are often completely discharged within 24 hours) and therefore a high energy loss in standby mode. They require a similarly complex charge control as lithium-ion batteries.

Other types of capacitors, such as classic electrolytic capacitors, only have a capacitance in the micro- or millifarad range and less and are therefore not able to store large amounts of energy, even if their rated voltage is very high.

1.2.2 Superconducting Coils

The magnetic field present in a current-carrying coil stores usable amounts of energy at high currents. The losses are only sufficiently low if the resistance of the coil is minimized by superconductivity. However, energy storage systems based on superconductivity require complex cooling and therefore have high standby losses. In the 1990s, superconducting magnetic energy storage (SMES) systems with an output of 1 MW for 10 seconds and an energy content of several kilowatt-hours were built to stabilize the power grid.

1.2.3 Flywheels

The energy content stored in flywheels depends on the square of the rotational speed and is proportional to the moment of inertia. Slowly rotating flywheels (with up to approx. 4000 rpm) are commercial products for uninterruptible power supply (UPS) systems with an output of 1.6 MW for 15 seconds (Powerbridge, Piller GmbH), corresponding to 6.7 kWh energy content, of which only 75% can be technically

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3 In this textbook, the term "ultracapacitor" or "supercapacitor" is always used for this class of energy storage. To avoid confusion, the term "double-layer capacitor" always refers to the electrode/electrolyte interface.

extracted. These flywheels are a technical and economical alternative to batteries for bridging times of a few seconds until the starting of diesel power generation units.

Very fast rotating flywheels (up to 100,000 rpm) are light and very powerful, whereby the power is a function of the generator coupled to it. Such flywheels have been used in motorsport.

All flywheels are characterized by very high self-discharge rates, even when using vacuum and magnetic bearings to minimize friction. The stored energy is generally lost after approx. 24 hours. Use in vehicles as a replacement for starter batteries is therefore not possible.

1.2.4 Compressed Air and Pumped Water Storage

Small compressed air energy storage, excluding compressed air storage for optimizing air supply in factories, is sometimes used for starting diesel engines for emergency power generation. A few large-scale compressed air energy storage systems for utility-scale energy storage (100 MWh range) have been built worldwide in the past but have a low energy efficiency and do not seem to be an option in the future.

Pumped water storage systems have energy capacities of around 100–10,000 MWh and are relevant energy storage systems in the electricity industry worldwide for covering peak loads and storing energy during times of low electricity demand. They are characterized by very high initial investment and environmental impact but low operating costs.

Very large battery storage systems with energy contents of several hundred MWh, which are currently being built in some regions, could become technical alternatives in the future.

1.3 Basic Properties of Batteries: Similarities and Differences

Batteries are electrochemical energy converters. The fundamental principles of all battery technologies are based on the same physical and chemical laws. The basic requirements for their design and operation are also very similar.

Batteries are DC voltage sources whose voltage is a function of the materials used and their local concentrations as well as the current flowing through them. In most cases, it is necessary to connect individual cells in series and integrate them into a power supply system using converters (DC/DC or DC/AC converters) and/or use loads with a wide range of input voltages. The maximum charging voltage is often approx. 1.5 times the minimum discharge voltage and even higher for some battery technologies and applications.

There are many different battery technologies, which differ in many other characteristics apart from their voltage level. Figure 1.2 shows an overview of the functional principle and different battery systems.

