VDI Zentrum Ressourceneffizienz

Ecological and economical Assesment of Resource Use

Stationary Energy Storage Systems in industrial Production

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Study: Ecological and economical Assesment of Resource Use – Stationary Energy Storage Systems in industrial Production

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LIST OF ABBREVIATIONS

AC	Alternating current
BattG	Law on the placing on the market, return and environmentally sound disposal of batteries and rechargeable batteries
CO_2	Carbon dioxide
$CO_{2\text{-eq}}$	Carbon dioxide equivalents
ct	Euro cents
DC	Direct current
DIHK	Association of German Chambers of Industry and Commerce e.V.
DOD	Depth of discharge
DLC	Double layer capacitors
EC	European Commission
RE	Renewable energy
EoL	End of Life
Engl.	English
ESS	Energy storage system
η	Efficiency
Euro/kWa	annual performance price in Euro per kilowatt
FESS	Flywheels: Flywheel Energy Storage System
FU	Functional unit
G_i	Weighting factor
GWh	Gigawatt hour
GWP	Global Warming Potential
ILCD	International Reference Life Cycle Data System

IPCC	Intergovernmental Panel on Climate Change
IT	Information technology
K_j	Criticality value
n. s.	Not specified
CED	Cumulative energy demand
SME	Small and medium-sized enterprises
CRD	Cumulative raw material demand
kW	Kilowatt
kWh	Kilowatt hour
CHP	Combined heat and power generation
LCA	Life Cycle Analysis
LCC	Life Cycle Costing
LCO	Lithium cobalt oxide
LFP	Lithium iron phosphate
$LiFePO_4$	Lithium iron phosphate
LIB	Lithium-ion battery
LMO	Lithium manganese oxide
LTO	Lithium titanium oxide (Li_4Ti_4O)
Mg	Ton (megagram)
MW	Megawatt
NCA	Lithium-nickel-cobalt-aluminum oxide
NMC	Lithium-nickel-manganese-cobalt oxide
NPV	Net Present Value
OPEX	Operational Expenditures
PbA	Lead-acid battery
PV	Photovoltaics

ReCiPe	Method for Impact Evaluation in Life Cycle Analyses
RLM	Registered power measurement
SMES	Electromagnetic energy storage systems
SoH	State of Health
SR	Flywheel
StromNEV	Electricity Grid Charges Ordinance
StromNZV	Electricity Grid Access Ordinance
Supercaps	Supercapacitors
UBA	Federal Environmental Agency
UPS	Uninterruptible power supply
V	Volt (nominal voltage)
VDI	Association of German Engineers e.V.
VRLA	Valve-regulated lead-acid battery
W	Watt
Wh	Watt hour

ABSTRACT

Stationary energy storage systems are a necessary component of a future power supply system with high proportions of regenerative energies. Used in distributed industrial applications, they help increase resource efficiency while minimising the cost of power. Storage solutions for the short- to medium-term storage of electrical energy are therefore regarded as a contribution to the medium- to long-term success of the energy turnaround being driven forward in Germany.[1]

In industrial production, it is expected that stationary energy storage systems will play an important role in future intelligent power grids. Battery-based electricity storage systems are already being used today to temporarily store available renewable energy sources (e.g. photovoltaics) and make them directly usable. Thus, the power demand at the production site can be partially covered. Companies, in particular small and medium-sized enterprises (SMEs), can use this technology to additionally buffer cost-intensive peak loads at production sites and reduce the connected load to the public power grid. Various battery technologies are particularly suitable for this purpose. Also relevant are super or double layer capacitors (supercaps), superconducting magnetic energy storage systems and flywheels, which are already available as energy storage systems for stationary operation in a small market.

At the machine level, flywheels have long served as intermediate storage for mechanical energy. In industry, uninterruptible power supply (UPS) for the emergency supply of production facilities and computer systems in the event of a power grid failure is one of the most important applications of electrical energy storage systems. In addition, in the course of the energy turnaround, the focus will continue to be on minimising peak loads in power consumption at the grid connection point. The integration of stationary energy storage systems into the processes of industrial production can therefore gain economic importance due to the increasing demand for flexibility options in the power grid.

1 Cf. UBA (2013).

With this in mind, this study provides an overview of the most important stationary energy storage technologies already available on the market as well as innovative new storage solutions for electrical energy. The focus is on electrical, electrochemical and mechanical energy storage systems for storing electrical energy, which can be used in the low-voltage network of SMEs. This consumer-side perspective is particularly relevant for companies that examine technical possibilities for operating energy-intensive processes, machines and plants economically within the framework of operational energy management.

To this end, the present study examines various possible applications for three selected decentralised stationary energy storage systems and carries out a comparative ecological and economical evaluation. The following technologies are compared:

- Lithium-iron phosphate batteries (a type of lithium-ion battery),
- Lead-acid batteries and
- Flywheel accumulator (rotating mass).

The comparison of the three energy storage technologies is based on an application scenario from industrial production. It highlights the **"minimisation of peak loads" and the possible cost reduction in grid charges for performance-measured commercial customers**.

The impact of energy storage systems on the environment is assessed using the methodological concept of Life Cycle Evaluation (LCA). In particular, the characteristic values "cumulative energy consumption" (CED) and "cumulative raw material consumption" (CRD) are determined on the basis of the VDI Directive VDI 4600 and VDI 4800 Sheet 2 (draft). In addition, the greenhouse gas potential of the respective energy storage systems and other indicators (criticality of supply, water consumption and land requirements) are evaluated.

The economical analysis is based on life cycle costing. The possible savings are related to the total costs of the energy storage systems under consideration (investment, operating and disposal costs).

The results of the ecological and economical comparative calculation illustrate the need for further development of energy storage technologies for this purpose. Under the current framework conditions, investment in stationary energy storage technologies is not yet economically viable for SMEs if they are to be used to minimise peak loads in the power grid. With regard to energy and resource efficiency, the energy storage systems do not have any advantages over direct energy procurement from the public supply network for the purpose considered here. Due to the high conversion losses, the integration of storage systems for electrical energy at the level of the operational low-voltage grid does not make sense. A positive ecological and economical effect will only be achieved by exploiting further technical possibilities to improve efficiency and exploit dissipative process energies (e.g. braking energy). To this end, there is a further need for research and development in corresponding technologies.

1 INTRODUCTION

Stationary decentralised energy storage systems can contribute to increasing resource efficiency and reducing costs in industrial production. Today they are mainly used on the level of DC links in tool machines, forming machines with higher capacities and machining equipment.[2] For sensitive industrial manufacturing processes, stationary energy storage systems are used for uninterruptible power supply. Energy storage systems also help to ensure power quality, for example by frequency stabilization for highly synchronous industrial drives. Industrial processes in which the energy input is recuperated (recovered) and can, for example, be reused at machine level are particularly suitable for the use of energy storage systems. State-of-the-art technology includes electrolytic capacitors, flywheel accumulators and lead-acid batteries. Lithium-ion battery technology is[3] also already state-of-the-art, but has not been widely used to date.

In the future, the integration of stationary energy storage systems into other industrial production processes will be of interest. In industrial production, stationary energy storage systems have the potential to give renewable energies an important role in future intelligent power grids. SMEs in particular can use these technologies to buffer cost-intensive peak loads and tap energy efficiency potential. The use of energy storage systems is suitable for optimising industry-specific technologies and for cross-sectional technologies such as compressed air, pumps, fans and lighting.[4]

The technological development of energy storage systems has experienced a noticeable upswing in recent years. The high level of innovation dynamics will continue in the future. Lithium-ion batteries, for example, are becoming increasingly interesting for applications with high demands on service life and cycles, especially in the area of power storage system and other highly dynamic processes. Super- and double layer capacitors as well as superconducting magnetic energy storage systems are already available as energy

[2] Cf. telephone conversation with Mark Richter, Fraunhofer IWU, Chemnitz (Appendix A).

[3] Cf. Fahlbusch, E. (2015), p. 339 et seqq.

[4] Cf. Fahlbusch, E. (2015), p. 339 et seqq.

storage systems for stationary operation in a small market and will gain in importance.[5]

Energy storage systems are relevant if the use of storage systems reduces the load drawn from the grid, increases the proportion of self-generated electrical energy or compensates for production interruptions due to power failures or frequency fluctuations. In this way, storage system can contribute to noticeable cost reductions or avoidance of costs (downtime costs, consequential costs, etc.) in the event of machine or production downtime. Depending on the application, the investment and operational expenditures of the storage system must be compared with the losses prevented due to machine failure with machine damage, loss of production, etc., or the power and load procurement costs. As a result of rising production figures, triggered, for example, by government subsidy programmes and further technical developments, lower investment costs for storage systems are to be expected.

Due to decreasing investment costs for stationary applications, the payback periods of the storage systems are reduced. For SMEs, the use of these technologies is becoming more and more interesting from an economic point of view. Table 1 shows application examples in various application fields of storage technologies in industrial production.[6]

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5 Cf. Wietschel, M. et al. (2015), p. 192.

6 Cf. telephone conversations: Jens Fischer, VEA – Bundesverband der Energie-Abnehmer e. V.; Winfried Wahl, RRC Power; Mark Richter, Fraunhofer IWU and Prof. Dr. Hanke-Rauschenbach, Universität Hannover (Appendix A).

Table 1: Application examples for the use of energy storage system technology in industrial manufacturing[7, 8]

Field of application in operation	Application examples
Uninterruptible power supply	- Highly synchronous industrial drives - Production lines - IT sector - Semiconductor industry - Rubber and plastics production - Injection molding machines - Welding robot
Optimisation of own consumption, Emergency power, Autarchy/island systems	- Companies with their own power generation plants (CHP and PV plants) - Micro grids
Load management - Compensation for weak network infrastructure (avoidance of network expansion) - Load curve smoothing for grid charge reduction - Load shifting (atypical grid use)	- Flexible production processes - Companies with energy management and own electricity procurement - Chemistry - Electric steel - Cement - Metalworking - Electroplating - Food - Paper - 3-shift operations
Minimisation of peak loads	- Close to the machine in DC links, dynamic industrial processes with high loads: Forming machines, tool machines, machining equipment, servo presses, process chain in the automotive industry, pressing tools - Processes with braking energy (recuperation): Forklift trucks, lifting platforms, loading systems (harbours, shelving systems) - Atypical grid use
Provision of control power and control energy	- Stationary large storage system - Modular storage systems in energy-intensive industry

[7] Cf. telephone conversations: Jens Fischer, VEA - Bundesverband der Energie-Abnehmer e. V.; Winfried Wahl, RRC Power; Mark Richter, Fraunhofer IWU and Prof. Dr. Hanke-Rauschenbach, University of Hanover, (Appendix A).

[8] Cf. Gobmaier, T. (2014), p. 5.

2 ENERGY STORAGE TECHNOLOGIES IN INDUSTRIAL PRODUCTION

2.1 Overview of energy storage technologies

There are a number of energy storage technologies that primarily serve to store power or energy.

Power storage is suitable for large power changes, especially in ultra-short and short-term intervals.[9]

Energy storage allows the temporal decoupling of power generation and consumption[10] by storing and releasing energy as needed in short and medium time intervals.[11]

Stationary energy storage systems can be classified according to typical charging/discharging times and type of energy storage (Figure 1).

9 Cf. Fraunhofer ISI (2015), p. 10.
10 Cf. Sterner, M. and Stadler, I. (2014), p. 32.
11 Cf. Fuchs, G. et al. (2012), p. 23.

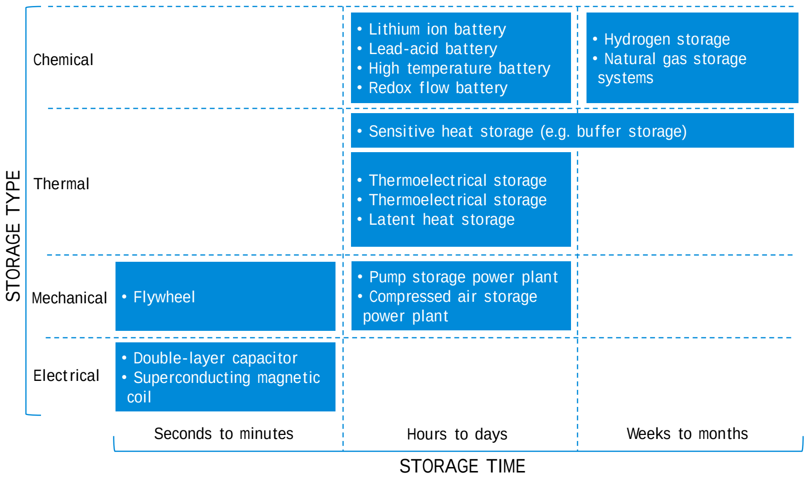

Figure 1: Classification of energy storage technologies by duration and type of storage[12]

The energy storage system capacity (Wh) is particularly important for energy storage. The storage capacity of today's energy storage systems ranges from small decentralised storage systems with less than 10 kWh to very large central energy storage systems with over 1,000,000 kWh. For power storage, on the other hand, the charging and discharging times as well as the power that can be called up at short notice (W) are of importance. Three storage classes are distinguished on the basis of the duration of energy and power supply:[13]

[12] According to Agentur für Erneuerbare Energien (2012), pp. 7 and 10 ff; Sterner, M. und Stadler, I. (2014), pp. 35 - 37; Ausfelder, F. et al. (2015), pp. 36 and 66 and Fuchs, G. et al. (2012), p. 26.

[13] A subdivision of the energy storage systems according to storage duration is not uniformly defined in the literature and can be divided into two short and long-term storage systems or, as here, into three classes, cf. Sterner, M. und Stadler, I. (2014), pp. 41 - 42.

- Short-term storage systems: Seconds to minutes,[14]
- Medium-term storage systems: Hours to days[15] and
- Long-term storage systems: Days to months.[16]

Short-term storage systems feed energy immediately after their activation and reach their maximum performance after just a few seconds. Their energy/performance ratio is less than 15 minutes. The duration of the energy supply is approx. a quarter of an hour with several charging and discharging cycles per day, depending on the area of application. Typical industrial applications include uninterruptible power supply (UPS), frequency and voltage regulation, and peak load minimisation.[17]

Medium-term storage systems have an energy performance ratio of one to ten hours. As a rule, no more than two full cycles are driven per day. Such storage systems can guarantee a power supply of several hours. Typical industrial applications are UPS, own power use (e.g. from photovoltaic systems) as well as load shifting and optimization.[18]

Long-term storage systems are not used in industrial production and are therefore not explained in detail.

In the following, selected technologies from the multitude of existing electricity storage technologies that are already used in industrial production are described. Furthermore, storage technologies are cited that can contribute to cost reduction, flexibilisation, increased independence from grid providers and a reduction in environmental impact.

2.1.1 Flywheel / flywheel mass accumulator

Flywheels ("Flywheel Energy Storage System", FESS for short) store electrical energy in the form of kinetic energy by rotating a flywheel mass (e.g.

[14] Cf. Agora Energy Turnaround (2013).
[15] Cf. Fuchs, G. et al. (2012), pp. 23 - 24.
[16] Cf. Fuchs, G. et al. (2012), p. 14.
[17] Cf. Fuchs, G. et al. (2012), p. 23.
[18] Cf. Fuchs, G. et al. (2012), pp. 23 - 24.

flywheel): An electrically driven motor sets the flywheel in motion and increases the speed. By braking the flywheel, the stored kinetic energy is converted back into electrical energy by a generator. Of particular importance is the speed of modern flywheel/flywheel mass accumulators. This has a decisive influence on the size of the storable energy. This means that flywheels with a high rotational speed achieve higher energy densities than flywheels with lower rotational speeds. However, the increase in speed is limited by the tensile strength and density of the material used. Today, lightweight materials with high mechanical tensile strengths such as glass or carbon fibre reinforced plastics are used.[19]

There are two types of flywheels:

- metallic low-speed flywheels (5,000 to 10,000 revolutions per minute, energy density of 5 Wh/kg) and
- modern high-speed flywheels made of fibre composite materials (10,000 revolutions per minute, energy density: 100 Wh/kg).

Flywheels, minus losses, can release the entire stored energy (deep discharge) in seconds or minutes. They have very high power densities and efficiencies of up to 95 %. However, flywheel accumulators also have high rest losses of approx. 20 % per hour,[20] which are caused by friction losses on the rolling or plain bearings. These are to be reduced by the increased use of vacuum chambers or magnetic bearings with superconductors.

The resulting friction also requires expensive cooling for operation.[21] Flywheels can usually be used where high power has to be provided or stored for a short time. Flywheel accumulators are used, for example, for recuperation in lifting systems and for uninterruptible power supply.[22]

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[19] Cf. Sterner, M. and Stadler, I. (2014), p. 511 et seq.and 518 et seq.

[20] Cf. Renewable Energy Agency (2012), pp. 12 - 13; Ausfelder, F. et al. (2015), p. 36 and Energy Experts (2017).

[21] Cf. Sterner, M. and Stadler, I. (2014), pp. 515 - 516 and Energy Experts (2017).

[22] Cf. Flynn, M. M. et al. (2007) and Agentur für Erneuerbare Energien (2012), p. 27.

2.1.2 Electromagnetic energy storage systems (SMES)

Superconducting magnetic energy storage systems (SMES) store energy in a magnetic field generated by direct current in a superconducting coil. After the end of the charging process, the current flow is maintained by the generated magnetic field.

In order to reduce or completely avoid conduction losses in the coil, the superconducting material (usually niobium-titanium or niobium-tin) must be[23] cooled down to a temperature below its transition temperature. The transition temperature is approx. -269 °C (helium) or -196 °C (nitrogen). Liquid nitrogen or liquid helium is used[24] for cooling. Losses are caused, for example, by the cooling process, the transfer into lines and inverter losses. This leads to comparatively high self-discharge rates of 10 - 15 % per day.[25] SMES achieve a cycle efficiency of around 90 - 95 %.[26]

The following fields of application are generally considered for SMES:[27]

- Short-term storage,
- Grid stabilisation or protection of the voltage quality,
- Power supply for stand-alone systems as well as
- the uninterruptible power supply.

This allows them to be used, for example, in niche applications. This also includes the compensation of fluctuating loads in critical processes, e.g. in semiconductor production.

The technology is still in the development phase - in particular, research is being conducted into the use of superconducting materials with higher transition temperatures. The use at a temperature jump above the boiling point

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[23] The transition temperature is a critical temperature below which materials can conduct electricity without resistance, see Agentur für Erneuerbare Energien (2012), p. 15.
[24] Cf. Rummich, E. (2015), p. 219.
[25] Cf. Renewable Energy Agency (2012), p. 15.
[26] Cf. Renewable Energy Agency (2012), p. 14.
[27] Cf. Sterner, M. and Stadler, I. (2014), p. 194.

of liquid nitrogen (-196 °C) could considerably reduce the cooling costs. So far, however, the material costs of these superconductors are still too high.

2.1.3 Supercapacitors (Supercaps)

In contrast to classical capacitors, supercaps (or double layer capacitors) use an electrolyte that is separated from the two electrodes of the capacitor by a dielectric layer. The energy storage system takes place in the electric field between the electrodes and the ions of the electrolyte. This means that the capacity of a supercap can be considerably increased compared to conventional capacitors, but has so far been lower than that of pure electrochemical storage systems. Compared to these supercaps, however, have significantly higher power densities, response times and cycle lifetimes. This makes them particularly suitable as power storage systems with high charging cycles.

Due to the high cycle efficiencies of over 90 %[28], they are also suitable for use in applications with very frequent charging and discharging cycles of up to one minute. Medium- to long-term energy storage system in supercaps has so far been hampered by the comparatively high self-discharge rates and high energy-specific costs.

Due to the high investment costs, supercaps have so far only been used in demonstration projects in industrial production. Cost reductions are to be achieved primarily through the establishment of mass production, e.g. for use in hybrid electric vehicles. Parallel to this, the use of supercaps will in future also be influenced by the market penetration of high-performance lithium-ion batteries.

2.1.4 Lead-acid batteries (PbA battery)

Lead-acid batteries are among the oldest and most widespread electrochemical energy storage systems.[29] They are still used today in particular for emergency power supply. Valve-regulated lead-acid batteries (VRLA) are most suitable for use as stationary energy storage systems, as they require

28 Cf. Sterner, M. and Stadler, I. (2014), p. 179.
29 Cf. Ausfelder, F. et al. (2015), p. 57.

the least maintenance. They are regarded as a mature technology line, so that fundamental further developments are no longer to be expected.

Compared to other available battery technologies (e.g. lithium-ion batteries, nickel-cadmium batteries), lead-acid batteries are comparatively inexpensive. However, they have lower power densities of approx. 180 W/kg and lower energy densities of approx. 25 - 50 Wh/kg.[30] Due to the low volumetric energy density of approx. 60 - 75 Wh/l[31], lead-acid batteries require more floor space than alternative battery storage systems. These differences are expected to increase as other technology lines evolve. In the medium term, the importance of lead-acid storage technology is therefore expected to decline compared to other technologies.[32]

Another problem is the decreasing capacity of lead-acid batteries with each discharge, especially with increased deep discharges. Therefore, lead-acid batteries also have a relatively low number of cycles of 100 - 2,500 cycles.[33] The high proportion of the toxic heavy metal lead is another problem. The manufacture and disposal of lead-containing electrodes in non-European countries is particularly harmful to health and the environment.