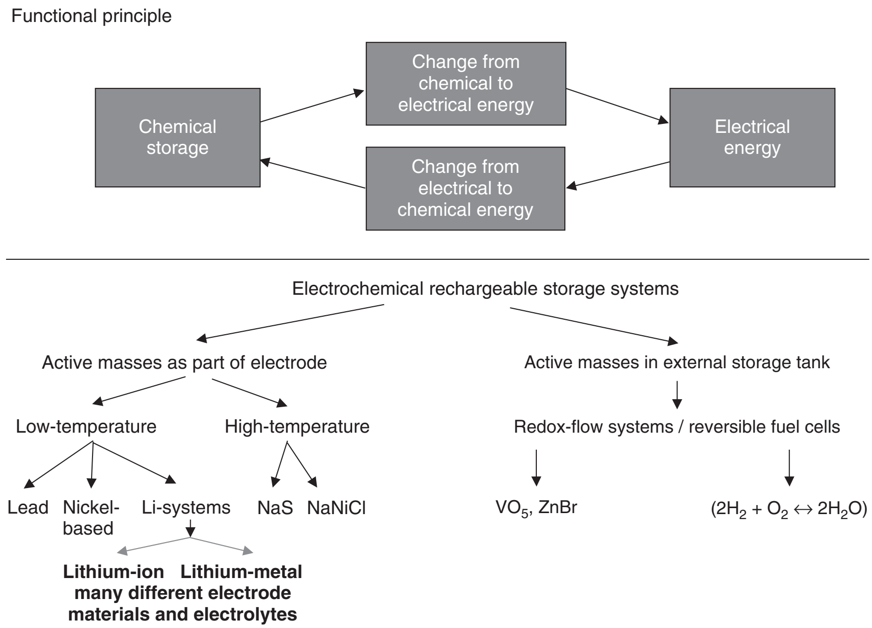

Figure 1.2 Overview of the functional principle of batteries and various materials. For details, see chapters 12–14.

In all cases, chemical energy is converted directly into electrical energy. Only in the case of accumulators, that is, rechargeable galvanic secondary elements, it is possible to convert electrical energy back into chemical energy (and vice versa) easily and frequently. All such systems are referred to below as batteries.

An important differentiation between batteries concerns systems in which the active material is an integral part of the electrodes, and therefore energy content (Wh) and power (W) are always coupled, and battery systems in which the active materials are stored externally in tanks and pumped into the space between the electrodes – so-called flow batteries or redox flow batteries. In flow batteries, the energy content can be increased as required using large tanks without increasing the power provided by the reaction chamber. Flow batteries are related to fuel cells in which one of the active materials (hydrogen) is supplied from a tank and the other active material (oxygen) is taken from the air. Metal–air systems are also related to flow systems and fuel cells, except that one of the active materials (the metal) is in solid form (and can be renewed by mechanical exchange, if necessary), while the oxygen is taken from the air – possibly requiring a purification stage.

Battery technologies differ in terms of internal resistance, energy content, specific energy (Wh/kg), energy density (Wh/l), specific power (W/kg), power density (W/l), permissible temperature range, options for monitoring the battery system, calendar and cyclical service life, and the system components required for safe and economical operation and their operating conditions. Modifications of design and materials also lead to considerable differences in properties within a battery technology.

Most of the materials used in batteries are toxic and/or corrosive. If environmental impacts during production, use, and disposal as well as investment costs and the total costs of operation are taken into account, the range of properties to be considered when choosing a battery system expands considerably. The dominance of lead-acid and lithium-ion batteries is due to their favorable overall properties for many different applications. Current market research shows that at the time of writing this book (2024), the value of lithium-ion and lead-acid batteries constitutes over 80% of all battery sales, with the share of lead-acid batteries slightly below that of lithium-ion batteries since 2023. Growth rates are expected to be slightly higher for lithium-ion batteries than for lead-acid batteries.[4] In terms of energy content, lead-acid batteries dominate lithium-ion batteries by a huge margin.

1.4 Bridging Time

A common classification of batteries is based on their bridging time, the ratio of energy content to the power that can be constantly drawn from a battery until the end-of-discharge voltage is reached.

For all batteries, the amount of energy that can be drawn decreases with increasing power. The diagram of the characteristic curve of the specific energy content (kWh/kg) at different specific outputs (kW/kg) is known as the Ragone diagram. Figure 1.3 is a Ragone diagram based on data sheet information for various battery technologies, see Ref. [2] for details of the calculation.