2.1.5 Lithium-ion batteries (LIB)

Lithium-ion batteries (LIB) have gained significantly in importance in recent years. Especially in the mobile sector, e.g. for use in electric vehicles, they are the dominant battery technology.[34] This is mainly due to their comparatively very high energy densities, which lie between 50 and 260 Wh/kg or 160 and 670 Wh/l (Table 2). Like other battery technologies, they have fast response times. Their self-discharge rate is comparatively low at high cycle efficiencies of over 90 %. Compared to lead-acid batteries, they also have a

[30] Cf. Renewable Energy Agency (2012), p. 16; Rummich, E. (2015), p. 154; Ausfelder, F. et al. (2015), p. 57; DCTI (2014), p. 27; Sterner, M. and Stadler, I. (2014), p. 217; Fuchs et al. (2012), S. 54; Sabihuddin, S. et al. (2015), p. 184; Steinhorst, M. P. et al. (2013), p. 29; Fraunhofer ISI (2015), p. 22 – 23 und Elsner, P. und Sauer, D. U. (2015), S. 23.

[31] Cf. Rummich, E. (2015), p. 173.

[32] Cf. Renewable Energy Agency (2012), p. 16.

[33] Cf. Rummich, E. (2015), p. 154; Ausfelder, F. et al. (2015), p. 57; DCTI (2014), p. 27; Sterner, M. and Stadler, I. (2014), p. 217; Fuchs et al. (2012), p. 54; Sabihuddin, p. et al. (2015), p. 184; Steinhorst, M. P. et al. (2013), p. 29; Fraunhofer ISI (2015), p. 22 – 23 und Elsner, P. and Sauer, D. U. (2015), p. 23.

[34] Cf. National Platform on Electric Mobility (2016), p. 19.

significantly longer cycle life. The range of cycle life is comparatively wide and is primarily influenced by the active material of the cathode and the degree of discharge (DOD).[35]

Lithium-ion batteries can be used as short- to medium-term energy storage systems (hours to days). It is also conceivable to use it as a power storage system in the larger power range (from 20 kW), but this requires a high degree of cost degression.

Lithium-ion batteries are available in different designs with a range of different material combinations for the electrodes and electrolytes. The cathode materials lithium cobalt oxide (LCO), lithium-nickel-manganese-cobalt oxide (NMC), lithium manganese oxide (LMO) and lithium iron phosphate (LFP) accounted for large market shares in 2012.[36] Further cell chemistries are under development. The anode materials mainly use graphite, which is characterised by low material costs. An interesting alternative is lithium titanium oxide (LTO), which contributes to improved performance, service life (number of full cycles) and safety of the cell.[37] A disadvantage is the low specific energy density.[38]

Each material combination has specific advantages and disadvantages. Which materials are used depends on the fields of application and the associated requirements. These are, for example, safety, charging and discharging times or performance spectrum. Development potential is seen in lithium-air and lithium-sulphur concepts, among other things, which are still in the research stage and are not expected to reach market maturity until 2025.[39]

[35] Cf. Ausfelder, F. et al. (2015), p. 57.

[36] Cf. Pillot, C. (2013), p. 21.

[37] Cf. Scrosati, B. and Garche, J. (2010), p. 2423 and Zaghib, K. et al. (2011), p. 8.

[38] Cf. Battery University (2017); Han, X. et al. (2014), p. 40 and Scrosati, B. and Garche, J. (2010), p. 2423.

[39] Cf. Fraunhofer ISI (2010) and Fraunhofer ISI (2015), p. 11.

Table 2: Lithium-ion storage systems with different cathode materials[40]

Criteria	LCO	LMO	NMC	NCA	LFP
Name	Lithium cobalt oxide	Lithium manganese oxide	Lithium-nickel-manganese cobalt oxide	Lithium Nickel Cobalt Alumina	Lithium iron phosphate
Environment	Health risk due to the heavy metal cobalt	Non-toxic/ low environmental impact	Health risk due to the heavy metals cobalt and nickel	Health risk due to the heavy metals cobalt and nickel	Non-toxic/ low environmental impact
Safety	High safety risk at high temperatures and overloads	Relatively high safety and chemical stability	Increased safety risk	Safety risk due to overloading (thermal overheating)	Relatively high safety and chemical stability
Nominal voltage [V	3.7[a)]	3.9[a)]	3.6[a)]	3.6[a)]	3.3[a)]/1.9[b)]
Energy density [Wh/l]	320 – 500	290 – 340	490 – 580	480 – 670	160 – 260
Energy density [Wh/kg]	110 – 180	100 – 120	180 – 210	180 – 250	80 – 120
Discharge current [C]	1 – 2	3 – 20	1 – 10	1 – 10	10 – 50
Service life[c)] [Cycles]	300 – 1,000	1,000 – 2,000	500 – 2,000	500 – 1,000	1,000 – 8,000/10,000[b]
Cost relevance of cathode materials	High cost share of cobalt	Costs are in the middle range	High cost share of cobalt	High cost share of cobalt	Costs are in the lower range
Areas of application	**Energy storage** Household appliances	**Power storage** Electr. tools, medical devices, military applications, electro-mobility	**Energy and power storage systems** Electr. tools, household appliances, medical devices, electro-mobility	**Energy and power storage systems** Electric tools, household appliances electro-mobility	**Energy and power storage systems** Electric tools, household appliances, electro-mobility, emergency lighting

[a)] For graphite anode [b)] For LTO-($Li_4Ti_5O_{12}$-)anode [c)] Service life bandwidths in Table 3, p. 27 larger, as no differentiation in cell chemistry, different assumptions for discharge depth (DOD) and different investigation period of individual studies reflect different development status.

Performance increases are expected in terms of power and energy density. It can be assumed that the service life will be significantly increased. In addition, procurement costs will fall as a result of further market development. It is possible that high-performance lithium-ion batteries could penetrate Supercapacitor applications in the future.[41] Lithium-ion batteries are regarded as one of the most important storage technologies.

[40] Cf. Stahl et al. (2016); Rahimzei, E. et al. (2015), p. 24 – 26; Kunkelmann, J. (2015); eNOVA (2015); Pillot, C. (2013); Fraunhofer ISI (2015); Tübke, J. (2010); DCTI (2014); EASE (2016); Zenke, W. (2012), p. 26 – 27; Baumann, M. J. (2012), p. 12 and Kairies, K.-P. (2017), p. 34 – 35.

[41] Cf. Fraunhofer ISI (2015), p. 10.

2.1.6 Sodium high-temperature batteries

Unlike other battery types, high-temperature sodium batteries use a solid electrolyte. However, in order to allow the charge carrier to move, the battery must be kept at an operating temperature of 270 - 350 °C. In daily use, this temperature can be maintained by the reaction heat; however, the use as a long-term energy storage system is prevented by this restriction.

High-temperature sodium batteries are used both as sodium-nickel and sodium-sulphur batteries. For both types there is currently only one manufacturer, which hinders a broad application. Other disadvantages of high-temperature batteries are their low efficiency of around 75 %, the potential danger[42] of solid electrolyte breakage, the need for a complicated thermal management system, the low number of cycles and the initial and operating temperatures required.[43]

One of the biggest advantages of this technology is that the raw materials required are widely used and cheap, especially compared to lithium-ion batteries.

2.1.7 Redox-flow batteries

Redox flow batteries differ from other battery types mainly in that the electrolyte is stored in two tanks outside the actual reaction unit, an electrochemical cell. The ion exchange between the electrolytes takes place by means of a membrane.[44]

Since the capacity of a redox flow cell is only determined by the size of the tank, these systems can be scaled very easily.[45] Due to their low energy densities, however, the space requirement is comparatively large. For example, a 100 kWh redox flow battery requires around 24 m^3 and weighs around ten tons. This corresponds to an energy density of approx. 10 kWh/kg. In addition[46], an operating temperature between 10 °C and 30 °C is required to

[42] Cf. Sterner, M. and Stadler, I. (2014), p. 281.
[43] Cf. Sterner, M. and Stadler, I. (2014), p. 280 and Rummich, E. (2015), pp. 163 - 166.
[44] Cf. Ausfelder, F. et al. (2015), p. 59.
[45] Cf. Ausfelder, F. et al. (2015), p. 60.
[46] Cf. Ausfelder, F. et al. (2015), p. 60.

operate a redox flow battery.[47] Their efficiency is between 66 and 80 %, depending on the reaction material.[48]

Redox flow batteries are therefore primarily suitable for medium to large energy storage systems that store energy over time scales in the daily to weekly range for example. Another reason is that they have a very low self-discharge of <1 % per year.[49] For this reason, redox flow batteries are more likely to be discussed for use in grid-connected systems.

Demonstration plants with vanadium or zinc bromide solutions for redox flow batteries are already in use. It is expected that the battery type will be commercially available on a large scale in a relatively short time. Their distribution will probably also depend on the availability of low-cost redox materials.

2.2 Comparison of storage technologies

The design of storage technologies is primarily oriented to the concrete area of application. This determines the power and capacity of the energy storage system to be used. In applications where energy is only stored for a short time but must be made available quickly, power storage systems are used. Accordingly, their design is primarily based on the available capacity, while the energy storage system capacity and also the energy-related costs of the storage facility are of secondary importance. Accordingly, the costs per power unit (€/kWh) are decisive. The evaluation of the service life of storage systems also depends on the application. A distinction is made between cycle life and calendar service life. In applications with frequent charging and discharging cycles, cycle life is a significant economic factor. If, on the other hand, the energy storage systems are rarely used and long downtimes are to be expected, the calendar service life is decisive.

Some technologies have a wide range of feasible outputs or capacities. This is due on the one hand to the flexibility of the technology itself and on the other hand to its scalability: In modular systems, many units with low

[47] Cf. Ausfelder, F. et al. (2015), p. 60 and Sterner, M. and Stadler, I. (2014), p. 286.
[48] Cf. Sterner, M. and Stadler, I. (2014), p. 290.
[49] Cf. Ausfelder, F. et al. (2015), p. 60.

capacities are connected in series to form a system of high performance. Table 3 provides an overview of the comparison of important technical and economic parameters of the technologies described above.

Table 3: Technical and economic characteristics of power and energy storage systems[50]

	Cycles-service life	Service life	Costs	Performance sizes	Storage systems sizes
SHORT-TERM POWER STORAGE (SECONDS TO MINUTES)					
	Number	Years	€/kW	kW	kWh
Flywheel	0,000 - 10 million	15 – 20	27 – 8,000	1 – 10,000	<5,000 (scalable)
Supercaps	10,000 - 1 million	5 – 30	20 – 9,019	10 – 200,000	<100 (in the small kWh range)
SMES	20,000 - 1 million	15 – 30	180 – 915	100 – 10,000	0.1–15
High performance lithium ion battery	500 – 10,000	5 – 20	158 – 3,608	Scalable (up to several thousand kW)	Scalable (in the one- to two-digit MWh range)
Lead-acid battery*)	100 – 2,500	3 – 20	150 – 812	<50,000	<50,000
MEDIUM-TERM ENERGY STORAGE SYSTEM (MINUTES TO HOURS)					
	Number	Years	€/kW	kW	kWh
Energy storage system lithium ion battery	300 – 15,000	5 – 20	158 – 3,608	Scalable (up to several thousand kW)	Scalable (in the one- to two-digit MWh range)
Lead-acid battery	100 – 2,500	3 – 20	45 – 992	<50,000 (scalable)	<50,000 (scalable)
Redox Flow Battery	800 – 20,000	2 – 25	100 – 1,153	<100,000 (scalable)	Scalable (several 1,000 kWh)
Sodium sulphur battery	2,500 – 8,250	10 – 20	210 – 645	Scalable (up to two-digit MW)	Scalable (up to three digit MWh)

*) No specific data available for high performance lead-acid batteries. The data cover the entire bandwidth.

2.3 Fields of application in industry

The technical and economic requirements for the storage technologies are determined by the concrete use. An evaluation is therefore always only possible within the framework of the individual application. They specify technical parameters (form of energy, output, capacity and reaction time) and economic parameters (energy prices, useful life). In addition, there are energy-legal framework conditions such as statutory regulations, charges, levies and taxes, etc. For companies, the key question when selecting a storage technology is therefore: “Which storage system type is best suited for 'my' specific purpose from an economic and ecological perspective?“

[50] For editorial reasons, the sources of Table 3 in Appendix B can be reproduced.

There is no blanket business model for the use of storage technologies in industrial practice. Each application must be considered individually from an economic point of view. However, profitability is always strongly dependent on the respective load profiles, performance and energy prices and production flexibility. Table 4 summarises the energy storage systems with their power ratings and service lives used today in industrial production (Chapters 2.3.1 - 2.3.5).[51]

Table 4: Fields of application and their sizes of energy storage systems in industrial production

Field of application in operation	Scale and technologies
Uninterruptible power supply	- 0.001 MW up to two hours - Lithium-ion batteries, lead-acid batteries - Supercapacitors, flywheels
Optimisation of own consumption, Emergency power, Autarchy/island systems	- 2 MW up to five hours - Lithium-ion batteries, lead-acid batteries
Load management	- 2 MW up to four hours - Lithium-ion batteries, lead-acid batteries - Sodium-sulphur batteries, redox-flow batteries
Minimisation of peak loads	- 1 MW up to one hour - Flywheels, Supercaps, Lithium-Ion Batteries
Provision of control power and control energy	- 1 - 5 MW up to one hour - Flywheels, Supercaps, Lithium-Ion Batteries

2.3.1 Uninterruptible power supply

Uninterruptible power supply systems (UPS systems) guarantee a reliable electrical power supply even in moments of unstable supply from the public power grid. In addition to protection against power failures, UPS systems ensure the quality of the power supply. Many industrial companies install UPS systems to prevent production downtime and other hazards and to maintain the most critical processes in the event of a power outage. UPS systems are of great economic importance here.[52]

Depending on the energy storage system used, power outages of a few seconds up to 30 minutes can be buffered in practice. Diesel aggregates are usually used to bridge longer lasting failures. Battery systems are

[51] Cf. Wahl, W. und Igel, p. (2017), p. 10; Wahl, W. (2016), p. 8; Fraunhofer ISI (2015), p. 7; and Gobmaier, T. (2014), p. 5.

[52] Cf. telephone conversation with Winfried Wahl, RRC Power, (Appendix A).

established in the uninterruptible power supply market. In addition, flywheel accumulators are increasingly being used. Typical operating times of UPS systems with batteries are between five and 30 minutes. Using energy storage system solutions for up to 60 minutes is cheaper than diesel generators. In contrast, the operating time of flywheel accumulators is only eight and 30 seconds. Flywheel accumulators usually require less space than batteries with comparable performance.[53]

The selection depends on the application. The use of lead-acid batteries has the disadvantage that only 50 % of the rated power can be used in one cycle. Depending on the technology, 80 - 99 % are available when using a lithium-ion system. Which technology is used depends on the economic efficiency. Smaller UPS systems of an IT system are usually still operated with lead-acid batteries, but this is uneconomical with increasing size.[54] Table 5 summarizes the typical characteristics of the uninterruptible power supply.

Table 5: Application profile uninterruptible power supply

Application profile uninterruptible power supply	
Storage technologies (short-term storage systems)	Flywheel, lead-acid battery, lithium-ion battery (also combinations)
Typical services	Very high (up to several MW)
Typical capacities	Low (from a few Wh)
Response times	A few milliseconds
Withdrawal durations	A few seconds to 30 minutes
As needed	Controlled shutdown of processes, storage systems of information or start-up of an emergency power supply
Demands	UPS systems must be able to deliver high performance very quickly and reliably and achieve good efficiencies with long service lives (are used irregularly).

2.3.2 Optimisation of own requirements in trade and industry

Investments in customer generation plants are worthwhile for most companies if they succeed in using as much of the electricity generated as possible themselves. Independent of the technology used, customer generation plants are therefore always designed and dimensioned in such a way that their own potential for integrating the generated electricity can be used as optimally

53 Cf. Piller (2011), p. 3, p. 9 and p. 19.

54 Cf. telephone conversation with Winfried Wahl, RRC Power, (Appendix A).

as possible. Since many companies require both electricity and heat in the production process, the use of combined heat and power (CHP) plants makes sense. In practice, the number of companies generating their own electricity has increased in recent years. According to DIHK estimates, approx. 25,000 companies currently operate their own plants and 25,000 others are planning to do so. Overall, industry generates 20 % of its own electricity needs. To date, approx. 60 % of this is generated in CHP plants, 8 % of which with renewable energies.[55]

Energy storage systems can contribute to increasing the share of electricity from decentralised energy systems that is consumed by the individual. Here, the characteristics of the necessary storage cycles are determined by the power supply of the self-generation and by the load behaviour of the connected consumers. If electricity generation mainly takes place during the day and at midday (e.g. with photovoltaic systems), energy storage systems take up the surplus electricity and make it available again in the evening and morning hours. In this way, it is possible to reduce the amount of electricity drawn from the power grid (Table 6).[56]

Large customers in industrial production pay an average of approx. 16 ct/kWh. If the investment costs for an own generation plant can be raised and the electricity produced is used locally, savings of up to 10 ct/kWh can be achieved. Without energy storage system, the companies' own consumption rates are between 20 % and 30 %. With appropriate storage systems, the quota can be increased to between 60 % and 75 %.[57] The generation of own electricity is still mostly carried out using conventional technologies (e.g. generators) and only sporadically with photovoltaic systems.

The generation costs of photovoltaic electricity have fallen steadily. They are currently below 6 ct/kWh in large plants. The electricity purchase prices show that decentralised power generation can be profitable. The decisive factors are the investment costs of the generation plant, the level of own consumption and the electricity tariffs. At present, the production costs of self-generated photovoltaic electricity plus storage system for a new plant are

[55] Cf. DIHK (2014), p. 4.
[56] Cf. DCTI (2014), p. 15.
[57] Cf. Wahl, W. und Igel, p. (2017), p. 12.

approx. 30 ct/kWh.[58] For existing photovoltaic systems, profitability could be achieved in some cases, especially with decreasing costs of battery storage systems.[59]

Table 6: Application Profile Optimization of Own Requirements

Application Profile Optimization of Own Requirements	
Storage technologies	Lead-acid batteries, lithium-ion batteries, high-temperature sodium batteries, redox-flow batteries
Typical services	From a few kW
Typical capacities	Several kWh
Response times	Sufficient of all technologies
Withdrawal durations	Minutes up to ten hours
As needed	Energy storage systems offer the possibility of using a higher proportion of the electricity generated by the company itself during operation.
Demands	Even larger quantities of electrical energy have to be stored for up to ten hours with low losses.

2.3.3 Minimisation of peak loads

A peak load is a short, high power demand in the power grid. This occurs, for example, when several devices or machines of a company start up at the same time or a short-term, power-intensive machining operation is carried out (e.g. induction heating).

With energy storage systems, peak loads can be reduced because they absorb energy when the load is below a defined maximum load. As soon as the load exceeds a certain limit, the stored energy is fed into the operational low-voltage grid (0.4 kV). This limits the above-average amount of electricity that can be drawn from the grid. If very high outputs with energy storage systems are provided at short notice, the investment costs per kilowatt are relevant. Depending on the duration of the energy purchase, the costs per stored kilowatt hour are less important. In addition, cycle stability and power density are essential requirements for the technologies used.

Currently, typical storage sizes of approx. 100 kW have a supply duration of up to one hour. In this area of application, lithium-ion batteries have potential if cycle lifetimes are increased in the future with significant cost degression. Flywheel accumulators can also become economical as power storage

[58] Cf. DIHK (2015), p. 20.
[59] Cf. Wahl, W. und Igel, p. (2017), p. 12.

systems in the future, especially in the minute range, if their acquisition costs fall as a result of an increasing supply.

Three applications in industrial production are described below. The use of supercapacitors at the machine level was tested as part of research work at the Fraunhofer IWU. In tool machines, such as milling machines, measurements in real production operation showed a minimisation of peak loads by up to 67 % (Figure 2).[60]

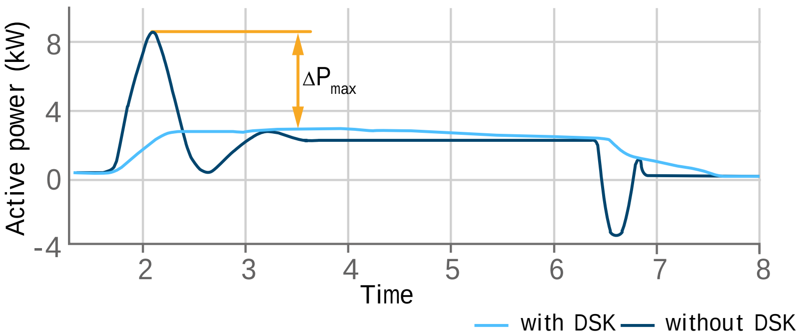

Figure 2: Example for the reduction (light blue) of peak loads (dark blue) on toolmachines with and without the use of double layer capacitors (DLC)[61]

In another application, the use of energy storage technologies within a process chain for the production of powertrain components was investigated.[62] Using the example of the process chain for manufacturing powertrain components (e.g. a shaft in the transmission of an automobile), the energy flows of all manufacturing steps as well as various manufacturing processes (forming, machining and welding) and assembly processes were analysed. A combination of flywheels and lithium-ion batteries was then used in five to six machines. Together with intelligent operational management, the peak loads of the machines could thus be reduced by a total of 80 %.

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[60] Cf. ESiPinno (2015), p. 56 et seq.

[61] Judge, M. (2016), p. 15.

[62] In the E^3 research factory "Resource-efficient production" (ESiPinno conference proceedings, p. 80 f.), the Fraunhofer IWU researches sustainable solutions for production technology.

A third use case is atypical grid use, which allows companies to reduce their grid charges by at least 20 %.[63] Companies can contribute to the relief of the public power grid if they do not demand peak loads in times of high electricity demand (peak periods) (Figure 3). Example calculations show that by reducing the load from 586 kW to 308 kW over two hours, companies can save up to 25 % of the grid charge in a peak load window. Energy storage systems can help companies to achieve atypical grid use by providing the electricity that was stored during periods of low grid load during high-load phases.[64, 65]

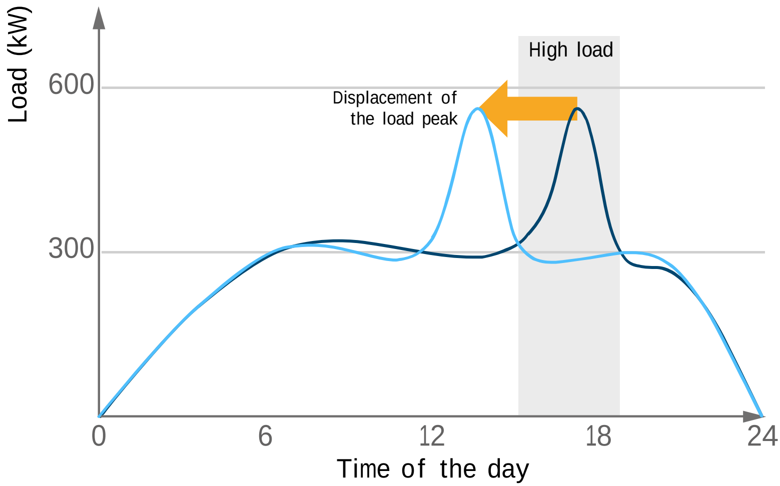


Figure 3: Schematic representation of a reduction in grid charges due to atypical grid use in a high-performance period of approx. two hours[66]

Table 7 summarises the characteristics of the application profile for minimising peak loads.

[63] Up to 80 % for large consumers with a purchase quantity of at least 10 GWh/a.

[64] Cf. DIHK (2015), p. 6.

[65] Cf. telephone conversations with Jens Fischer, VEA - Bundesverband der Energie-Abnehmer e. V.; Winfried Wahl, RRC Power; Mark Richter, Fraunhofer IWU (Appendix A).

[66] According to DIHK (2015), p. 6.

Table 7: Application profile for minimisation of peak loads

Application profile for the minimisation of peak loads	
Storage technologies	Supercaps, flywheels, lithium-ion batteries
Typical services	High, up to 1 MW
Typical capacities	Up to several hundred kWh
Response times	Seconds
Withdrawal durations	Seconds (at machine level) to hours (at system level)
As needed	With energy storage systems, peak loads can be reduced and thus the performance prices lowered.
Demands	The energy storage systems are frequently loaded and unloaded and must have a high cycle stability.

2.3.4 Load shifting

The aim of load shifting (also known as load levelling) is to minimise energy costs by balancing the power supply between peak and off-peak periods. This means that consumption is shifted in relation to the usual production process. This requires an upstream or downstream load increase. Companies with high electricity requirements can specifically use energy storage systems for this purpose, which complete several charging and discharging phases daily and cover the power supply in the range from minutes to a few hours (Table 8). Load shiftings are suitable for energy-intensive consumers who have supply contracts with time tariffs or who procure their electricity themselves on the electricity exchange.

The application of load shiftings has so far been tested in practice, above all in the power-intensive industry. From the companies' point of view, the financial value of a load shifting is decisive. In southern Germany, a load shifting potential of one gigawatt for one hour was calculated for the energy-intensive industry. For this purpose, the chlorine, cement, paper, electrical steel and metal industries with annual electricity consumption of over one gigawatt hour were considered. On this scale, participation in the balancing energy market offers additional financial incentives.[67]

The more evenly a consumer's electricity consumption is, the greater the cost savings for the company and downstream for the need for a maintained infrastructure. In industrial practice, this means that the load is shifted in time or stored locally at peak times (usually from 8 a.m. to 6 p.m.). Large consumers have the potential to reach 7,000 - 8,000 full load hours if load

[67] Cf. Agora Energiewende (2013), p. 51.

shifting is used correctly. In the case of large-scale consumers, an analysis of the load profiles can be carried out within the framework of comprehensive energy management by means of energy audits in order to reduce the total consumption at the same time with targeted control of the loads.[68] With a load shifting, machines can be better utilized and high peak loads can be reduced due to parallel operation. Correspondingly designed storage systems are helpful here. This requires professional data collection systems to produce timetables and consumption forecasts. The important energy flows in the company must be documented. Then an energy storage system can make its maximum contribution as an element of overall optimisation.[69] Table 8 summarises the typical characteristics of a load shifting.

Table 8: Application profile Load shifting

Application profile Load shifting	
Storage technologies	Lead-acid, lithium-ion, sodium high-temperature, redox flow batteries
Typical services	Average power up to several kW
Typical capacities	Up to several kWh
Response times	Insignificant
Withdrawal durations	Minutes up to several hours
As needed	Relocation of power supply from peak to off-peak periods
Demands	Storage systems have to store and release electrical energy with a high degree of efficiency several times a day.

2.3.5 Provision of control power and control energy

In the electricity market, there must be a balance between electricity generation and consumption at all times. The control power is used to compensate for fluctuations in the power grid. If demand is higher than supply, positive balancing energy (more electricity into the grid) is needed. If the supply is higher than the demand, negative balancing energy is used (electricity from the grid). Depending on the time availability, a distinction is made between primary, secondary and tertiary control power. In the future, grid-guided energy storage systems will also be able to provide control power, which has so far mainly been provided by conventional power plants.

Operators of energy storage systems can generate additional income on the market for balancing energy, but must meet certain conditions

[68] Cf. Wahl, W. (2016), p. 5.

[69] Cf. telephone conversations with Mark Richter, Fraunhofer IWU (Appendix A) and Wahl, W. (2016), pp. 6 et seq.

(prequalification requirements).[70, 71] For example, a minimum size of one megawatt is required on the primary balancing market (also possible in the supplier pool), which must be available in a maximum of 30 seconds. A minimum size of 5 MW, available from 30 seconds to 60 minutes, is set for bidding on the secondary and tertiary regulated market.[72]

For most industrial consumers, participation in the primary regulatory market is unrealistic due to time constraints. The secondary and tertiary control energy markets, on the other hand, can be economically realistic sales markets for SMEs that maintain their own energy storage system facilities. In order to be able to exploit the opportunities in this field of application, the market signals from the control energy and electricity wholesale markets must reach medium-sized companies better. Up to now, central large storage systems (pumped storage systems, large batteries) in particular have been active on the markets. In principle, several smaller decentralised storage systems can also be marketed together. Technically speaking, flywheels are particularly suitable in the seconds range, but battery storage systems can also be used, which today already achieve reaction times in the seconds to minutes range. Table 9 shows a characteristic application profile.[73]

Table 9: Application Profile Control Power and Control Energy

Application Profile Control Power and Control Energy	
Storage technologies	Large stationary storage tanks (pumped storage tanks, batteries)
Typical services	High, from 1 - 5 MW
Typical capacities	Up to several MWh
Response times	Milliseconds
Withdrawal durations	Seconds up to a few hours
As needed	Stabilisation of the energy system, security of supply
Demands	Storage must be operational in milliseconds and provide high performance, participants in provider markets must meet various requirements.

2.4 Summary

Stationary energy storage systems can increase efficiency in industrial production while at the same time minimising costs. In principle, flywheels, supercapacitors, electromagnetic energy storage systems and batteries can be

[70] Cf. DIHK (2017a), p. 23.
[71] Cf. Agora Energiewende (2013), p. 86.
[72] Cf. Beck, H. P. et al. (2013), pp. 12 et seqq.
[73] Cf. DCTI (2014), p. 12 f. and Fraunhofer ISI (2015), p. 34.

used as technical solutions. For stationary applications in the kilowatt range, lithium-ion and lead-acid batteries are currently the main competitors. In the megawatt range, lithium-ion batteries compete with redox flow batteries.

A key factor in the future use of energy storage technologies at all levels of industrial production is their integration into active energy management. The following prerequisites are central:

(1) Simulation and design of energy storage systems,

(2) Design of the integration capability and interfaces of the energy storage systems for commercial use and

(3) economic dimensioning of the energy storage systems by adequate operational management.

The use of energy storage systems for uninterruptible power supply is state-of-the-art and has been established for decades. Improvements due to technological advancements can be found in particular in power storage systems and lithium-ion batteries. The machine-oriented use of energy storage systems to minimise peak loads, e.g. in the forming machines of the automotive industry, is economically relatively easy from today's point of view. Energy storage systems are already being used successfully in industry to increase energy efficiency, for example in the recovery of braking energy.

In SMEs there is a high potential for the use of power storage systems in numerous processes. They can be used to minimise losses in practical operation due to overdimensioning of individual production components, suboptimal operating modes or standby operation.

In demanding environments, such as in halls or at an entire site, storage systems are from today's point of view economical if multiple benefits can be realized, for example by minimising peak loads in-house combined with the optimisation of own power generation. For companies with high annual production hours, a load shifting with energy storage systems can be profitable. This option will be of particular interest in the future as electricity prices rise and storage system costs fall. In addition, companies can also act as market suppliers of balancing energy. In view of the required output sizes on the control energy markets, this is currently profitable above all for large industrial companies and far removed from the machine level with which small and medium-sized companies are familiar. In the medium term, several SMEs could be organised in pooling solutions.

Table 10 summarises the research results and highlights the current market relevance of storage technology.

Table 10: Comparison of the market relevance of energy storage systems

Storage system technology	UPS/ Emergency power	Optimisation of auxiliary power	Minimisation of peak loads	Load shifting	Control power/control energy
Lead-acid batteries	Market relevance: established use; Cycle life: good	Market relevance: established use; Cycle life: average	Market relevance: established energy storage system Not yet established as a power storage system	Market relevance: currently low	Market relevance: currently low
Lithium-ion batteries	Market relevance: increasing relevance; Cycle life: good	Market relevance: established use; Cycle life: good	Market relevance: established energy storage system Not yet established as a power storage system	Market relevance: perspective; Cycle life: good	Market relevance: currently still low
Redox Flow Batteries	Market relevance: individual distribution and demonstration plants, especially in the USA and Japan, size in the MWh range	Market relevance: Perspective, but rather in the MWh range; Cycle life: good	Market relevance: individual distribution and demonstration plants, especially in the USA and Japan, size in the MWh range	Market relevance: perspective; Cycle life: good	Market relevance: individual distribution and demonstration plants, especially in the USA and Japan, size in the MWh range
Sodium high temperature batteries	Market relevance: currently none to low	Market relevance: Perspective if energy consumption for operation is reduced	Market relevance: currently none to low	Market relevance: Perspective if energy consumption for operation is reduced	Market relevance: currently none to low
Flywheel accumulators	Market relevance: established use; Cycle life: good	Market relevance: currently none to low	Market relevance: tried and tested at machine level, recuperation applications in research	Market relevance: currently none to low	Market relevance: established, but not widespread
Double-layer capacitors	Market relevance: established use; Cycle life: good	Market relevance: currently none to low	Market relevance: perspective, especially in the short-term area; Cycle life: good	Market relevance: currently none to low	Market relevance: currently none to low

high market relevance, moderate/perspective market relevance, low to no market relevance

2.5 Objective of the study

The objective of this study is a comparative ecological and economic evaluation of three selected decentralised stationary energy storage system solutions based on a technical, ecological and economic perspective. The comparison is based on a concrete application scenario in industrial production in small and medium-sized enterprises (SMEs). The following research questions are examined in detail in this context:

- What costs of material, energy, water and, if necessary, surface area have to be met over the life cycle of the decentralised stationary energy storage system units?
- Which supply-critical raw materials are used in the energy storage technologies under consideration?
- Which greenhouse gas emissions, expressed in CO_2 equivalent, are emitted per energy storage system under consideration?
- What are the costs for the energy storage systems?

The subject of this study is a comparison of three abstract energy storage systems in the context of a generic application scenario. This generalisation is necessary in order to limit the analysis to the essentials with regard to the diversity of the technical characteristics of energy storage systems and the modalities of their use in industrial manufacturing processes. No concrete models of energy storage systems and no concrete examples of use in a company are analysed. Instead, the analysis is based on a model application scenario (chapter 3.1). This reflects the conditions of a generic SME-relevant manufacturing process in which energy storage systems are used. The selection of the three technologies to be assessed from the energy storage systems analysed (Chapter 3.3) is based on this application scenario.

The main target groups of the study are small and medium-sized enterprises with energy-intensive processes, machine and plant manufacturers, consultants and research institutions. The selection of the analysed energy storage system solutions depends on the needs of this target group. The results of the study should enable SMEs to evaluate the usefulness of an investment in stationary energy storage system from an ecological and economic perspective. Furthermore, the study is to serve as a source of information for initiatives and associations as well as institutions of the Federal Government, the Federal States and their representatives.

3 METHODOLOGY FOR THE ANALYSIS OF ECOLOGICAL AND ECONOMIC IMPACTS

3.1 Definition of an application scenario for the use of energy storage systems in SMEs

The first step for the comparative ecological and economic evaluation of stationary energy storage technologies is the definition of an application scenario in industrial manufacturing. Such a scenario is necessary because this study is not based on a concrete case study. Instead of a single case, this study should cover the widest possible range of industrial applications of energy storage systems in SMEs. However, due to the high heterogeneity of industrial production in SMEs, it is not possible to generalise SME-relevant applications for the design of a typical energy storage system.[74] The evaluation refers to a scenario that specifies the demand for electrical energy to be stored within the framework of generic manufacturing processes. The definition of the scenario is based on the following criteria:

- Prospects of economic benefits for SMEs,
- Relevance for manufacturing processes in SMEs and
- Fulfilment of the technical framework conditions for the suitability of the energy storage systems with regard to the intended purpose.

It can be assumed that companies have a special interest in **cost savings**. In addition to the introduction of an energy management system, the **reduction of grid charges** can lead to savings in energy costs. These are levied on power-measured grid users with an annual purchase of 100,000 kWh or more. Within the framework of the current system of grid charges, **minimising peak loads** can reduce the grid charges. However, it should be noted that not all commercial customers are measured for performance and that the proportions of the performance-based grid charges also vary depending on the voltage level and hours of use. The amount of the grid charge is assigned to a performance price group based on the share of peak load in annual electricity consumption (annual usage duration in h/a). Grid users with

[74] **Cf. telephone conversation with Mark Richter, Fraunhofer IWU (Appendix A).**

an annual usage duration of more than 2,500 hours[75], in particular, receive 57 % to 83 % of the grid charge, depending on the voltage level.[76] The total load profile of the grid user is relevant for the grid charges. In this respect, the energy storage system to be installed must be designed to optimise the total load profile and not the profile of a single energy-intensive process.

There are two approaches for companies to achieve such **savings potential by reducing grid charges**:

(1) A **so-called atypical grid use** - this is the reduction of peak loads during certain periods (peak load windows) in the sense of the Power Grid Charges Ordinance (StromNEV). This variant corresponds to the peak load 1 sketched in Figure 4.

(2) An absolute **reduction of** the specific maximum annual load (at all times) in the sense of the Electricity Grid Access Ordinance (StromNZV). This variant corresponds to the peak load 2 shown in Figure 4.

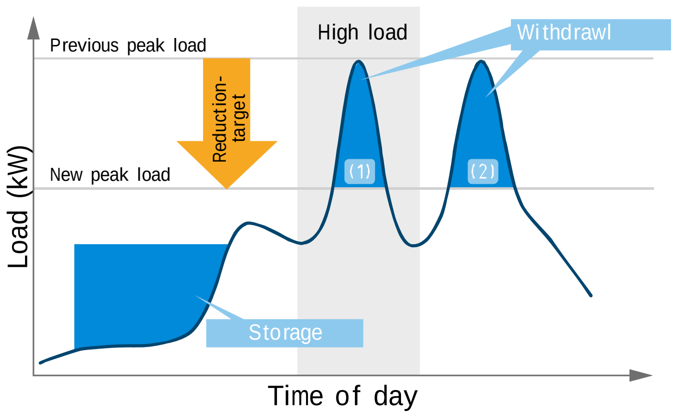


Figure 4: Schematic representation of the minimisation of peak loads by energy storage systems

[75] Annual electricity demand divided by annual peak load.
[76] Cf. BNetzA (2015), p. 14.

Atypical grid use (peak load 1, Figure 4)

Atypical grid use (peak load 1) is about avoiding peak loads in periods of high electricity demand in public grids (so-called peak load window, Figure 5).

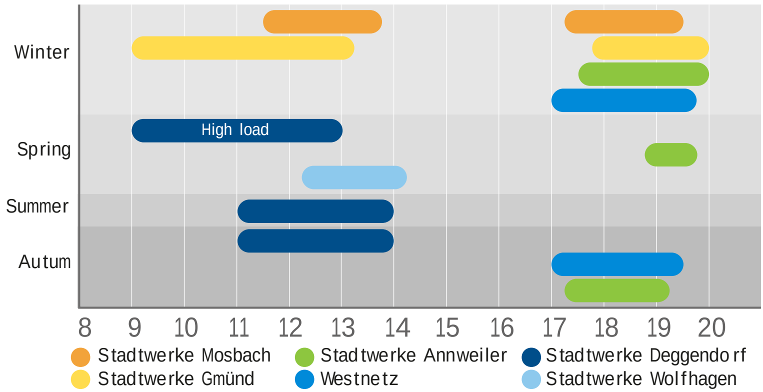


Figure 5: Examples of peak load windows in the low-voltage grid of various energy supply companies from 2017[77]

If, for the following year, a company commits itself to a verifiable capping of its own peak loads by at least 100 kW within the respective peak load window, the grid use charge to be paid may be reduced. Since 2005, the Electricity Grid Charges Ordinance (StromNEV) has regulated the charges to be paid by commercial electricity customers for connection to public power grids.[78] The power grid operators can therefore pass on the costs of electricity transmission to the final consumers, i.e. their customers. At the same time, StromNEV allows an individual reduction of the grid use fee for atypical grid use. Energy supply companies must offer grid users who can prove that they have their peak load outside the defined peak load window an individual, reduced grid charge. In 2016, the Federal Grid Agency registered more than 4,500 companies that operate an atypical grid use and pay reduced fees for it.[79] These grid charges shall not be less than 20 % of the published grid charges and shall be approved by the competent regulatory authority. The

[77] Cf. Mosbach (2017), Annweiler (2017), Deggendorf (2017), Gmünd (2017), Westnetz (2017) and Wolfhagen (2017).

[78] Ordinance on charges for access to electricity supply networks (StromNEV).

[79] Cf. BNetzA (2016).

extent of the savings potential for the final consumer depends on the load reduction achieved. In the low-voltage grid (0.4 kV), this must account for at least 30 % of the predicted peak loads. In the context of atypical grid use, the purpose of an energy storage system would be to reduce peak loads by 100 kW in order to achieve the legally prescribed minimum shift of peak loads. The minimum value (trivial limit) for the reduction in grid charges to be achieved by shifting peak loads is € 500 per year.

Absolute reduction of the specific annual maximum load (peak load 2, Figure 4)

The second possibility for cost savings lies in the reduction of the specific maximum annual load and thus of the performance price to be paid. This possibility is based on the regulation in the Electricity Grid Access Ordinance (Strom NZV).[80] Accordingly, the price of a consumer's service is based on its highest peak load, even if this occurs only once a year and the average value (band load) is significantly lower. However, this regulation only applies to power-measured grid users with more than 100,000 kWh of power consumption per year. From this size the electricity price consists of a fixed part (power price in €/kWa) and a variable part (work price in €/kWh). The performance prices per kilowatt connected load amount to between 80 and 120 euros per year; depending on the load profile, they are a considerable cost factor. If an operation with an assumed peak load of 160 kW and an average power consumption of 30 kW reduces the peak load to 60 kW, the electricity procurement costs could be reduced by 10,000 Euro per year at a power price of 100 €/kW. In such cases[81], energy management is usually worthwhile for companies.[82] Within this framework, the use of energy storage systems could be a way of minimising peak loads if other methods of energy management have already been exhausted.

The use of an energy storage system to **minimise peak loads** illustrated in the above constellations according to StromNEV (peak load 1) and StromNZV

[80] Ordinance on Access to Electricity Networks (Electricity Grid Access Ordinance - StromNZV).

[81] Cf. Wahl, W. und Igel, p. (2017) p. 12: Energy cost reduction potentials through application of applicable law and economic solutions through electrical energy storage system, last examined on 07/03/2017 (sent after discussion, still unpublished).

[82] Cf. Wagenblass, D. (2016).

(peak load 2) represents a typical, albeit not universal, application in SMEs. This is an appropriate subject for the application scenario of this study for the following reasons:

(1) The minimum value of 100 kW for minimising peak loads set by StromNEV applies to many SMEs in relevant sectors. The reduction of the grid charge results in economic advantages for SMEs.