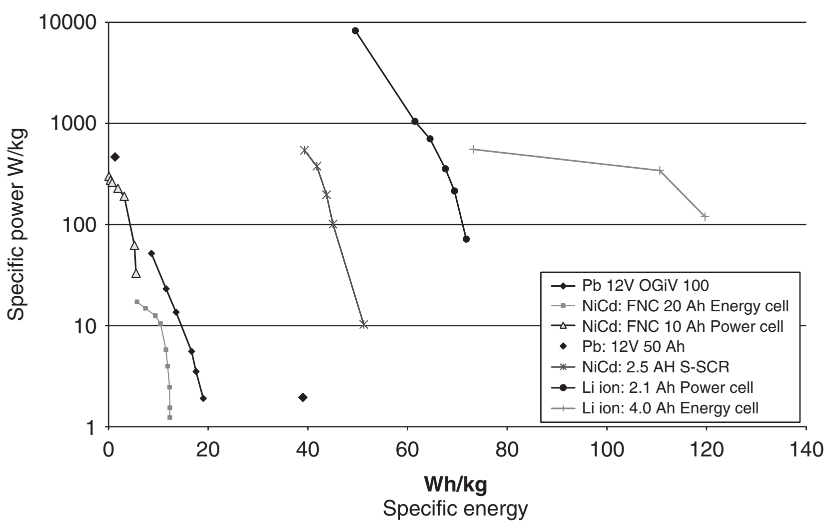

Figure 1.3 Ragone diagram of various battery technologies based on data sheet information (see Ref. [2] for further details).

4 www.grandviewresearch.com.

For more precise sizing of a battery system and to optimize the technical and economic use of batteries, a method was proposed in Ref. [3] to create a Ragone diagram based on measurements of discharge curves at different power levels. The method described in Ref. [3] results in deviations from the diagram shown in Figure 1.3. These can be significant for the design of battery systems.

Figure 1.4 shows a different representation of power and energy content. This makes the frequent division of storage systems into short-term and long-term storage systems particularly clear. The straight lines in the figure represent equal bridging times regardless of the energy content of the energy storage system under consideration. Bridging times of a few seconds are relevant for power quality applications to stabilize the voltage in the electricity grid during short interruptions of power. Bridging times of 15 minutes to a few hours are required in applications for ensuring the power supply in the event of a power failure (emergency lighting systems, UPS systems) for computers and telecommunications equipment, etc. In the field of renewable energies, bridging times of approx. one day to several days are required, depending on the system design, and a bridging time of several months would be required for seasonal balancing between generation and consumption (energy systems based primarily on hydropower, wind power, or photovoltaics). Task 1.1 shows how large electricity storage systems would have to be designed for the Federal Republic of Germany if the electricity generation system were to be based exclusively on wind power and photovoltaic systems.

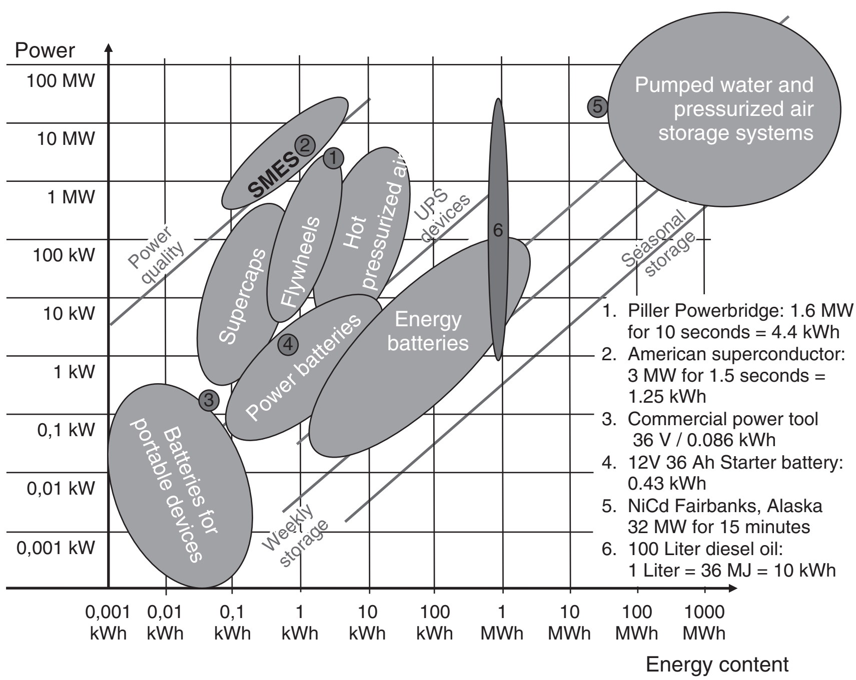

Figure 1.4 Comparison of energy storage systems based on the respective bridging time.