(2) The technical requirements of the intended use can be met with the aid of energy storage systems available on the market.

Application scenario

The application scenario defined for this study is the "minimisation of peak loads".

The application scenario "Minimisation of peak loads" is specified as follows under consideration of the technical boundary conditions for the use of storage technologies in practice:

- The users of the energy storage systems are SMEs with low-voltage power connections.[83] The operating mode is 1-shift operation, weekdays between 7:00 - 17:30.
- The use of energy storage systems ensures that peak loads are reduced by at least 100 kW within the peak load window specified by the energy supplier.

The application scenario "Minimisation of peak loads" is specified for this study with the parameters listed in Table 11.

[83] At the low-voltage level (0.4 kV) common in SMEs, the technical designation is 400 V three-phase alternating current. This so-called three-phase current is common, for example, for tool machines.

Table 11: Specification of the application scenario “Minimisation of peak loads“ for a generic industrial production process[84]

Application parameters	Specification
Operating mode of production in SMEs	1-shift operation, weekdays between 7:00 - 17:30 hrs
Working days per year [d/a]	250
Operating hours per day [h/d]	10
Operating hours per year [h/a]	2,500
Average load (band load) [kW]	150
Specific maximum annual load [kW]	300
Total duration of peak loads [h/d]	1
Power consumption [kWh/a]	375.000
Performance price [€/kW and a]	30
Total electricity price (incl. taxes and charges) [ct/kWh] [85,86]	13
Total electricity costs per year [€/a]	57,750

The scope of the application scenario discussed here is limited to the conditions of the low-voltage grid with 400 V three-phase current existing in SMEs, i.e. before the grid connection point to the medium-voltage level. The effects of energy storage system on the power supply infrastructure (medium voltage/high voltage) are not examined in this study. However, the life cycle evaluation also takes into account the upstream chains of electricity generation.

3.2 Determination of the functional unit

According to DIN EN ISO 14044, the functional unit is defined as the quantified benefit of a product system for use as a comparison unit.[87] A uniform reference value for the function of the considered energy storage technologies is necessary in order to relate the cost data as well as the material and energy flows to be determined to a uniform denominator in the course of the economic and ecological analysis. The functional unit therefore describes the benefit to be provided, i.e. the storage and provision of electrical energy, under certain boundary conditions (the duration).

[84] Cf. Austrian Energy Agency (2014), p. 43 and 28; Neugebauer, R. (2012), p. 16; TU-Darmstadt (2017), p. 14 and Fraunhofer ISI (2015a), pp. 3 and 42 et seq.

[85] The total electricity price of load-measured consumers with a power consumption of over 100,000 kWh per year is made up of the performance price, the work price and taxes and charges as well as the location of the company and the connection level.

[86] Cf. DIHK (2017b), p. 3.

[87] Cf. DIN EN ISO 14044:2006 (2006), p. 11.

On the basis of Chapter 3.1 and taking into account the findings of expert interviews, the functional unit was defined as follows.

Functional unit

“Minimisation of peak loads in the power consumption of an SME of 100 kW active electrical power for one hour per working day over a comparison period of one year“

This narrative description of the function expected from the energy storage systems contains the following elements:

- Purpose: Peak load reduction according to the minimum shift to StromNEV (100 kW),
- Scope of application: small and medium-sized enterprises and
- Application conditions: economically reasonable.

The comparison period of one year describes a period analysed in the life cycle evaluation for the purpose of comparing different technologies with different service lives. The actual period of use of the respective energy storage systems in SMEs covers a longer period of time.

The characterisation of the technical prerequisites and product service life required for the functional unit and the allocation of the material and energy quantities required for this (the so-called reference flows) are carried out in the following chapters 3.3 and 3.4.

3.3 Selection of three energy storage technologies for the comparison of the end of evaluation

The most important influencing variables for defining a storage technology are the load profile and the information on operational management in the company, such as switch-on times of the machines and production breaks etc.[88, 89] Due to the high heterogeneity of production processes to be found

[88] Cf. ESiPinno (2015), p. 29.
[89] Cf. telephone conversation Mark Richter, Fraunhofer IWU (Appendix A).

in SMEs and the machines used for this purpose, very different characteristics arise in practice in the electrical load profiles. Due to this wide range of power purchases, the energy storage systems considered in this study are selected on the basis of the application scenario defined in 3.1.

The selection of the energy storage technologies for the ecological and economic comparison was based on a multi-criteria evaluation (Appendix C). The main selection criterion was the suitability of the respective energy storage systems (Chapter 2.1) for providing the functional unit under the conditions defined in the application scenario (suitability for minimising peak loads in SMEs, Chapter 3.1). During the selection process, an intersection of the following criteria was taken into account:

- Market maturity/development status (qualitative, Table 10),
- Efficiency of the energy storage system (in %),
- Storage loss (in %),
- Specific energy density (in Wh/kg),
- Calendar service life (in years),
- Cycle stability (number of charge and discharging cycles) and
- Handling/safety aspects (verbally argumentative).

The energy storage technologies presented in Chapter 2.1 were evaluated on the basis of the above criteria. In addition to the batteries (electrochemical storage), supercaps (capacitive storage) and flywheels (Rotational energy) as potential options. A total of five different battery systems were available for the electrochemical storage technologies. In addition to the classic lead-acid batteries, these were two different types of lithium-ion batteries (Lithium iron phosphate batteries and lithium-nickel-manganese-cobalt oxide batteries, Table 2), the novel redox flow batteries and the high-temperature sodium batteries (Appendix C). Depending on data availability, either semi-quantitative or qualitative evaluations were made (Appendix C). In individual cases, further aspects were added, which will be explained in the following evaluation of the individual storage types. The limited availability of product-specific data from publicly accessible information sources was a limiting selection criterion.

As a result of the selection process and taking into account the results of expert interviews, the following energy storage technologies were selected for further investigation.

Storage technologies selected for evaluation

(1) Lead-acid batteries, type VRLA[90] (chapter 2.1.4),

(2) LFP batteries (Lithium iron phosphate(LiFePO4) with graphite anode, Chapter 2.1.5) and

(3) Flywheel accumulators (High-speed flywheels, Chapter 2.1.1).

<u>Lithium-ion, redox flow and sodium high-temperature batteries</u>

Looking at all the technical characteristics and functional properties (Table 2, Appendix C), there are clear overall advantages for **lithium-ion batteries**. In the important criteria of efficiency (up to 98 %) and storage loss (0.1 % per day), the two lithium-ion batteries achieve the best results. The Lithium iron phosphate batteries and **redox flow batteries** have the longest service life of up to 20 years. In comparison, the redox flow batteries achieve the highest number of cycles of more than 10,000 cycles. With similar values, the **sodium high-temperature batteries** and the Lithium iron phosphate batteries (1,000 - 10,000 or <1,000 - 8,000 cycles). The lithium-nickel-manganese-cobalt oxide batteries, on the other hand are only 500 - 2,000 cycles. In terms of safety, there are risks above all with high-temperature sodium batteries and lithium-nickel-manganese-cobalt oxide batteries. In comparison, there are Lithium iron phosphate batteries are to be classified as harmless. In addition to lead-acid batteries, however, both lithium-ion batteries have a comparatively high distribution and market maturity as well as a high level of development.

[90] VRLA accumulator stands for "valve-regulated lead-acid battery", a low-maintenance design with pressure relief valve with gel-like electrolyte. A refill of distilled water is not necessary with this battery type.

Lithium-ion batteries (80 - 210 Wh/kg) and high-temperature sodium batteries (80 - 250 Wh/kg) have the highest energy density, whereby a clear disadvantage of the Lithium iron phosphate batteries compared to lithium-nickel-manganese-cobalt oxide batteries (80 - 120 Wh/kg compared to 180 - 210 Wh/kg, Table 2). In contrast to mobility applications, however, the specific energy density in the stationary area under consideration here is not so important.

Due to the longer service life compared to lithium-nickel-manganese-cobalt oxide batteries, the greater cycle stability and the better safety aspects, the lithium iron phosphate batteries were assessed as the most suitable among the batteries considered and selected as a technology alternative for comparison.

Lead-acid batteries

Lead-acid batteries were also chosen as the classic battery type. Of all industrial batteries, lead-acid batteries account for around 90 to 95 % of the batteries placed on the market each year. The clear advantages of lead-acid batteries lie in their market maturity and development status. The established battery type has been widely used in industrial applications for many years, whereas the "newer" technologies such as lithium-ion batteries have only recently entered the market. A further advantage of lead-acid batteries is their safety and the handling that has been established for years. The type of lead-acid battery (VRLA) under consideration here does not present a fire risk as is the case with high-temperature sodium batteries or lithium-ion batteries.

There are clear disadvantages in terms of technical features and functional properties. Especially with regard to efficiency, service life and cycle stability, lead-acid batteries have lower characteristic values than other battery types. Despite these disadvantages, lead-acid batteries have been established as the standard in industrial applications for decades. This is due, among other things, to their relatively lower acquisition costs,[91] the uncritical problem of resources (lead) and their largely recyclable nature. In accordance with Directive 2006/66/EC on batteries and accumulators and waste

[91] Cf. energy experts (2017).

batteries and accumulators, a large proportion of lead-acid batteries are expected to be recycled from industrial applications. The recycling efficiency for lead-acid batteries is around 95 %, depending on the recycler. In comparison, the recycling efficiency of lithium-ion batteries is lower, especially with regard to lithium. There are currently no established recycling processes for high-temperature sodium batteries and redox flow batteries.

Flywheels

As a technological alternative to electrochemical storage systems, **flywheels** are basically suitable for use in the application scenario considered here. The storage times in the minute range are sufficient to buffer short-term peak loads. This requires staggered loading and unloading management. In addition, flywheels have been used for years as a component of a modern uninterruptible power supply (UPS) for grid stabilisation in data centers. A comparison of the technical characteristics and functional properties shows that flywheels are characterised by similarly good characteristic values as the battery storage systems (Appendix C). Flywheels, for example, have an efficiency comparable to that of lithium-ion batteries of 80 - 95 % or a higher efficiency than the other remaining battery types (sodium high-temperature batteries: 70 - 90 %, redox flow batteries: 65 - 90 %). The calendar service life and cycle stability also recommend the use of flywheel technology. With regard to cycle stability, flywheels achieve the highest value with more than 1 million cycles, while the calendar service life of 15 to 20 years in the range of lithium iron phosphate batteries and the redox flow batteries (<20 years each). However, there are disadvantages, especially in comparison to the batteries, in terms of storage losses, since a high self-discharge occurs here due to friction losses. This greatly restricts the time between charging and discharging.

Supercaps

The **supercaps** show that their storage behaviour is not suitable for minimising peak loads in SMEs under the conditions defined in the application scenario (Chapter 2.3.3). Supercaps are suitable for charging and discharging cycles of up to one minute, but not for energy storage system beyond several minutes, as defined in this scenario. In addition, due to the high investment costs in industrial production, supercaps have so far only been used in demonstration projects.

In summary, the three selected energy storage system types are lead-acid battery, Lithium iron phosphate battery and flywheel accumulator are considered fundamentally suitable for providing the benefit defined in the functional unit. All three technologies can be configured by combining several cells in such a way that they can deliver the required power in the form of an energy storage system over the period of one hour defined in the application scenario. An electronic battery management system ensures[92] that charging and discharging processes are adapted to the actual load curve of the consumer (when peak loads occur). The corresponding scaling of the cell count is taken into account in the inventory of the reference flow for the respective energy storage system types (Chapter 3.4). Thus, an approximate comparability of the three energy storage systems is possible for the purpose of economic and ecological comparison. However, it should be noted that the concrete interpretation of the technical parameters of the respective storage types must be the subject of a case-by-case analysis. In practice, the cost-dependent quality differences of different products play a decisive role in the design of a peak load management system. These details could not be taken into account in this generic investigation.

3.4 Inventory of energy storage system facilities including the upstream and downstream life cycle phases

The energy storage systems examined in this study are abstract systems. This means that not concrete products are considered, but model energy storage systems. These were designed for the purpose of the study on the basis of available technical information. In addition to the actual storage systems, the electronic and electrotechnical auxiliary devices required to store electrical energy and make it available again when required are also taken into consideration. These include an electronic control device which regulates the loading and unloading of the storage system according to the load conditions

[92] The electrochemical energy storage systems consist of interconnected cells (= battery). This principle is also possible for high-speed flywheel accumulators, since a single flywheel can be considered equivalent to a battery cell.

in the company and the specified peak time window. In addition it requires with lithium iron phosphate batteries of an electronic battery management system (temperature control, voltage monitoring, charge management) at cell level. Furthermore, a multi-stage current transformer is required which converts the 400 V three-phase current of the low-voltage grid into direct current at the voltage level of the respective batteries (and vice versa). This also applies to flywheels. In addition, a cooling device is required to cool the energy storage system and the electrical engineering in order to dissipate the heat generated by efficiency losses.

Energy storage systems can only be integrated into existing production sites with the help of an overall system designed in this way. However, the selection and dimensioning of a suitable energy storage system technology and its additional electrical equipment is a complex engineering task and can only be carried out in a specific application context. For the purpose of this study, a highly simplified model system outlined in Figure 6 is used.

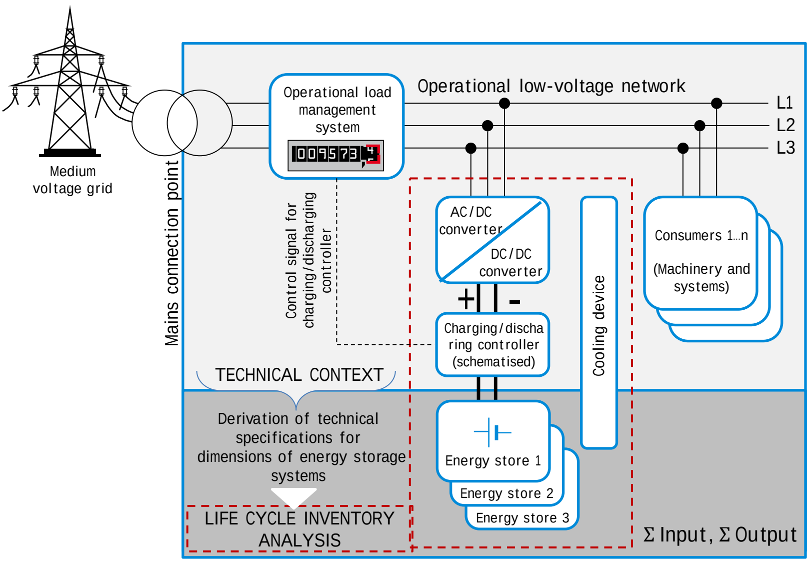


Figure 6: Technical framework of the considered energy storage system in SMEs

The model system comprises the essential components of the energy storage systems to be compared in the form of a Life Cycle Inventory (Figure 6: Area framed in red). The Life Cycle Inventory divides the energy storage systems into two areas: the actual energy stores 1 - 3, i.e. lead-acid batteries, lithium iron phosphate batteries and flywheel accumulators. For these components, the Life Cycle Inventory contains a quantitative description of the respective material inventory and the specific efficiencies on the basis of generic data from literature sources and expert statements (Figure 6: lower section). The electrotechnical components of the energy storage systems (current transformer, control and cooling) are dimensioned the same for all three energy storage systems to be compared in the Life Cycle Inventory, i.e. the quantitative description of this part of the Life Cycle Inventory (Figure 6: upper section) is identical for all three energy storage systems (ceteris paribus), because this part of the system is approximately independent of the energy storage system technology used. The one Lithium iron phosphate batteries additionally required charge management and cell protection system are regarded as an integral part of the individual cells.

3.4.1 Nominal capacity calculation of the Energy storage systems

The assumptions outlined in Figure 7 apply to the modelling of the electrical systems and the dimensioning of the storage systems. To determine the **nominal capacity**, the **basic capacity of** the battery cells must first be determined, which is based on the useful capacity and the efficiencies of the components. In order to achieve the required useful capacity of the energy storage system of 100 kWh, the (discharge-side) power losses of the current transformers and the power losses of the battery cells must be added to compensate for this energy dissipation.

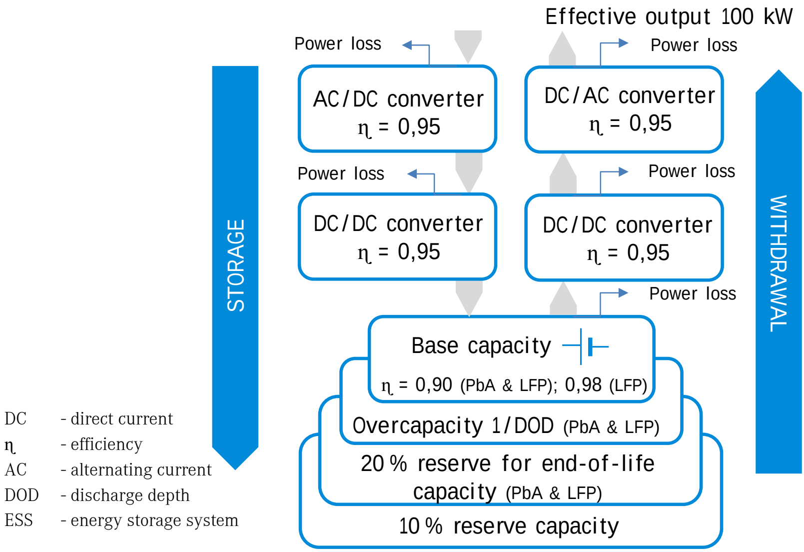


Figure 7: Assumptions on power losses and dimensioning of ESS with lead-acid batteries (PbA), lithium iron phosphate batteries (LFP) or flywheels (SR)

The basic capacity is calculated using the following formula:

$$Basic\ capacity = \frac{Useful\ capacity}{(\eta_{DC/AC} * \eta_{DC/DC} * \eta_{Energy\ storage\ systems})}$$

with η = efficiency, DC = direct current and AC = alternating current

In order to be able to safely maintain a useful capacity of 100 kWh at the end of the life cycle of the energy storage systems, the battery cells must be dimensioned beyond this basic capacity. The following assumptions apply:

(1) Overcapacity for a cell-friendly discharge depth (DOD): Batteries react sensitively to deep discharge conditions. A complete discharge leads to irreversible damage of the electrodes and shortens the service life of the batteries considerably. Therefore, in practice, the entire capacity of the batteries cannot be used and, depending on the type of battery, must be compensated by oversizing the basic capacity. This depends

on the discharge depth recommended by the manufacturer. This is not necessary for flywheels.

(2) Additional reserve due to capacity loss until the end of life: Batteries usually reach the end of their service life when the rated capacity has dropped to 80 % of the original capacity.[93] Below 80 % nominal capacity, the ageing of the electrodes accelerates and the battery becomes susceptible to sudden failure. Therefore, 20 % capacity will be added to the initially installed basic capacity. This is not necessary for flywheels.

(3) Additional reserve capacity of 10 % to ensure the required peak load reduction in the event of unfavourable performance of the energy storage system.

The following **nominal capacities** for the selected energy storage systems are calculated from the formula presented and the assumptions made.

Required useful capacity Energy storage system: 100 kWh

Lead-acid battery (PbA):

Basic capacity of the battery :	100 kWh * (1/(0.95*0.95*0.90))	= 123 kWh
Overcapacity (1/DOD):	123 kWh * (1/0.6)	= 205 kWh
+ Reserve on final capacity:	123 kWh * 0.2	= 25 kWh
+ Additional reserve:	123 kWh * 0.1	= 12 kWh

<u>Nominal capacity $_{PbA}$: 242 kWh</u>

Lithium iron phosphate batteries (LFP, LiFePO4 batteries):

Basic capacity of the battery:	100 kWh * (1/(0.95*0.95*0.98)	= 113 kWh
Overcapacity (1/DOD):	113 kWh * (1/0.8)	= 141 kWh
+ Reserve on final capacity:	113 kWh * 0.2	= 23 kWh
+ Additional reserve:	113 kWh * 0.1	= 11 kWh

<u>Nominal capacity $_{LFP}$: 175 kWh</u>

[93] Cf. Powerthru (2016), p. 3 for VRLA batteries and Zhanga et al. (2011) for lithium iron phosphate batteries.

Flywheel (SR):

Basic capacity of the SR:	100 kWh * (1/(0.95*0.95*0.90))	= 123 kWh
+ Additional reserve:	123 kWh * 0.1	= 12 kWh

Nominal capacity $_{SR}$: 135 kWh

In contrast to the electrochemical energy storage systems, no overcapacity is estimated for the flywheels because they have no critical discharge depth and no age-related degradation.

3.5 System boundary and quantification of the Life Cycle Inventory

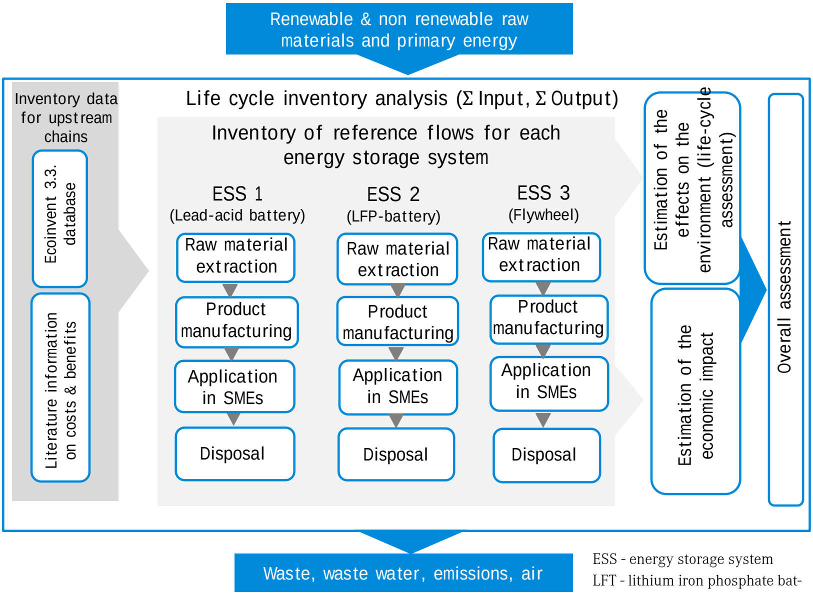
3.5.1 Determination of the system boundary

The analysis of ecological impacts is based on the life cycle concept and the evaluation of economic effects on the basis of life cycle costing (LCC). The methodology evaluates all relevant cost types (expressed in euro and related to the functional unit) associated with a given product and borne directly by one or more actors in the life cycle of the product.[94] Also costs beyond the pure investment costs, such as costs for operating materials, maintenance and disposal, are systematically recorded here. Thus, a direct comparison of different objects of investigation can determine which option is the most economical from an economic point of view and from the perspective of an SME wishing to use energy storage technologies. The methodological basis for conducting life cycle cost analyses for various applications is anchored in various international and national directives and guidelines.[95]

The impact on the environment is assessed using the methodological concept of Life Cycle Evaluation (LCA). Life cycle evaluations assume that each product or product system goes through several stages in its life cycle which differ in terms of their environmental impact. The product life cycle can be divided into four phases: the extraction and processing of raw materials, the manufacture of the finished product, followed by transport and the actual

[94] Cf. Hunkeler, et al. (2008), p. 154.
[95] Cf. e.g. DIN EN ISO 15663-2:2001.

utilisation phase in which a product fulfils its intended use, and disposal as waste (Figure 8).



ESS - energy storage system
LFT - lithium iron phosphate battery

Figure 8: Boundary of the study

A comparative life cycle evaluation helps, in particular, to identify several products or to compare functional alternatives with regard to their environmental impacts and to compare their respective advantages and disadvantages. This can uncover any conflicts of objectives and problem shifts that may arise when decisions are made. Such a shift of environmental problems can occur both between the individual phases of life (such as shifting environmental impacts from the manufacturing to the application phase) and between different environmental aspects or media (e.g. greenhouse gas emissions versus resource use).

This study uses an orienting life cycle evaluation that does not consider all impact categories typically considered in LCA studies. In particular, the characteristic values "cumulative energy demand" (CED)[96], "cumulative raw

[96] Cf. VDI 4600:2012-01.

material consumption“ (CRD)[97], supply criticality, land use corresponding to the environmental impacts are determined. These input-based indicators are also based on the life cycle approach and allow an ecological evaluation of products on the basis of their technically measurable influencing variables. Recycling credits are not taken into account because the underlying methodological basis for the life cycle evaluation according to VDI Directives VDI 4600 and VDI 4800 Sheet 1[98]does not provide for credits for resource-saving effects through recycling. Instead, market shares of recycled materials (mainly metals) are included in the raw material input of the manufacturing phase. This will enable a reliable evaluation of resource efficiency, which is considered to be particularly relevant to the SME target group. In addition, key figures for relevant environmental impacts (greenhouse gas potential, water consumption) are determined.

3.5.2 Ecological evaluation: Quantification of the Life Cycle Inventory

In preparation for the life cycle evaluation, inventory information on the selected energy storage technologies was compiled. A review of the data records recorded in the commercial databases “ecoinvent V3.3“ and “GaBi“ as well as the free databases “PROBAS“ revealed numerous data gaps on various components of the respective energy storage systems. These data gaps were closed by a literature search.

For lead-acid batteries, a composition was found in the literature[99] which corresponds to the VRLA type and is very current. However, inventory data for the production of lead (II, IV) oxide were missing. These were also found in the literature[100]. In addition, a battery management system was added to ensure control during charging and discharging. The corresponding data were taken from the literature on lithium-ion[101] batteries. For lead-acid batteries, less complex charging management electronics are estimated.

[97] Cf. VDI 4800 sheet 2 (draft 2016).
[98] Cf. VDI 4800 Sheet 1 (2016), p. 15.
[99] Cf. Sullivan, J. L. and Gaines, L. (2012), p. 137.
[100] Cf. Sullivan, D. et al. (1980).
[101] Cf. Majeau-Bettez, G. et al. (2011), p. 14.

For the lithium-iron phosphate battery, the first step was to refer to a current review article on lithium-ion[102] batteries. Here it was worked out which publications are based on which inventory data. Three sources[103] with relevant data on lithium iron phosphate batteries were identified. These were investigated and only one source[104] had the necessary level of detail to model the battery.

For the flywheel accumulators primary data of Rosseta Technik GmbH i.L. were used for modelling.[105] Literature data were used to model the necessary carbon fibre-reinforced plastic[106].

The modelling of the necessary infrastructure (switch cabinets with current transformers incl. transformers) is based on expert estimates by EAM Elektroanlagenbau Mannheim GmbH. The values sketched in Figure 7 apply to the modelling of the electrical systems and the dimensioning of the storage systems.

3.5.3 Economic evaluation: Quantification of the Life Cycle Inventory

The economic evaluation considers an operating period of the energy storage systems of 20 years each in order to bring the systems with different service lives to a comparable level. In all cost-benefit analyses, the challenge is that costs and benefits are spread over the period under consideration.

In the analysis carried out here, investment costs are incurred repeatedly at different points in time, depending on the service life. In addition, the relevant operational expenditures must be quantified and considered. However, the statements to be derived from this should be related to a certain point in time. The Federal Environment Agency states that this is the case:

"The timing of the realisation of the costs and benefits (or returns) of today's decisions plays a major role in economic analyses. In business analyses,

[102] Cf. Peters, J. F. et al. (2017).
[103] Cf. Zackrisson, M. et al. (2010); Majeau-Bettez, G. et al. (2011) and Amarakoon, S. et al. (2013).
[104] Cf. Majeau-Bettez, G. et al. (2011).
[105] Cf. telephone conversation Dr. Frank Täubner, Rosseta Technik GmbH i. L. (Appendix A).
[106] Cf. Suzuki, T. and Takahashi, J. (2005), p. 16 and Warren, C. D. (2016), p. 10.

future costs and returns are discounted to the present time with a market interest rate (or a calculation interest rate), because the market interest rate represents the opportunity costs of capital for the investors."[107]

Discounting is a method that allows future costs (and benefits) to be converted to a net present value (NPV). In this case, the determination of the interest rate for conversion has a significant effect on the results due to the very long observation period.

"In the *case of macroeconomic evaluations, all experts agree that a discount rate lower than the market rate must be applied. As a rule, the real capital market interest rate is used for low-risk bonds. This capital market interest rate can be used for short to medium-term periods - approximately up to 20 years. Looking back, it can be seen that the real market interest rate - apart from short-term fluctuations - has levelled off again and again at 2.5 percent to 3 percent over the past 150 years. [...] A discount rate of 3 percent can be expected for short-term periods (up to approx. 20 years)."*[108]

To determine the total costs, all future costs and profits are converted on the basis of the net present value. To determine the net present value (NPV), all costs that are not due until the future are discounted. Discounting is calculated on the basis of an interest rate of 3 %. The base year[109] is 2016. For cost data on energy storage systems dating from the years 1992 - 2017, the value of 2016 was converted on the basis of data from the consumer index.

3.5.3.1 Selection of cost items

The focus of the economic evaluation is on small or medium-sized enterprises with low-voltage electricity connections, as specified in Table 11. Investment costs, operational expenditures and cost savings as well as revenues from the disposal of energy storage systems are considered over a period of 20 years. In the case of the lead-acid battery, a service life of eight years means that several new purchases and disposals will be required over a period of 20 years. The other two energy storage systems have a service

[107] UBA (2012), p. 33.
[108] UBA (2012). p. 33.
[109] This corresponds to the convention used by UBA to accept the interest rate.

life of 20 years and are procured and disposed of only once. It can be assumed that the service life of the flywheel can be extended to well over 20 years through maintenance.

The following items in the cost-benefit balance are taken into account:

- Investment costs and recurring procurement of the energy storage system and its additional equipment (current transformer, cooling),
- Operational expenditures: Maintenance costs for energy storage system and auxiliary equipment,
- Operational expenditures: Cost of the power consumption caused by the power dissipation of the energy storage systems,
- Operational expenditures: Electricity costs of the additional equipment necessary for normal operation of the energy storage systems (current transformers, cooling), also taking into account energy costs incurred by the typical standby consumption of the current transformers and the required cooling of the energy storage systems and the current transformers,
- Rental costs for the accommodation of the energy storage systems in the company corresponding to an estimated space requirement,
- Disposal costs (collection and waste treatment) by an expert disposal companyand
- Cost savings: Grid charge reductions, corresponding savings through reduced peak loads (= avoided costs).

The costs are shown in the balance sheet at realistic average values. The cost estimates were based on publicly available data and on our own estimates. The assumed purchase prices for the individual energy storage systems are based on data from a market overview of energy storage systems and represent the status as of 2017. In[110] addition, selected experts were surveyed to close data gaps and verify assumptions made.

Investment cost

The investment costs consist of the costs for the energy storage systems themselves (battery cells or flywheel modules) as well as the costs for additional equipment required for operation (current transformer, cooling system).

The purchase prices of the battery systems or the flywheel accumulator systems depend on the required number of battery cells or flywheel modules. The required useful capacity of the energy storage system was defined on the basis of the power of the energy storage system (100 kW) defined in the application scenario and the duration of the peak loads to be bridged (totalled one hour per working day). The energy storage system shall provide 100 kWh of electrical energy. In addition, the specific power losses of all system components must be taken into account. This increases the required nominal capacity of the actual energy storage systems. In addition, oversizing of energy storage systems is taken into account in order to ensure the provision of useful capacity until the end of their service life (Chapter 3.4.1).

For the **lead-acid battery**, the required useful capacity is 160 kWh (Chapter 3.4.1), the nominal capacity of the battery to be provided for this is 242 kWh. The energy storage system consists of 14 individual cells with a useful capacity of 11.88 kWh each.[111] This results in a total capacity of 166.32 kWh. The price of a single lead-acid cell in the complete system is stated as € 13,500. The investment costs per battery system are thus € 189,000. The service life of the battery cells is calculated from the number of charging cycles and reaches eight years at 250 working days per year (assumption: one charging cycle per working day). As a result, 2.5 new lead-acid batteries will have to be purchased over the period under consideration (20 years)

[110] Cf. C.A.R.M.E.N. e.V. (2017).

[111] The data basis on which the calculations are based, C.A.R.M.E.N. e.V. (2017), records the useful capacity of the batteries, including the permissible discharge depth (factor 1/DOD).

(only one-off investment costs for current transformer and refrigerating plant).

The **lithium iron phosphate battery** requires a useful capacity of 147 kWh (see 3.4.1) and has a nominal capacity of 175 kWh. Four lithium iron phosphate cell modules with a useful capacity of 40 kWh each (160 kWh in total) are selected to provide these. On the basis of the technically achievable number of charging cycles, a service life of 20 years can be expected. Since the market prices for individual lithium iron phosphate cells as a complete system are given as € 50,500 or € 55,000, the mean value was calculated. The one-off investment costs for the entire system amount to € 222,500. It is not necessary to repeat the investment during this period.

For the market prices of **flywheel accumulators** there are very different data in the literature (218 - 20,000 €/kWh). This enormous price range reflects the very different technical concepts and performance characteristics of existing flywheel technologies. Verifiable investment costs for the flywheel energy storage system required here were determined on the basis of expert data. Flywheel modules with a nominal capacity of 4 kWh each and a service life of 20 years[112] are considered. The unit price of a complete flywheel system (including current transformer) is € 80,000. An energy storage system with 34 flywheel modules is required to realise the 100 kWh capacity required in the application scenario. The flywheel modules are operated in parallel and can be accommodated in containers, for example, as is the case in commercially available energy storage systems for uninterruptible power supply for industrial plants and computer centres. The one-off investment costs for the entire system will then amount to € 2,740,413. A new investment is not necessary in the period under consideration of 20 years.

According to experts, the investment costs for a suitable refrigerating plant amount to € 2,500. With regard to the service life of such equipment, a new purchase within the period under consideration shall not be counted.

[112] Cf. telephone conversation Dr. Täubner, Rosseta Technik GmbH i. L. (Appendix A).

Operational expenditures

The energy storage systems and their ancillary equipment are installed inside a company and can be stacked on shelves. For the battery-based energy storage systems, a space requirement of 5 m^2 is expected, for the flywheel storage system 25 m^2 is assumed. The rental costs required for this are taken into account, even if these areas are already available at the company's location (possible additions are not taken into account). The average monthly rent for commercial space is estimated at 5 €/m^2.

The operation of the refrigerating plant generates energy consumption in full load operation as well as in the standby times of the energy storage systems. The following operating times per working day are assumed:

- 2 hours full load operation during charging,
- 1 hour full load operation during unloading and
- 21 hours standby operation.

Based on an output of 0.5 kW, the annual consumption is 750 kWh for full operation and 525 kWh for standby operation. This consumption is calculated on the basis of the average 2016 electricity prices for industry, which are 13.5 ct/kWh (excluding electricity tax).[113]

Additional energy costs result from the efficiency-related power loss of the energy storage systems and current transformers. The costs were calculated on the basis of average electricity prices in 2016 for industry. For the lead-acid storage system and the flywheel storage system, an efficiency of 90 % each is assumed. The annual power loss is thus 26.7 kWh. Lithium iron phosphate batteries with an efficiency of 98 % generate a power loss of 20.2 kWh per year. It can be assumed that the maintenance costs for all three energy storage systems are relatively low. Lithium iron phosphate and flywheel storage systems require very little maintenance. Lead-acid batteries of the VRLA type are also referred to as low-maintenance. Also the refilling of deionized

[113] Cf. BDEW (2016), p. 23.

water is not necessary with this type.[114] The maintenance costs for all systems are therefore estimated at a flat rate of 20 € per month.

Disposal costs

Depending on the service life of the individual energy storage system components, spare parts (e.g. battery cells) are procured periodically. For electrochemical storage systems, the end of service life is usually reached when the charging capacity has fallen below 80 % of the initial value. The old energy storage systems would then have to be disposed of. The statutory provisions of the Battery Act (BattG) apply to the disposal of used batteries.

Cost modelling is based on the assumption that the users of energy storage systems hand over the spent batteries to a specialist waste management company that is certified for further treatment ("commercial spent battery disposer" pursuant to Section 2 (17) BattG). The flywheel systems, on the other hand, can be disposed of as normal scrap metal (mainly stainless steel and copper). Market prices for secondary raw materials apply to spent batteries and scrap metal. These are remunerated. For the purpose of cost modelling, the mean value of the remuneration for lead-acid and lithium-ion batteries was calculated on the basis of several waste management data. The range of remuneration for spent lead-acid batteries is between € 200 and € 650 per tonne[115], the average being € 442.44 per tonne. The remuneration for lithium-ion batteries is between € 160.74 and € 2009.29 per tonne.[116] However, there is currently no relevant demand for lithium iron phosphate batteries for recycling. Therefore, a minimum value of 160 € per tonne is assumed. For the flywheel, a remuneration of € 120.56 per ton of mixed scrap metal (collection price) was applied.[117] For the used batteries, a transport surcharge of 500 € was added for collection from the factory premises.

[114] Cf. Ausfelder et al. (2015), p. 57.
[115] Cf Rockaway Recycling (2017a) and Recycling Magazine (2017), p. 37.
[116] Cf Rockaway Recycling (2017b).
[117] Cf Rockaway Recycling (2017b).

Cost savings through reduction of grid charges

Cost savings result from two different ways of reducing grid charges (Chapter 3.1). The cost savings are treated as savings in the comparative economic calculation and are considered equally for all energy storage systems.

Option 1 is the so-called atypical grid use (reduction of peak loads during peak load windows). The calculation is based on a minimum value for the grid charge reduction in the amount of the legally stipulated minor limit of € 500 per year.

Option 2 is the absolute reduction of the specific maximum annual load in the sense of the Electricity Grid Access Ordinance (StromNZV).

Table 12 shows the work and performance prices for power-measured customers as a function of the voltage level of two exemplary network operators. If the peak load were reduced by 100 kW, a cost reduction of between € 320 and € 9,864 per year would be possible, depending on the voltage levels and grid area.

Table 12: Overview of the work and performance price as a function of the voltage level[118]

	Performance price [€/kWh]		Work price [ct./kWh]	
	<2500 h/a	>2500 h/a	<2500 h/a	>2500 h/a
High voltage	7.76 - 21.72	65.17 - 54.72	2.43 - 2.35	0.13 - 1.02
Medium voltage	10.52 - 45.60	83.77 - 72.60	3.58 - 3.72	0.65 - 2.64
Low voltage	11.12 - 49.08	49.87 - 98.64	4.12 - 6.46	2.57 - 4.48

For the low-voltage level considered here, a cost reduction in the power price achievable for SMEs by minimising the peak load by 100 kW to an assumed € 30 per kW and year amounts to. This results in a cost savings potential of € 3,000 per year.

[118] Cf. e.dis (2017), p. 1 and Westnetz (2017a), p. 1.

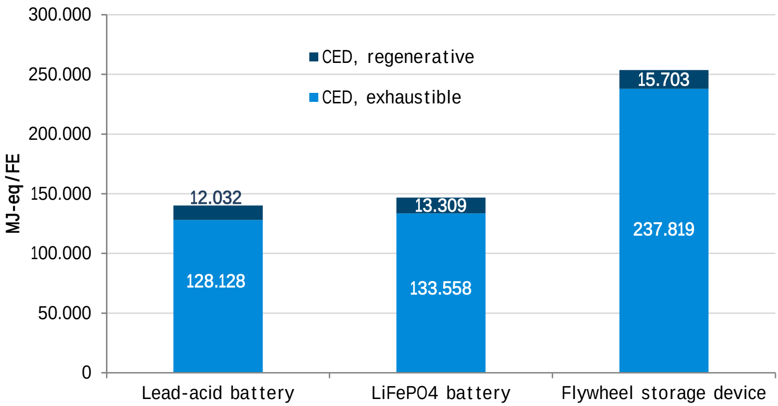
4 RESULTS OF THE ECOLOGICAL AND ECONOMIC EVALUATION

4.1 Results of the ecological evaluation

4.1.1 Cumulative energy demand

For the consideration of the cumulated energy input the methodology from the VDI Directive 4600 “Cumulated energy demand (CED); terms, calculation methods“[119] is used.

For reasons of clarity, only the two categories “CED, renewable“ and “CED, exhaustible“ are presented. Figure 9 shows the summed results of the manufacturing, utilisation and disposal phases of the energy storage systems considered for the CED.



LiFePO4 - Lithium Iron Phosphate Battery

Figure 9: Accumulated energy expenditure per functional unit

The results show that the flywheel accumulator with almost 254,000 MJ (about 71,000 kWh) has the highest energy consumption of the three technologies. The lithium-iron phosphate battery and the lead-acid battery, with requirements of around 147,000 MJ and 140,000 MJ respectively, are significantly lower.

[119] Cf. VDI 4600:2012-01.

In the case of the flywheel accumulator, production accounts for 63 % of the CED. A further 35 % is generated in the utilisation phase by the power losses during storage and retrieval of the electricity and by efficiency losses during electrochemical energy conversion in the battery itself.

In the case of the lithium iron phosphate battery, the proportions of CED in the manufacturing phase are about the same as in the utilisation phase.

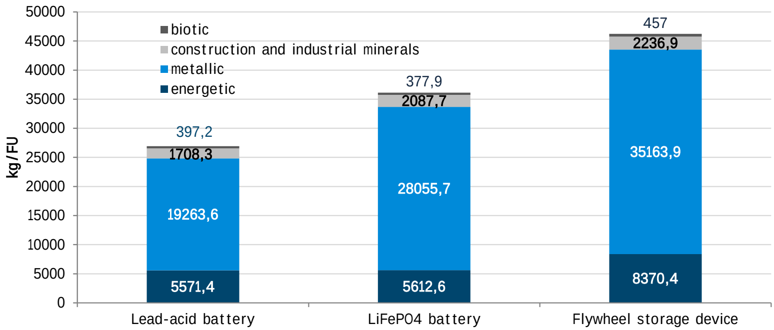
With the lead-acid battery, 65 % of the effort is caused by efficiency losses. The production of the system (including the switch cabinet) accounts for 32 % of the expenditure.

4.1.2 Accumulated raw material costs

The methodology from VDI Directive 4800 Part 2 “Resource Efficiency - Evaluation of Raw Material Expenditure“[120] is used to consider the cumulative raw material expenditure. According to this standard, the results are presented in the unit megagram (Mg) (= metric ton).

The Directive distinguishes between four different types of cumulative raw material input: energetic, metallic, building and industrial minerals and biotic. The cumulative results of the manufacturing, utilisation and disposal phases of the energy storage systems under consideration for the cumulative raw material expenditure are shown in Figure 10.