With batteries and many other energy storage technologies, the relationship between energy content and power is determined by technical and economic factors. In fuel-based energy systems, on the other hand, power and energy content are independent of each other. For a better understanding, Figure 1.4 shows the energy content of 100 l of diesel fuel. Since there is no technical link between energy content (proportional to the size of the tanks) and power (dimensioning of the engines), the associated power range extends over several orders of magnitude, and the term "bridging time" is no longer applicable without further information.

The points shown represent various energy storage systems – the marked areas are only intended as a guideline.

Figure 1.4 shows that few energy storage systems are technical and economic alternatives for any specific application (bridging time and power).

1.5 Comparison of Battery Technologies

When comparing different battery technologies, it is necessary to know the specific application so that the data presented in a comparison can also be used to select the most suitable storage technology. The following list provides an overview of the most important points to consider:

1) Definition of the system environment:
   Energy storage systems require various additional components to ensure safe, reliable, and economical operation. When comparing large lead-acid and lithium-ion batteries, the comparison of cells is often only of minor importance because, for safety reasons, lithium-ion batteries must be equipped with various monitoring and protective devices in an overall system, which are not required for lead-acid batteries. All safety and monitoring devices that are necessary for safe and long-lasting operation must be included. The comparison of systems with different safety standards and expected service lives is only meaningful if the differences are carefully evaluated from a technical and economic point of view.
2) Costs:
   The costs of the overall system must be considered with comparable system delimitation.
3) Energy content:
   Only the energy content that can actually be used during operation and with which the desired service life can be achieved should be considered. In many battery systems, for operational and/or service life reasons, the usable energy content must be significantly limited compared to the energy content of the fully charged battery.
4) Volume and weight:
   The overall system must be considered.
5) Other technically relevant properties:
   - response time to performance requirements;
   - temperature range within which the system can be operated;

- additional heating or cooling in the system must be taken into account because they affect weight, volume, and costs; and
- maintenance and monitoring options.

6) Other economically relevant properties:
   - maintenance costs over the service life,
   - energy consumption when stationary and in use, and
   - efficiency.

General comparisons of energy storage systems, as shown in Figure 1.4 or as shown in tabular form in many studies, can only serve as a guideline. Detailed comparisons without a description of the specific application often do not allow any useful conclusions to be drawn. When describing the applications and additional conditions to be considered, the number of suitable energy storage technologies is often considerably reduced. For technical and economic reasons, there is often only one energy storage technology that can be considered for the application in question. Pumped storage plants do not compete with flywheel mass storage systems!

1.6 Applications and Integration of Batteries into Overall Systems

Batteries are usually coupled in parallel with generation systems and consumers. In many cases, this arrangement leads to a highly dynamic current load on the battery with frequent changes between charging and discharging currents. This behavior is immediately clear in hybrid vehicles, whose battery constantly alternates between absorbing braking energy and releasing energy to support acceleration. However, batteries for autonomous power supply systems or in standby parallel operation are also often subject to a rapid change from charging to discharging currents due to the residual current ripple and the control characteristics of the chargers and consumers. Measurements often show a superposition of the battery current with an alternating current, the amplitude of which can significantly exceed the value of the direct current. This is discussed in more detail in the overview of applications for electrochemical energy storage systems from chapter 15 onward.

It is often useful to differentiate between portable, mobile, and stationary applications, whereby a distinction between grid-connected and autonomous energy supply systems is helpful for stationary applications.

1) Mobile applications:
   In some traction applications, the battery (e.g. industrial trucks and electric vehicles) is discharged during use, interrupted only by occasional regenerative braking, etc. and then recharged in a separate step.

   However, hybrid vehicles have their own power generation unit (combustion engine, etc.) as part of the overall mobile system, which can also charge the battery during use. The battery current and state of charge fluctuate greatly depending on the operating strategies.