[120] Cf. VDI 4800 sheet 2 (draft 2016).



LiFePO4 - Lithium Iron Phosphate Battery

Figure 10: Accumulated raw material costs per functional unit

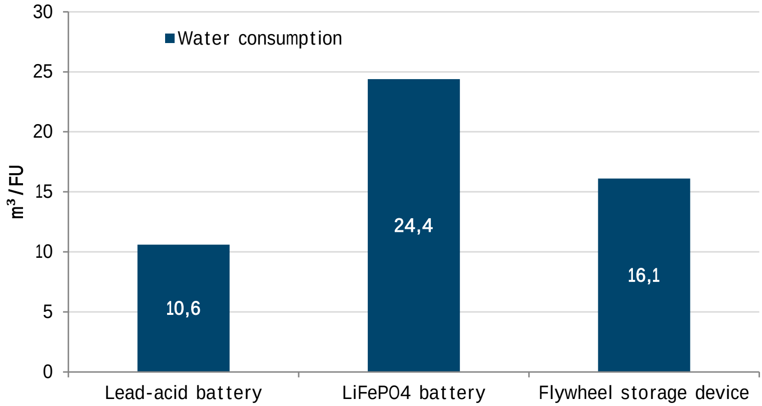
The flywheel accumulator also requires the highest raw material input in terms of cumulative raw material input, at just under 46 Mg/FE (8.4 Mg energetic, 35.2 Mg metallic, 2.2 Mg construction and industrial minerals and 0.5 Mg biotic). The expenditure of the lithium iron phosphate battery is 10 Mg lower with 36 Mg/FE (5.6 Mg energetic, 28.1 Mg metallic, 2.1 Mg building and industrial minerals and 0.4 Mg biotic). The requirement of the lead-acid battery is 9 Mg below the lithium-iron phosphate battery with just under 27 Mg/FE (5.6 Mg energetic, 19.2 Mg metallic, 1.7 Mg construction and industrial minerals and 0.4 Mg biotic). The production of the flywheel accumulator requires almost 88 % of the total raw material requirement, while the utilisation phase, i.e. the efficiency losses, consumes only 11 % of the raw material input.

In the case of the lithium iron phosphate battery, the distribution over the various phases is similar to that of the flywheel accumulator: Production requires 88 % of the raw material input and the utilisation phase 11 %.

In the case of the lead-acid battery, only just under 80 % of the raw material input is consumed in the manufacturing phase. The utilisation phase accounts for 19 % of total raw material expenditures.

4.1.3 Water consumption

The current evaluation method ILCD 2011, midpoint (v1.0.10, August 2016) is also used to assess water consumption for openLCA[121]. The total water consumption for the production, use and disposal of the energy storage systems under consideration is shown in Figure 11.



LiFePO4 - Lithium Iron Phosphate Battery

Figure 11: Water consumption per functional unit

With all three energy storage systems, no water is consumed in the energy storage itself during the utilisation phase. The water consumption figures presented here relate primarily to the manufacturing phase of the energy storage systems and to energy generation processes. Water is required for various processes of raw material extraction and material processing. In contrast to greenhouse gas emissions, the lithium iron phosphate battery has the highest water consumption of the three technologies at around 24 m^3. Around 16 m^3 are required for the flywheel accumulator and almost 11 m^3 for the lead-acid battery.

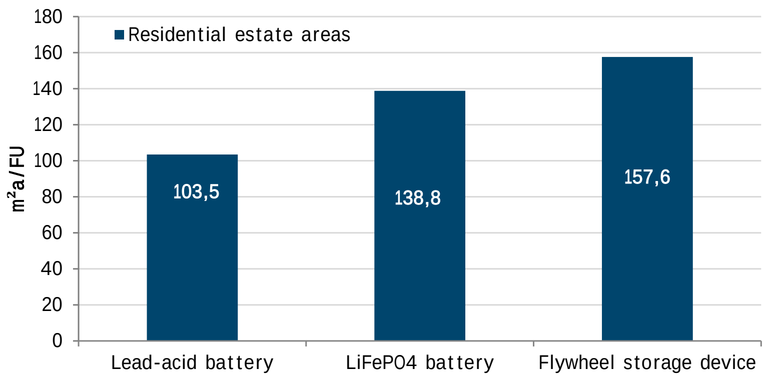
The water consumption of the flywheel accumulator is distributed as follows: 62 % for production, 35 % for the utilisation phase and 3 % for disposal. For the lithium iron phosphate battery, 79 % is needed for production, 19 % for the utilisation phase and 2 % for disposal. In the case of the lead-acid battery,

[121] Cf. openLCA (2015).

just under 55% of the demand is for the utilisation phase and only 37 % for production. Disposal requires almost 8 % of the total water consumption.

4.1.4 Land use

The ReCiPe Midpoint (H) V 1.11 December 2014[122]evaluation method for openLCA[123] is used to consider the area required to provide the raw materials. Here the category “urban land occupation“ is used for quantification. The space required by the company's energy storage systems is not included in this analysis. This space requirement is estimated to be relatively small (Chapter 3.5.3.1), as the energy storage systems are stackable and can be integrated into existing premises. The total area taken up for the production, use and disposal of the energy storage systems under consideration is shown in Figure 12.



LiFePO4 - Lithium Iron Phosphate Battery

Figure 12: Use of space per functional unit

At just under 158 m² per year, the use of urban soil is highest for the flywheel accumulator. In the case of the lithium iron phosphate battery, it is around 19 m² less per year at around 139 m². The lead-acid battery shows the lowest effects in this category with almost 104 m² per year.

[122] Cf. ReCiPe (2014).
[123] Cf. openLCA (2015).

With the flywheel accumulator, production requires the largest proportion of the surface area (approx. 75 %). The utilisation phase accounts for 22 % of the land requirements and the disposal for the remaining 3 %. The use of land for the production of energy storage systems results from the extraction of raw materials and the necessary mining facilities for ore extraction and processing. The land requirement in the utilisation phase results, among other things, from electricity generation (use of fossil and renewable energy sources and power plants). In the case of waste disposal, the space required is attributable to the waste treatment facilities.

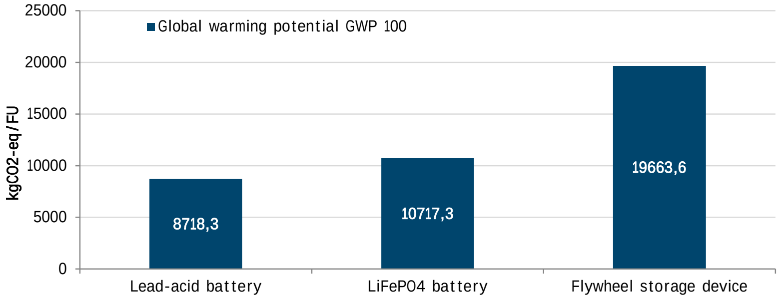
For the lithium iron phosphate battery, 85 % of the total area is required for production, while 13 % of the total area is required in the utilisation phase and 2 % in the disposal phase.

For the lead-acid battery, 77 % of the total area is required for production. In the utilisation phase, 14 % of the total area is used, while almost 3 % of the total area is occupied in the disposal phase.

4.1.5 Global warming potential

For the evaluation of the greenhouse gas potential, the current evaluation method ILCD 2011, midpoint (v1.0.10, August 2016) for openLCA[124], which uses the current IPCC values to convert all relevant emissions into CO_2 equivalents. The total greenhouse gas potentials for the production, use and disposal of the energy storage systems under consideration are shown in Figure 13.

[124]Cf. openLCA (2015).



LiFePO4 - Lithium Iron Phosphate Battery

Figure 13: Greenhouse gas potentials per functional unit

The flywheel accumulator with 19,700 kg CO_2 equivalents has the highest greenhouse gas potential. The production, use and disposal of the lithium iron phosphate battery result in a total of 10,700 kg CO_2 equivalents. The lead-acid battery converts 8,700 kg CO_2 equivalents over the entire life cycle.

The manufacture of the lead-acid battery accounts for 33 % of greenhouse gas emissions. Almost 64 % of emissions result from efficiency losses in the utilisation phase and less than 3 % of total emissions are generated during disposal.

The lithium iron phosphate battery produces the largest share of emissions (57 %) during production. 41 % of greenhouse gas emissions are generated by efficiency losses in the utilisation phase and only 2 % of total emissions are generated by disposal.

The production of the flywheel accumulator causes almost 49 % of the emissions, the utilisation phase approx. 28 % and the disposal approx. 22 % of the total emissions.

4.2 Raw material criticality

For the evaluation of the criticality of the raw materials used, the methodology from VDI Directive 4800 Part 2 “Resource Efficiency - Evaluation of Raw

Material Expenditure“[125] is used. The Directive is based on a system of 13 indicators divided into three groups. Table 13 shows the indicators.

Table 13: Indicators of the VDI Directive 4800 Part 2

Geological, technical and structural indicators	Geopolitical and regulatory indicators	Economic indicators
Ratio of reserves to global annual production	Herfindahl-Hirschman index of reserves	Herfindahl-Hirschman index of companies
Degree of coupled production/ Auxiliary production	Herfindahl-Hirschman Index of Country Production	Degree of increase in demand
Degree of penetration of functional EoL recycling technologies	Political country risk	Technical feasibility and economic efficiency of substitutions in main applications
Efficiency of storage and transport	Regulatory country risk	Annualised price volatility
Distribution rate of natural occurrences/growing areas		

Each commodity receives a rating for each indicator, with the rating scale ranging from 0 to 1 and intermediate steps 0.3 and 0.7. An evaluation of individual raw materials is carried out using a number. The individual indicator values are sorted according to size. Weighting factors G_i are calculated according to the following formula

$$G_i = \frac{2^{(i-1)}}{3^i}$$

is calculated. These are multiplied with the indicator values and according to the following formula

$$K_j = \frac{1}{\sum_{i-1}^{j} G_i}$$

is added to an overall criticality. VDI 4800 contains evaluations for many of the raw materials to be considered based on calculations, estimates and expert opinions. The complete table is listed in the Directive. However, gold is not listed. This missing value was compensated by a conclusion by analogy.

[125] Cf. VDI 4800 sheet 2 (draft 2016).

For gold, the data for silver were used, as this is very close to gold in terms of production structure, scarcity and geopolitical distribution.

The metals relevant for the energy storage systems and their aggregated criticality values are shown in Table 14.

Table 14: Aggregated and rounded criticality values

Metal	Criticality value		Application in storage technology
	Aggregated	Rounded	
Aluminium	0.71	0.7	All
Iron	0.72	0.7	All
Copper	0.72	0.7	All
Nickel	0.79	0.7	Flywheel accumulator
Silver	0.81	0.7	All
Gold (Silver)	0.81	0.7	All
Lithium	0.87	1	Lithium iron phosphate battery
Tin	0.89	1	All
Antimony	0.90	1	Lead-acid battery
Neodymium	0.90	1	Flywheel accumulator
Chrome	0.92	1	Flywheel accumulator

For the metals chromium, neodymium and antimony the criticality value 1 results, i.e. a very high supply risk. They are mainly found in the flywheel and in the lead-acid battery. Lithium in the lithium iron phosphate storage system and tin as a component of all energy storage systems are classified with an equally high criticality value.

For the other metals, a rounded criticality value of 0.7 is calculated. Metals (except nickel) can be found in all technologies because they are processed in the electrical components.

An examination of the metals used in the energy storage systems leads to the conclusion that securing their supply for the manufacture of the energy storage systems is currently associated with a medium to high risk.

4.3 Results of the economic evaluation

4.3.1 Investment cost

The user's investment costs strongly depend on the typical technology-specific service life of the respective energy storage systems. A total of 35 battery cells are required for the lead-acid batteries within the 20 year period under consideration, because the cells have to be replaced 2.5 times.[126] This results in investment costs of € 397,088 for lead-acid batteries over the entire period.

The investment costs for the lithium iron phosphate batteries and the 34 flywheel accumulator modules - both technologies have a service life of 20 years - amount to € 210,000 and € 2,720,000 respectively. In addition, for the lead-acid energy storage system and the lithium-iron phosphate storage system, one-off investment costs of € 10,000 are assumed for the current transformer (for the flywheel energy storage system, the current transformer is part of the modules). The investment costs for the cooling system are the same for all energy storage systems and amount to € 2,500 (based on 2016). Further details can be found in Table 15.

Table 15: Investment costs for storage system cells

Energy storage systems and components	Total Cells/ Module	Price per cell/module	Costs per procurement	Costs over the entire period*
	Piece	€/piece	€	€
Lead-acid battery	14	€ 13,500	€ 189,000	€ 397,088
Lithium iron phosphate battery	4	€ 52,500	€ 210,000	€ 210,000
Flywheel	34	€ 80,000	€ 2,720,000	€ 2,720,000
Current transformers (for lead-acid & lithium-iron phosphate storage systems)	1	€ 10,000	€ 10,000	€ 10,000
Refrigerating plant	1	€ 2,500	€ 2,500	€ 2,500

* discounted net present value

4.3.2 Operational expenditures

The operational expenditures and savings from the reduction in grid charges shown in Table 16 are calculated for the entire period under review and discounted to one year. The costs for rent, air conditioning and maintenance are the same for all three technologies due to the underlying assumptions. The same applies to the saved grid charge, because the function (minimisation of peak loads) is considered to be the same for all three energy storage systems.

[126] Only half of the last investment cycle is included in the cost accounting (allocation), because these 14 cells can still be used for another four years.

The cost savings from the reduced grid charge and the operational expenditures for all three energy storage systems add up to € 44,632 over the period under review. The additional energy costs resulting from the different power losses of the respective energy storage systems are deducted from this cost saving. For the lead-acid system and flywheel storage system, the discounted energy costs over the entire period amount to € 13,406. For lithium iron phosphate batteries it is 10,143 €.

In total, the following economic savings potentials result over the entire operating period: € 20,706 for the lead-acid storage system and € 23,970 for the lithium-iron phosphate energy storage system. Due to the higher costs for the space required, the savings potential for the flywheel storage system is only € 2,853. Under the given application scenario, it is therefore possible to achieve cost savings in all three variants during the utilisation phase, since the savings from the reduction in grid charges exceed the operational expenditures.

Table 16: Savings and operational expenditures

Position	Cost factors	Costs per element	Annual costs	Total period
	Element	€/Element	€/Year	€
Savings				
Grid charge reduction (1)	Year	€-500 /year	€-500	€-7,439
Grid charge reduction (2)	kW	€-30 /kW per year	€-3,000	€ -44,632
Operational expenditures				
Rent (PbA & LFP)	5 m^2	5 €/m2	€ 300	€ 4,463
Rent (Flywheel)	25 m^2	5 €/m2	€ 1,500	€ 22,316
Air conditioning (full operation)	750 kWh/a	0.135 €/kWh	100 €	Total: € 2,530
Air conditioning (standby)	525 kWh/a	0.135 €/kWh	€ 700	
Maintenance	12 months	20 €/month	€ 237	€ 3,527
Costs due to power loss of the respective energy storage systems				
Lead-Acid-ESS	26.7 kWh	0.135 €/kWh	€ 901.13	€ 13,406
LFP-ESS	20.2 kWh	0.135 €/kWh	€ 681.75	€ 10,143
Flywheel-ESS	26.7 kWh	0.135 €/kWh	€ 901.13	€ 13,406
Total per energy storage system				
Lead-Acid-ESS				**-20,706**
LFP-ESS				**-23,970**
Flywheel-ESS				**-2,853**

ESS - Energy Storage System; PbA - Lead Acid ESS; LFP - Lithium Iron Phosphate ESS

4.3.3 Disposal costs

The disposal costs for the cells and components of the energy storage systems relate to their weight. At the end of the life cycle, the energy storage systems are disposed of as scrap metal, whereupon there is a market-related remuneration less transport costs. Each of the energy storage systems contains different metals that can be sold by the disposers as secondary materials. It is therefore assumed that the disposal of energy storage systems can generate revenue from scrap metal, which varies depending on the metal and the current scrap price (this revenue is shown as a minus value in the invoice as it is deducted from the costs).

The assumed scrap prices are for 2017 and are considered representative of the current world market. However, scrap prices may rise or fall by the time the energy storage systems are disposed of. For lead-acid batteries, the invoice amounts to a remuneration of € 3,935. The revenue for lithium iron phosphate batteries is € 324 and € 1,838 for the flywheel storage system, which is mainly made of steel. For lead-acid batteries and lithium-iron phosphate batteries, collection costs must be added (€ 845 for lead-acid batteries and € 269 for lithium-iron phosphate batteries). For the flywheel storage system, the collection costs are already included in the remuneration.

Table 17: Disposal costs of energy storage systems

Element	Cost factors	Remuneration	Revenue per disposal	Discounted proceeds over Whole period
	Units	€/unit	€/disposal	€
Collection costs				
Collection	Transport	500 €/collection	500 €	Lead acid: € 845 LFP: € 269
Income from scrap metal				
Lead-Acid-ESS	5.33 t/system	-442.44 €/t	€ -2,329	€ -3,935
LFP-ESS	3.68 t/system	-160.74 €/t	€ -584	€ -324
Flywheel-ESS	27.5 t/system	-120.56 €/t	€ -3,320	€ -1,838

ESS - energy storage system; LFP - lithium iron phosphate ESS

4.3.4 Total costs from the point of view of the ESS user

Table 18 shows the total costs for all the energy storage systems under consideration over a period of 20 years, broken down by cost item. In addition, for each energy storage system, the amount of the monthly reduction in grid charges is indicated in order to offset the total costs in the period under consideration (break even). For this, the reduction in the grid charge would have to be at least € 283 for the lead-acid storage system and € 157 for the lithium-iron phosphate storage system. The flywheel storage system would require a reduction in monthly grid charges of € 1,889 due to the high investment costs and higher space requirements.

Table 18: Comparison of total cost accounting over a period of 20 years

Element	Costs	Total costs*
	€	€
Lead-acid storage system		
Investment cost (incl. current transformer & refrigerating plant)	€ 409,588	
Operational expenditures	€ 23,926	
Cost savings grid charge (2)	€ -44,632	
Disposal costs	€ -3,091	
		€ 385,791
Break-even grid charge reduction	-283 €/kW per year	
Lithium iron phosphate storage system		
Investment cost (incl. current transformer & refrigerating plant)	€ 222,500	
Operational expenditures	€20,663	
Cost savings grid charge (2)	€ -44,632	
Disposal costs	€ -55	
		€ 198,475
Break-even grid charge reduction	-157 €/kW per year	
Flywheel storage system		
Investment costs (incl. refrigerating plant)	€ 2,722,500	
Operational expenditures	€ 2,853	
Cost savings grid charge (2)	€ -44,632	
Disposal costs	€ -1,838	
		€ 2,717,809
Break-even grid charge reduction	-1,889 €/kW per year	

* discounted net present value

4.4 Sensitivity analysis

4.4.1 Configuration of the flywheel storage system

The results of the economic evaluation show that the flywheel storage system is not suitable for the operating mode described in the application scenario due to the high investment costs. With regard to the technical properties, these short-term storage systems cannot be compared with electrochemical energy storage systems in an economically sensible way. The latter are better suited for medium storage times than flywheels.

Since a possible future need for alternative storage technologies is expected, the investigation of the flywheels was also carried out for the purpose of being able to make an evaluation of technically and economically reasonable operating conditions.

From a technical point of view, flywheel storage systems would be suitable for minimising peak loads in SMEs if they were smaller and therefore more cost-effective. In the following, a scenario for the minimisation of peak loads will be examined, which can be realised with the help of short-term storage systems. In contrast to the time span of several hours between injection and withdrawal shown in Figure 4, a much shorter storage time may be sufficient in some cases (Figure 14). Under the following conditions, it is possible to use flywheels to minimise peak loads within certain peak load windows (atypical grid use) as well as to reduce the specific annual peak load:

- The peak loads are short, i.e. a few minutes, or occur at intervals, so that energy can be stored in the flywheel storage system between successive peak loads.

- The peak load is predictable and the storage takes place shortly before a peak load.

The power drawn outside the peak loads offers sufficient distance to the maximum permissible maximum load to enable charging of the short-term storage systems within peak load windows (Figure 14).

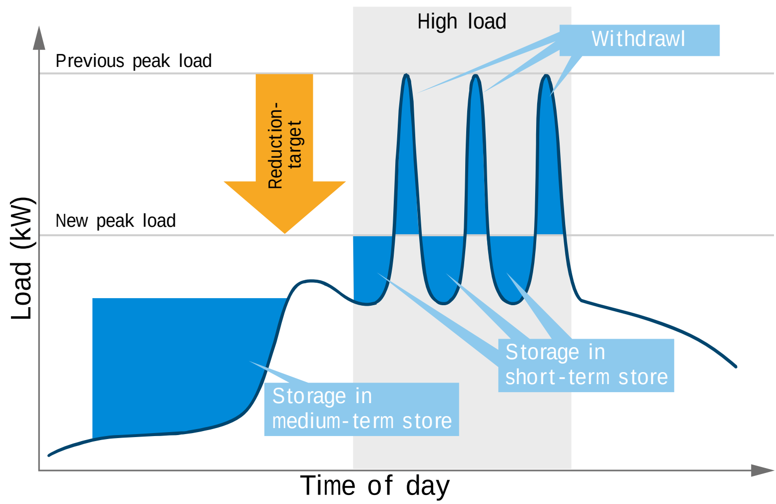


Figure 14: Schematic diagram of the minimisation of peak loads with intermediate charging cycles for flywheels

Such an adapted operating mode of the flywheel storage systems is suitable for bridging repeated short-term peak loads in the minute range. This results in a higher number of charging cycles which, however, have no effect on the service life of the flywheel storage system due to the technology used. A new investment is not necessary during the period under review. Under such conditions a smaller dimensioning of the flywheel energy storage system is possible under consideration of economic considerations. The following sensitivity analysis examines the impact of such a technical modification of the energy storage system with regard to ecological and economic aspects.

With regard to investment costs, it is stated that the flywheel storage system should be of a similar size to the lead-acid and lithium-iron phosphate storage systems. At a unit price of € 80,000 per flywheel module, it is assumed that the flywheel storage system will contain a maximum of three flywheel modules with a total capacity of 12 kWh. This number is derived from an investment sum comparable to that of battery-based energy storage systems. The resulting investment costs for the modified flywheel storage system amount to € 240,000.

The 100 kW power output required in the application scenario can be easily achieved with this equipment. The consequence of this adjustment is a shortening of the maximum bridgeable duration of the peak loads. With a power output of 100 kW, the flywheel storage system with a total capacity of 12 kWh is already discharged after 7.2 minutes. The flywheel storage system must then be recharged until the next peak load occurs. In contrast to electrochemical energy storage systems, flywheels can be recharged very quickly and can be operated in interval mode without any problems.

However, no complete functional equivalence to electrochemical energy storage systems is achievable with the configuration shown, because flywheels can provide 100 kW of power, but store less energy (kWh). The three flywheel modules together store only 12 kWh of energy, while the battery-based energy storage systems store 100 kWh. The latter are not well suited for short interval operation, as batteries cannot be recharged as quickly as flywheels. Rapid charging of lead-acid batteries and lithium-iron phosphate batteries with higher charging currents would significantly shorten the service life of these batteries.[127] In addition, the service life of these would be massively reduced as a result of the higher number of charging cycles. The capacity of the battery storage systems has therefore been chosen so high that several short peaks can be bridged without intermediate charging. For flywheels, however, the number of loading cycles has no influence on the service life.

4.4.2 Results of the ecological sensitivity analysis

The results presented below represent the comparison of the modified flywheel storage system (Chapter 4.4.1) with the unchanged lead-acid and lithium-iron phosphate storage systems (Chapter 3.4.1) under the operating modes outlined in Figure 14[128]

The results for the cumulative energy expenditure show that in this scenario the lithium-iron phosphate storage system causes the highest energy expenditure of the three technologies with 147,000 MJ. At almost 140,000 MJ (around 39,000 kWh), the lead-acid storage system is just under this figure,

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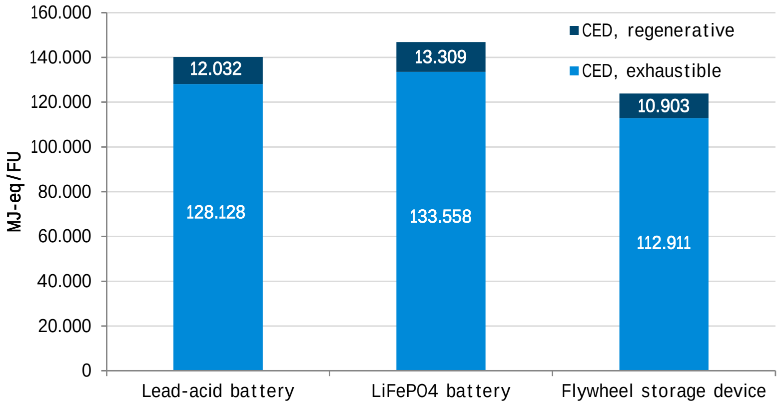
[127] Cf. Zhanga, Y. et al. (2011), p. 1513.

[128] With the flywheel energy storage system, a higher efficiency (η=0.98), as shown in Figure 10, because the self-discharge of this storage type is considerably lower with short storage intervals than with long storage intervals.

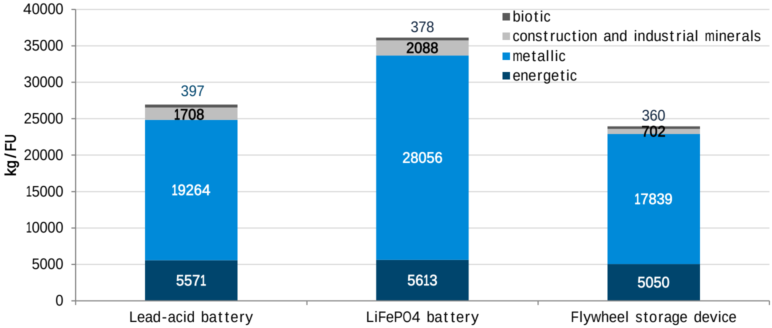
while the smaller flywheel storage system requires only 124,000 MJ (Figure 15).



LiFePO4 - Lithium Iron Phosphate Battery

Figure 15: Comparison of cumulative energy consumption with modified flywheel storage system

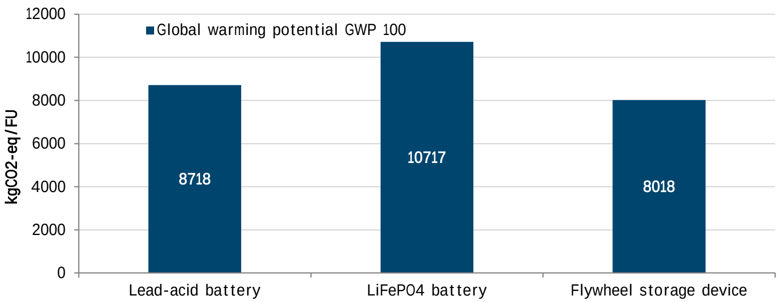
The lithium iron phosphate storage system also requires the highest raw material input for the cumulative raw material input (Figure 16) with 36 Mg (5.6 Mg energetic, 28.1 Mg metallic, 2.1 Mg construction and industrial minerals and 0.4 Mg biotic). The cost of the lead-acid storage system is reduced by 9 Mg to 26 Mg (6 Mg energetic, 19 Mg metallic, 1.7 Mg building and industrial minerals and 0.4 Mg biotic). The smaller dimensioned flywheel storage system with almost 24 Mg (5.0 Mg energetic, 17.8 Mg metallic, 0.7 Mg construction and industrial minerals and 0.4 Mg biotic) is below the other two technologies.



LiFePO4 - Lithium Iron Phosphate Battery

Figure 16: Comparison of cumulative raw material input with modified flywheel storage system

In terms of greenhouse gas potential (Figure 17) the lithium-iron phosphate storage system causes the most emissions with 10,700 kg CO_2 equivalents. The lead-acid storage system produces 8,718 kg CO_2 equivalents and the flywheel storage system 8,000 kg CO_2 equivalents. In the flywheel storage system, the friction losses during loading and unloading as well as the conversion losses cause an increased electricity requirement and are therefore responsible for almost 69 % of greenhouse gas emissions.



LiFePO4 - Lithium Iron Phosphate Battery

Figure 17: Comparison of greenhouse gas potentials with modified flywheel storage system

4.4.3 Results of the economic sensitivity analysis

The investment costs for the modified flywheel storage system amount to € 240,000 (based on 2017). The investment costs for the cooling system remain the same at € 2,500 (based on 2016). Further details can be found in Table 19.

Table 19: Investment costs with modified flywheel storage systems

Energy storage technology / component	Total number Cells / Units	Price per cell / Unit	Costs per procurement	Costs over the entire period
	Piece	€ / piece	€ / Procurement	€
Lead-acid battery	14	€ 13,500	€ 189,000	€ 397,088
Lithium-iron phosphate battery	4	€ 52,500	€ 210,000	€ 210,000
Flywheel	3	€ 80,000	€ 240,000	€ 240,000
Refrigerating plant	1	€ 2,500	€ 2,500	€ 2,500

The operational expenditures (Table 20) for the smaller dimensioned flywheel storage system change mainly due to the significantly reduced space requirement (5 m^2 instead of 25 m^2) and the lower electricity costs due to the lower power dissipation.

Table 20: Savings and operational expenditures with modified flywheel storage system

Position	Cost factors	Costs per element	Annual costs	Total period
	Element	€ / Element	€ / Year	€
Savings				
Grid charge reduction (1)	Year	€-500 /year	€-500	€-7,439
Grid charge reduction (2)	kW	€-30 /kW per year	€-3,000	€ -44,632
Operational expenditures				
Rent	5 m^2	5 €/m2	€ 300	€ 4,463
Air conditioning (full operation)	750 kWh/a	0.135 €/kWh	100 €	Total: € 2,530
Air conditioning (standby)	525 kWh/a	0.135 €/kWh	€ 700	
Maintenance	12 months	20 €/month	€ 237	€ 3,527
Costs due to power loss of the respective energy storage systems				
Lead-Acid-ESS	26.7 kWh	0.135 €/kWh	€ 901.13	€ 13,406
LFP-ESS	20.2 kWh	0.135 €/kWh	€ 681.75	€ 10,143
Flywheel-ESS	20.2 kWh	0.135 €/kWh	€ 681.75	€ 10,143
Total per energy storage system				
Lead-Acid-ESS				€ -20,706
LFP-ESS				€ -23,970
Flywheel-ESS				€ -23,970

ESS - energy storage system; LFP - lithium iron phosphate ESS

The proceeds from the scrapping of three flywheel modules with a total weight of 2.43 t amount to € 162.

Table 21 lists the total costs over the period under consideration of 20 years for all the energy storage systems under consideration, including the modified flywheel accumulators. The required monthly reduction in grid charges per energy storage system is also given for the sensitivity analysis, in order to just balance the total costs in the period under consideration (break even).

Table 21: Comparison of the total cost calculation with modified flywheel storage system (observation period of 20 years)

Element	Costs	Total costs*
	€	€
Lead-acid storage system		
Investment cost (incl. current transformer refrigerating plant)	€ 409,588	
Operational expenditures	€ 23,926	
Cost savings grid charge (2)	€ -44,632	
Disposal costs	€ -3,091	
		€ 385,791
Break-even grid charge reduction	-283 €/kW per year	
Lithium iron phosphate storage system		
Investment cost (incl. current transformer & refrigerating plant)	€ 222,500	
Operational expenditures	€20,663	
Cost savings grid charge (2)	€ -44,632	
Disposal costs	€ -55	
		€ 198,475
Break-even grid charge reduction	-157 €/kW per year	
Flywheel storage system		
Investment costs (incl. refrigerating plant)	€ 242,500	
Operational expenditures	€ 23,970	
Cost savings grid charge (2)	€ -44,632	
Disposal costs	€ -162	
		€ 218,368
Break-even grid charge reduction	-178 €/kW per year	

* discounted net present value

The savings potential required by reducing the grid charge remains unchanged for the lead-acid storage system and the lithium-iron phosphate system. For the smaller dimensioned flywheel storage system, a reduction of the grid charge of 178 € would be sufficient.

It should be noted that the minimisation of the peak load assumed in this model calculation with the adapted flywheel storage systems refers to shorter time intervals per peak load than with the battery systems. As a result, the desired reduction in grid charges in the sense of atypical grid use with the smaller dimensioned flywheel accumulators is only possible under the circumstances mentioned in Chapter 4.4.1. There are no restrictions with electrochemical energy storage systems.

5 DISCUSSION OF THE RESULTS

The results of the economic evaluation illustrate a decisive hurdle with regard to the use of energy storage systems to minimise peak loads. For all three energy storage systems, the investment costs are higher than the grid charges savings that can be achieved with the application scenario considered in this study. In comparison to energy storage systems, lithium iron phosphate batteries have the best cost-benefit ratio.

At present, the use of energy storage systems makes economic sense if there are other reasons for their use, such as process requirements, grid stabilisation or optimisation of auxiliary demand in combination with the use of renewable energies. Due to their high investment costs, flywheel storage systems are only suitable for bridging short-term peak loads in the minute range (see sensitivity analysis). In such cases they have clear advantages over electrochemical energy storage systems due to their high cycle stability.

The results of the ecological evaluation are largely dependent on the storage technology under consideration. While the lead-acid storage system has the greatest environmental impact during its utilisation phase (CED: 65 %; CO_{2-eq}: 64%), the flywheel storage system is manufactured (CED: 63%; CO_{2-eq}: 49%). The environmental impacts of the lithium-iron phosphate storage system are roughly the same in terms of production and utilisation phase (CED: 48 % to 49 %; CO_{2-eq}: 57 % to 41 %). The results of the study on cumulative raw material consumption (CRM) show similar conditions for all three energy storage systems for the production and utilisation phase (CRM production phase: 80 % for lead-acid storage system and 88 % for lithium-iron phosphate and flywheel storage system; CRM utilisation phase: 19 % for lead-acid storage system and 11 % for lithium-iron phosphate and flywheel storage system). As expected, disposal does not have a significant impact on the overall environmental impact of any of the energy storage systems.

Energetic losses are critical. As a result of the multi-stage current conversion (alternating current to direct current; transformation of the voltage levels), a striking energy dissipation occurs without energy being saved in any way by minimising the peak loads. Because of the power loss, energy storage system causes greenhouse gas emissions in the upstream chains of electricity generation.

When comparing the LCA results and the sensitivity analysis, it becomes clear that a smaller dimensioned flywheel storage system in connection with an adapted operating mode (intermediate charging) leads to noticeable improvements in the ecological performance. The selection of the cheapest energy storage system, from an ecological and economic perspective, therefore depends very much on the concrete load profile of a company and above all on the duration of the peak loads.

Optimisation possibilities in the use of energy storage systems:

- Use of DC motors on machines or systems that are run in batch mode and are known to lead to singular peak loads: These could be, for example, pumps and agitators for viscous substances (e.g. dough) or sporadically used lifting equipment for heavy loads. Other DC-based processes, such as galvanic processes, could also be connected directly to a DC source using a DC/DC converter.

- Use of brake energies to recharge the energy storage systems: This option uses the kinetic energy contained in rotating or moving plant components to generate electricity instead of converting it into heat by means of brakes. This type of electricity generation often takes place at intervals that are difficult to harmonise with the stability of the operational low-voltage grid. The use of energy storage systems, in particular flywheels, could be an economically and ecologically sensible supplement to minimise peak loads. Here, in addition to the application scenario considered in this study, there is actually an economic and ecological energy saving potential.

- Further use of used lithium iron phosphate battery cells (so-called “second-life batteries“) instead of new ones: The secondary use of used traction batteries from electric vehicles could in future develop into an economically viable alternative for participants in the standard services market.[129] Stationary applications place lower demands on the mechanical and electrical properties of batteries than mobile applications. It would therefore be conceivable that batteries that can no longer be used in

[129] Cf. Richter, S. et al. (2017), p. 145 f.

electric vehicles could continue to be used in stationary systems until the end of their physical service life. These installations would have to be heavily oversized to compensate for declining useful capacity and reduced reliability. However, this would not be a decisive obstacle for stationary purposes if a large supply of reasonably priced used traction batteries were to develop in the future. However, it is questionable whether lithium iron phosphate batteries will ever play a major role in the automotive sector compared to lithium-nickel-manganese-cobalt oxide batteries. At present, there is no market availability of “second-life batteries“ for the application purpose considered here in SMEs.

For technical reasons, the feasibility of reusing used traction batteries must be carefully considered. Since lithium iron phosphate cells do not have a reliably known state of health (Soh) at the end of their primary utilisation phase, all battery cells must be removed, individually tested and reassembled as a battery. In order to enable a reliable evaluation of the condition and the expected remaining life of the battery cells, the ageing process and diagnostics in the late phase of the battery life cycle must be further researched. The so-called Repurposing of used traction batteries would, in addition to the economic incentives, also have decisive advantages in terms of resource efficiency. The subsequent use of energy storage systems for long-lived stationary facilities prolongs their service life and thus increases the productivity of the material resources tied up in them. However, further investigations are required with regard to the energy efficiency losses of aged lithium iron phosphate batteries. As a result of the increasing power dissipation of lithium iron phosphate cells towards the end of their service life, the indirect greenhouse gas emissions of such energy storage systems could be much higher than shown in section 4.1.5 for new batteries. In addition, the use of Second Life batteries in SMEs would be likely to increase maintenance requirements in order to ensure the reliability and safety of the energy storage system.

6 CONCLUSIONS AND OUTLOOK

6.1 Conclusions

The results in Chapter 4 show for the illustrated example of an SME that the selected energy storage systems cannot yet achieve any economic added value from an ecological and economic point of view. In addition to the high investment costs, the efficiency losses during injection and withdrawal also reduce the economic profitability. In the current economic environment, the financial incentives for minimising peak loads are too low to outweigh the costs. In other areas of application, the use of energy storage systems can make economic sense, e.g. for uninterruptible power supply.

From an ecological perspective, the use of energy storage systems to minimise peak loads has no advantages. As a result of the power loss, the use of energy storage systems results in higher power consumption and thus higher greenhouse gas emissions than if peak loads were tolerated. In addition, the production of energy storage systems creates additional demand for energy and material resources. However, this overall ecological evaluation only applies within the system boundaries considered in this study. An ecological advantage of the use of energy storage systems in other fields of application, as presented in Chapter 2, cannot therefore be ruled out, e.g. the use of decentralised energy storage systems for the optimisation of own requirements in combination with renewable energies.

Currently - from an ecological and economic perspective - the minimisation of peak loads with a time shift of the loads (temporal load management) is easier to achieve in companies than with the use of energy storage systems. The latter have a rather low degree of efficiency due to the unavoidable energy losses during power conversion. Active energy management in SMEs remains a success factor, especially for energy-intensive companies. In the case of heterogeneous applications in industrial production, it depends on the individual case. The use of energy storage systems in SMEs is still in its infancy. In the future, the simulation and design of energy storage systems as well as the design of the integration capability and the interfaces from energy storage systems to commercial use will be key success factors. Storage systems can be economically dimensioned by means of operational management.

However, the results also show that economic feasibility is achievable, especially in applications with very high short peak loads and high performance prices. This will require further reductions in investment costs for storage technologies and combinations of different technologies (e.g. flywheel accumulators and lithium-ion batteries).

6.2 Outlook

At the level of high- and medium-voltage grids, grid capacity will remain a scarce commodity in the future. For this reason, it can be assumed that this good will continue to be priced accordingly. The minimisation of peak loads will also be able to make a relevant contribution to grid relief in the future as a contribution to atypical grid use.

However, it is to be expected that the system of grid charges will change, particularly with regard to distribution networks. If, for example, peaks in the supply of renewable energy are to be used efficiently, final consumers should be enabled to purchase increased power at these times without this leading to increased grid charges. However, this presupposes that the network does not reach its technical limits. For example, the Federal Grid Agency is currently discussing that many distribution networks are now dimensioned according to the feed-in of renewable energies and that peak loads are therefore no longer relevant for grid expansion.[130] In modernised networks, the benefit of a pure minimisation of peak loads is in question and may no longer be rewarded in the future in the grid charge system.

In the medium to long term, it can be assumed that the flexible use of energy storage systems by end consumers and the temporal load management in active distribution load management will be of great benefit.[131] In addition to minimising peak loads, these include load increase or load reduction. This means that network operation can also be supported outside peak load times or outside the peak load time of the individual consumer and critical network states can be prevented.

[130] BNetzA (2017), p. 23.
[131] Cf. BNetzA (2017), p. 23.

The flexibility of load demand could become a tradable commodity in the future because it complements distribution network management. This could provide an additional source of income for the operators of local energy storage systems. Flexibility options can also generate future revenues on the balancing energy market or spot market. At the same time, the sole focus of storage systems on minimising peak loads can be reduced and economic efficiency and resource efficiency can be increased.

For further network flexibility, not only the energy storage systems, but also the industrial production systems must be suitable for load management. This applies above all to batch production processes. In order to enable time-flexible production control, intermediate storage systems for semi-finished products may be required. Commercial processes should be reviewed for this potential. DENA's DSM Baden-Württemberg project, for example, provides initial indications of suitable processes and industries.[132]

[132] Cf. German Energy Agency (2017).

7 GLOSSARY

The **degree of self-sufficiency** (coverage ratio)[133] indicates the proportion of electricity demand that can be supplied simultaneously by PV energy. If an average degree of self-sufficiency of 50 % is achieved over an entire year, half of the annual electricity requirement can be supplied locally by the PV system. This reduces the amount of electricity drawn from the grid by half.

Operation & Maintenance costs[134] (O&M costs or **OPEX**) consist of fixed annual O&M costs (in €/kW*a) and variable O&M costs (in €/kWh). The fixed costs are, for example, insurance costs, interest or scheduled maintenance after a certain period of time. The variable operational expenditures are, for example, maintenance and repair costs or the price of electricity and depend on how much energy the energy storage systems stores each year.

The **share of own consumption**[135] corresponds to the share of the generated PV energy that can be used at the same time on site. If an annual average own consumption share of 50 % is achieved, half of the total annual production of the PV system can be used locally.

Deployment or response time[136] is the time that elapses from the request to reaching full performance of the system.