   In mobile applications, apart from traction, the battery is often only used for self-starting (so-called black start) of the overall system (power supply for the engine and onboard electronics, starting the combustion engine), independent of other energy sources.

The requirements for energy content, weight, and many other properties differ greatly between these areas of application.

2) Stationary applications:
In autonomous, non-grid-connected energy systems, the battery serves as the sole source of energy when primary energy generation is not available (no wind, no solar radiation, generator motor not in operation) and to absorb electrical energy when generation exceeds consumption. A constant alternation between charging and discharging processes must be assumed.

In grid-connected overall systems, the battery is usually used to secure the power supply in the event of grid failures and voltage problems (emergency power systems, UPS systems) and to provide and absorb power fluctuations to stabilize the power grid. With increasing electricity generation from wind power and photovoltaic systems, energy storage systems are also used to temporarily store electricity from renewable energies.

3) Portable applications:
The batteries in a device are designed to only be discharged during use and then recharged on a charger. Use during charging is the exception rather than the rule. The obvious criteria are low volume and weight.

References

1 Energy Research Center of Lower Saxony (2016). *Potentials of Electrochemical Storage in Electrical Grids in Competition with Alternative Technologies and System Solutions (ESPEN (Original Germna title: Potenziale elektrochemischer Speicher in elektrischen Netzen in Konkurrenz zu alternativen Technologien und Systemlösungen (ESPEN), Abschlussbericht), Final Report)*. Goslar: EFZN.

2 Wenzl, H., Benger, R., and Hauer, I. (2024). Power. In: *Encyclopedia of Electrochemical Power Sources*, 2e, vol. I (ed. J. Garche). Amsterdam: Elsevier.

3 Sarpal, I., Bensmann, A., Mähliß, J. et al. (2018). Characterisation of batteries with E-P curves: quantifying the impact of operating conditions on battery performance. *Electrical Power and Energy Systems* 99: 722–732.

Tasks

Task 1.1

Design of electricity storage systems with electricity exclusively generated from photovoltaic and wind power plants

Germany consumes around 500 TWh of electricity per year. An electricity system based exclusively on-wind and photovoltaics must be able to cover periods of

(Continued)

Task 1.1 (Continued)

no wind and no sun, sometimes referred to as "dunkelflaute." The maximum duration of no wind and no sun is usually given as 21 days.

Assume that the daily generation capacity is 10 GW even during such phases (generation by hydropower plants, combined heat and power plants that have to be operated due to heat demand, hazardous waste incineration plants, etc.).

- What quantities of energy need to be stored in electricity storage systems?
- Can you assume that the electricity storage units are fully charged at the beginning of a no wind, no sun period? What quantities of energy should still be available in the electricity storage systems at the end of the no wind, no sun period so that the supply remains secure in the event of an immediate shortfall in electricity demand from the generation units?
- What safety margins for the duration of a no wind, no sun period do you assume (maximum expected duration in the coming decades)? What percentage of the installed electricity storage systems will not be used at all or only once over the period under consideration?
- Which industries or groups of households will be the first to be shut down if the storage facilities are not large enough?

Task 1.2

System comparison of drivetrains

The drivetrain of an electrically powered vehicle consists of a vehicle battery, including all necessary components such as battery management system (BMS) and fuses; an electric motor, possibly with a single two-stage gearbox and differential; cables; and inverter. The drivetrain of a vehicle powered by an internal combustion engine consists of a tank, fuel lines and feed pump, starter, alternator, internal combustion engine, radiator with fan and water pump, multistage gearbox, clutch, differential, and exhaust system with exhaust gas purification.

a) Estimate the total weight of the two powertrains for comparable vehicles (e.g. Tesla Model S and BMW 5 Series) with the same range and engine power. To do this, use 75% of the specified range of the Tesla and weight data from the Internet.
b) How do the two drivetrains differ in terms of their specific energy?
c) Estimate the energy consumption of both cars per kilometer, including losses when the cars are parked and charging efficiency.
d) Is this comparison admissible? What conclusions can and cannot be drawn from it?