Ratio of **energy to output**[137] (E-P ratio, also C rate) in kWh/kW describes the ratio of installed capacity (energy) and installed output. The higher the E/P value, the longer a storage system can supply energy. Power storage systems generally have low E/P values.

Energy density (kWh/m^3)[138] as a measure of the available energy of a storage system to its volume in kWh/litre or kWh/m^3. The higher the energy density, the smaller the space required for installation. Flywheels, for

[133] Cf. Quaschning, V. (2017).
[134] Cf. Fraunhofer ISI (2015), p. 19.
[135] Cf. Quaschning, V. (2017).
[136] Cf. Fuchs et al. (2012), p. 20.
[137] Cf. Fuchs et al. (2012), p. 19.
[138] Cf. Fuchs et al. (2012), p. 19.

example, have an energy density of 10 kWh/m^3 and LIB, with 500 kWh/m^3, 50 times this.

Depth of discharge (DOD)[139] is the amount of energy discharged compared to the total storage capacity. The maximum value is 100 % DOD and corresponds to a fully discharged system. It should be noted whether the value of 100 % DOD corresponds to the total storage capacity or whether it refers to the amount of usable storage capacity. Some storage technologies do not allow complete discharge of the system for technical reasons.

The **calendar service life**[140] indicates the lifetime of an unused storage system.

A **load profile** [141]records the average power values of a point of consumption to the nearest quarter of an hour. A prerequisite for the existence of a load profile is a recording power measurement (RLM), which is usually carried out from an annual consumption of 100,000 kWh of electricity.

Power density (W/m^3)[142] describes the ratio of available power to the volume of the storage system. High performance applications require high power densities combined with low weight and volume.

Self-discharge[143] is the loss of energy content of a storage system due to friction, internal processes, etc.

Storage capacity C (kWh)[144] is the amount of energy that an energy storage system can store.

A **full cycle**[145] is a complete discharge and charging of a storage system.

The **DC link**[146] can be regarded as a storage system from which the motor can draw its energy via the inverter. The DC link can be structured

[139] Cf. Fuchs et al. (2012), p. 20.
[140] Cf. Fuchs et al. (2012), p. 21.
[141] Cf. energy marketplace (2017).
[142] Cf. Fuchs et al. (2012), p. 19.
[143] Cf. Fuchs et al. (2012), p. 20.
[144] Cf. Fuchs et al. (2012), p. 20.
[145] Cf. Fuchs et al. (2012), p. 21.
[146] Cf. Guetzgold Elektrotechnik GmbH (2017), p. 59.

according to three different principles. The type of DC link used is determined by the rectifier and inverter with which it is to be combined. There are three guys:

a) the DC link which converts the voltage of the rectifier into a direct current,

b) the DC link, which stabilizes or smoothes the pulsating DC voltage and makes it available to the inverter and

c) the DC link, which makes the constant DC voltage of the rectifier variable.

Cycle life (number of cycles/cycle strength)[147], expressed in number per day, week or year, is the number of full cycles of a storage system under certain conditions.

[147] Cf. Fuchs et al. (2012), p. 21.

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APPENDIX A

Expert interviews:

Mark Richter, Fraunhofer Institute for Tool Machines and Forming Technology IWU, Reichenhainer Str. 88, 09126 Chemnitz.

Winfried Wahl, RRC Power Solutions in Homburg (Saarland) (until May 2017).

Jens Fischer, VEA - Bundesverband der Energie-Abnehmer e. V. Hanover. Since 1950, the Bundesverband der Energie-Abnehmer e. V. has been the largest energy interest group of German SMEs.

Prof. Dr. Hanke-Rauschenbach, Universität Hannover, IfES – Fachgebiet Elektrische Energiespeichersysteme. http://www.ifes.uni-hannover.de/ees

Dr.-Ing. Marcel Weil, Institute for Technology Evaluation and Systems Analysis (ITAS), Research Unit Innovation Processes and Technology Consequences.

Dr. Jens Peters, Institute for Technology Evaluation and Systems Analysis (ITAS), Research Unit Innovation Processes and Technology Consequences.

Dr. Frank Täubner, Rosseta Technik GmbH i.L., Managing Director.

EAM Elektroanlagenbau Mannheim GmbH (the interviewed expert was guaranteed anonymity),

APPENDIX B

Overview of sources for Table 3

Table 22: Technical and economic characteristics of power storage systems

	Cycles-service life	Service life	Costs	Performance sizes	Storage systems sizes
SHORT-TERM POWER STORAGE (SECONDS TO MINUTES)					
	Number	Years	€/kW	kW	kWh
Flywheel[148]	10,000 - 10 million	15 – 20	27 – 8,000	1 – 10,000	<5,000 (scalable)
Supercaps[149]	10,000 - 1 million	5 – 30	20–9,019	10 – 200,000	<100 (in the small kWh range)
SMES[150]	20,000 - 1 million	15 – 30	180 – 915	100 – 10,000	0.1 – 15
High performance lithium ion battery[151]	500 – 10,000	5 – 20	158 – 3,608	Scalable (up to several thousand kW)	Scalable (in the one- to two-digit MWh range)
Lead-acid battery[152]	100 – 2,500	3 – 20	150 – 812	<50,000	<50,000

[148] Cf. DCTI (2014), p. 25; Fuchs, G. et al. (2012), p. 49; Sabihuddin, p. et al. (2015), p. 176; Steinhorst, M. P. et al. (2013), p. 22; Fraunhofer ISI (2015), pp. 22 – 23; Zakeri, B. and Syri, P. (2015), p. 592; Östergård, R. (2011), p. 10; Ausfelder, F. et al. (2015), p. 20; Kairies, K.-P. (2017), p. 31; Lazard (2016), p. 17; Luo, X. et al. (2015), pp. 525 – 526; Dekka, A. et al. (2015), p. 109.

[149] Cf. Sabihuddin, P. et al. (2015), p. 176; Steinhorst, M. P. et al. (2013), p. 18; Fraunhofer ISI (2015), pp. 22 – 23; Zakeri, B. and Syri, S. (2015), p. 592; Kairies, K.-P. (2017), p. 31; Lazard (2016), p. 17; Luo, X. et al. (2015), pp. 525 – 526; Dekka, A. et al. (2015), SP. 109; EASE (2016.), pp. 3 – 4; Deloitte (2015), p. 19.

[150] Cf. Fraunhofer ISI (2015), pp. 22 - 23; Zakeri, B. and Syri, p. (2015), pp. 592 - 593; Luo, X. et al. (2015), pp. 525 - 526; Dekka, A. et al. (2015), p. 109.

[151] Cf. Wietschel, M. et al. (2015), p. 175; EASE/EERA (2015), p. 20.

[152] Cf. Rummich, E. (2015), p. 154; Ausfelder, F. et al. (2015), p. 57; DCTI (2014), p. 27; Sterner, M. and Stadler, I. (2014), p. 600; Fuchs, G. et al. (2012), p. 54; Sabihuddin, P. et al. (2015), p. 184; Steinhorst, M. P. et al. (2013), p. 29; Fraunhofer ISI (2015), pp. 22 – 23; Elsner, P. and Sauer, D. U. (2015), p. 23; Zakeri, B. and Syri, P. (2015), p. 592; Wietschel, M. et al. (2015), p. 174; Lazard (2016), p. 17; EASE (2016), p. 9; Kairies, K.-P. (2017), pp. 32 – 33.

Table 23: Technical and economic characteristics of energy storage systems

	Cycles-service life	Service life	Costs	Performance sizes	Storage systems sizes
MEDIUM-TERM ENERGY STORAGE SYSTEM (MINUTES TO HOURS)					
	Number	Years	€/kW	kW	kWh
Energy storage system lithium Ion battery[153]	300 – 15,000	5 – 20	158 – 3,608	Scalable (up to several thousand kW)	Scalable (in the one- to two-digit MWh range)
Lead-acid battery[154]	100 – 2,500	3 – 20	45 – 992	<50,000 (scalable)	<50,000 (scalable)
Redox Flow Battery[155]	800 – 20,000	2 – 25	100 – 1,153	<100,000 (scalable)	Scalable (several 1,000 kWh)
Sodium sulphur battery[156]	2,500 – 8,250	10 – 20	210 – 645	Scalable (up to two-digit MW)	Scalable (up to three digit MWh)

[153] Cf. Wietschel, M. et al. (2015), p. 175; EASE/EERA (2015), p. 20.

[154] Cf. Rummich, E. (2015), p. 154; Ausfelder, F. et al. (2015), p. 57; DCTI (2014), p. 27; Sterner, M. and Stadler, I. (2014), p. 600; Fuchs, G. et al. (2012), p. 54; Sabihuddin, P. et al. (2015), p. 184; Steinhorst, M. P. et al. (2013), p. 29; Fraunhofer ISI (2015), pp. 22 – 23; Elsner, P. and Sauer, D. U. (2015), p. 23; Zakeri, B. and Syri, P. (2015), p. 592; Wietschel, M. et al. (2015), p. 174; Lazard (2016), p. 17; EASE (2016), p. 9; Kairies, K.-P. (2017), pp. 32 – 33.

[155] Cf. Fuchs, G. et al. (2012), p. 54; Sabihuddin, P. et al. (2015), p. 197; Steinhorst, M. P. et al. (2013), p. 29; Fraunhofer ISI (2015), pp. 22 – 23; Elsner P. and Sauer, D. U. (2015), p. 40; Zakeri, B. and Syri, P. (2015), p. 592; Wietschel, M. et al. (2015), p. 174; Lazard (2016), p. 17; EASE/EERA (2015), p. 20; Kairies, K.-P. (2017), p. 40.

[156] Cf. Fraunhofer ISI (2015), pp. 22 – 23; Sterner, M. and Stadler, I. (2014), P. 600; Dekka, A. et al. (2015), p. 109; Luo, X. et al. (2015), pp. 525 – 527; Zakeri, B. and Syri, S. (2015), pp. 592 – 593; Chen, H. et al. (2009), pp. 307 – 308; Kairies, K.-P. (2017), p. 39.

APPENDIX C

Table 24: Overview of technical parameters of energy storage technologies

Energy storage system technologies	Evaluation	
	Criterion 1: MARKET TIRE (Unit: qualitative)	
Lead-acid batteries	Products in use for years	+
Lithium iron phosphate batteries	Products in use for years	+
Supercapacitors	Available for several years / only just available for use by SMEs	+/o
Flywheel accumulators	As USV since years in application/for the application with SME only just available	+/o
High-temperature sodium batteries	Used commercially, but only for large storage applications	o
Redox-flow batteries	Products in use for years	+
Legend "+" Products in use for years; "o": first products available on the market; „-": Demonstrator available		
	Criterion 2: EFFICIENCY (Unit: %)	
Lead-acid batteries	60 - 90 %	o
Lithium iron phosphate batteries	80 - 98 %	+/o
Supercapacitors	80 - 98 %	+/o
Flywheel accumulators	80 - 95 %	+/o
High-temperature sodium batteries	70 - 90 %	o
Redox-flow batteries	60 - 90 %	o
Legend: "+" >= 90 % ; "o": > = 75 % - 90 %; "-": < 75 %		
	Criterion 3: STORAGE LOSS (Unit: %)	
Lead-acid batteries	0.01 - 0.4 % per day depending on quality	+
Lithium iron phosphate batteries	0.1 % per day	+
Supercapacitors	<40 % per day	-
Flywheel accumulators	>10 % per day; high self-discharge due to friction losses.	-
High-temperature sodium batteries	1 - 10 % per day due to thermal energy loss (cooling)	o
Redox-flow batteries	Tank 0.1 - 0.4 % per day; 100 % in a few hours	+
Legend "+"<1 %/day; "o": <1 % - 10 %/day; "-": >= 10 %/day		
	Criterion 4: SPECIFIC ENERGY DENSITY (Unit: Wh/kg)	
Lead-acid batteries	25 – 50	-
Lithium iron phosphate batteries	50 – 150	o
Supercapacitors	<50 (75)	-
Flywheel accumulators	5 – 100 (200)	o/-
High-temperature sodium batteries	80 – 250	+
Redox-flow batteries	10 – 90	-
Legend "+">= 90 Wh/kg; "o": >= 70 - 90 Wh/kg; "-": <70 Wh/kg		
	Criterion 5: CALENDAR SERVICE LIFE (Unit: Year (a))	
Lead-acid batteries	2 – 15	-
Lithium iron phosphate batteries	<= 20	+
Supercapacitors	4 – 30	o/+
Flywheel accumulators	15 – 20	+
High-temperature sodium batteries	10 – 20	+
Redox-flow batteries	<= 25	+
Legend: "+" >= 15 years; "o": >= 10 - 15 years; "-": <10 years		

Energy storage system technologies*	Evaluation	
	Criterion 6: CYCLE LIFE/STRENGTH (Unit: number of cycles)	
Lead-acid batteries	100–2,500	-
Lithium iron phosphate batteries	1,000 – 8,000 (10,000)[157]	o
Supercapacitors	<One million	+
Flywheel accumulators	>One million	+
Sodium high-temperature batteries	1,000 – 10,000	o
Redox-flow batteries	(800)[158] 10,000 – 20,000	+
Legend "+" > 10,000 cycles; "o": >= 5,000 - 10,000 cycles; "-": <5,000 cycles		
	Criterion 7: HANDLING/SAFETY (Unit: qualitative)	
Lead-acid batteries	VRLA batteries are low-maintenance and very safe (low risk of fire)	+
Lithium iron phosphate batteries	Long service life and low risk of fire, LFP does not decompose at high temperatures. Contains combustible organic electrolytes	+
Supercapacitors	Reliable, contains no critical components	+
Flywheel accumulators	Depending on design, safe to operate due to containment, a "thermal runaway" is not to be feared	+
Sodium high-temperature batteries	Fire of a large stationary battery has already occurred, followed by the introduction of safety concepts	o
Redox-flow batteries	Also when mixing the charged electrolytes uncritical	+
Legend: "+" no relevant safety risk; maintenance-free; no restrictions on use; "o": high safety risk; high maintenance requirements; significant limitations in application; "-": low safety risk; low maintenance requirements, low application restrictions		

* SOURCES FOR CRITERIA 1-7	
Lead-acid batteries	Rummich, E. (2015), p. 154; Ausfelder, F. et al. (2015), p. 57; DCTI (2014), p. 27; Sterner, M. and Stadler, I. (2014), p. 217; Fuchs, G. et al. (2012), p. 54; Sabihuddin, S. et al. (2015), p. 184; Steinhorst, M. P. et al. (2013), p. 29; Fraunhofer ISI (2015), p. 22 – 23; Elsner, P. and Sauer, D. U. (2015), p. 23.
Lithium iron phosphate batteries	Baumann, M. J. (2012), p. 12; Kowal, J. (2016), p. 33; Battery University (2017); Albright, G. et al. (2012), p. 6; Zenke, W. (2012), p. 26 - 27; Vetter, M. and Lux, p. (2016), p. 206; Pamina-Solar (2015), p. 10 and 16; Kairies, K.-P. (2017), p. 35.
Supercapacitors	Agency for Renewable Energies (2014), P. 28; Sabihuddin, S. et al. (2015), P. 201; Steinhorst, M. P. et al. (2013), P. 18; Deloitte (2015), P. 19; Zakeri, B. and Syri, S. (2015), S. 592; Dekka, A. et al. (2015), P. 109; Luo, X. et al. (2015), P. 525 – 526; Fraunhofer ISI (2015), P. 22 – 23; EASE (2016.), P. 3 – 4.
Flywheel accumulator	DCTI (2014), p. 25; Fuchs, G. et al. (2012), p. 49; Sabihuddin, p. et al. (2015), p. 176; Steinhorst, M. P. et al. (2013), p. 22; Fraunhofer ISI (2015), p. 22 – 23; Zakeri, B. and Syri, S. (2015), p. 592; Östergård, R. (2011), p. 10; Ausfelder, F. et al. (2015), p. 20; Kairies, K.-P. (2017), p. 31; Luo, X. et al. (2015), p. 525 – 526; Dekka, A. et al. (2015), p. 109.
Sodium high-temperature batteries	DCTI (2014), p. 32; Fuchs, G. et al. (2012), p. 56; Rummich, E. (2015), p. 163 - 167; Fraunhofer ISI (2015), p. 22 - 23; Sterner, M. and Stadler, I. (2014), p. 279 - 281; Elsner, P. and Sauer, D. U. (2015), p. 36.
Redox Flow Batteries	Fuchs, G. et al. (2012), p. 54; Sabihuddin, p. et al. (2015), p. 197; Steinhorst, M. P. et al. (2013), p. 29; Fraunhofer ISI (2015), p. 22 - 23; Elsner, P. and Sauer, D.U. (2015), p. 40; Zakeri, B. and Syri, p. (2015), p. 592; Wietschel, M. (2015), p. 174; EASE/EERA (2015.), p. 20; Kairies, K.-P. (2017), P. 40.

[157] For LTO ($Li_4Ti_5O_{12}$) anode.

[158] Lower extreme value, cf. Sabihuddin, S. et al. (2015), p. 197.

Table 25: Summary of material composition and its proportions in lithium-ion batteries[159]

Component	Materials	Percentage by mass
Casing	Aluminium, plastics, steel	10 - 40 %
Anode (negative electrode)	Graphite, lithium-alloyed material, e.g. titanate (Li4Ti5O12), silicon (Li22Si6), hard carbon (LiC_6)	10 - 20 %
Anode foil	Generally Copper (Cu)	5 - 10 %
Cathode (positive electrode)	Mixed oxides or metal oxides (e.g.: Cobalt ($LiCoO_2$), Mangan ($LiMn_2O_4$), Eisen ($LiFePO_4$) or Nickel ($LiNiO_2$)), Li_2CO_3, $LiCoO_2$, $LiMn_2O_4$, $LiNiO_2$, $LiFePO_4$ etc.	15 - 40 %
Cathode foil	Generally Aluminium (Al)	3 - 7 %
Electrolyte	(Liquid) organic electrolyte with conductive salt containing lithium-ions and other additives (aqueous electrolytes, non-aqueous electrolytes, solid state electrolytes), polyethylene, polypropylene, ethylene carbonate, carbonic acid diethyl ester, $LiPF_6$, $LiBF_4$, $LiClO_4$	10 - 20 %
Separator	Partial polymer membranes, ceramic separators, nonwovens and glass fibre separators	2 - 10 %

Table 26: Compilation of several percentage compositions of lithium-ion cells

Component	Materials	Percentage by mass	
		LFP graphite cf. Kleine-Möllhoff[160]	LFP graphite cf. Majeau-Bettez[161]
Cell envelope	Aluminium, plastics, steel	6 %	25 %
Anode (negative electrode)	Active material, conductive soot, Binders, additives	21 %	10 %
Anode foil	Aluminium	11 %	10 %
Cathode (positive electrode)	Active material, conductive soot, Binders, additives	40 %	31 %
Cathode foil	Copper	5 %	5 %
Electrolyte		15 %	15 %
Separator	Polymer	2 %	4 %

LFP - Lithium iron phosphate

[159] Own compilation based on Wetzel, M. (2015); Moss, R. L. et al. (2011); Sullivan, J. L. and Gaines, L. (2010), p. 14.

[160] Cf. Kleine-Möllhoff, P. et al. (2012), pp. 25 - 28.

[161] Cf. Majeau-Bettez, G. et al. (2011), p. 6. (The lithium-iron-phosphate battery shown reflects a composition for an increased energy supply (high energy)).

Table 27 Typical lithium-ion battery composition[162]

Components	Percent Mass		
	Min.	Max.	Medium
Anode	15 %	24 %	19.5 %
Copper foil (electrode substrate - negative)	1 %	12 %	6.5 %
Battery grade graphite/carbon (negative electrode material)	8 %	13 %	10.5 %
Polymer (binder)	<1 %	10 %	approx. 5 %
Auxiliary solvent	<1 %	6 %	approx. 3 %
Cathode	29 %	39 %	34 %
Aluminium (electrode substrate - positive)	4 %	9 %	6.5 %
Positive electrode material - Lithium manganese oxide (LMO spinel); Lithium-nickel cobalt manganese oxide (Li-NCM); lithium iron phosphate (LFP)	22 %	31 %	26.5 %
Polymer/other (binder)	<1 %	3 %	approx. 2 %
Auxiliary solvent	<1 %	11 %	approx. 6 %
Separator	2 %	3 %	2.5 %
Polymer (polyolefin)	2 %	3 %	2.5 %
Cell casing	3 %	20 %	11.5 %
Aluminium casing and pouch material (Polypropylene resin)	3 %	20 %	11.5 %
Electrolytes	8 %	15 %	11.5 %
Carbonate solvents (ethyl carbonate, lithium fluoride, phosphorus pentachloride)	7 %	13 %	10 %
Lithium hexafluorophosphates (LiPF6)	1 %	2 %	1.5 %
Battery Management System (BMS)		2 %	2 %
Copper wiring		1 %	1 %
Steel		1 %	1 %
Printed wire board		<1 %	<1 %
Battery Pack Casing/Housing	17 %	23 %	20 %
Polypropylene/polyethylene terephthalate Steel (housing material)	17 %	23%	20 %
Passive Cooling System	17 %	20 %	18.5 %
Steel and aluminum (sheet metals)	17 %	20 %	18.5 %

[162] According to EPA (2013), p. 33.

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Im Auftrag des:
Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit
NATIONALE KLIMASCHUTZ INITIATIVE