Impulses for the Energy Transition

Rightsizing—but the right way

Design of battery storage systems for more sustainability in the energy transition

White Paper

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The High Performance Battery Technology GmbH based in Bonn, Germany, specializes in the research and development of high tech batteries.

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Content

00 Foreword

The energy transition is an enormous challenge. It touches the physical foundations of our society, affects all areas of life and therefore requires a profound and comprehensive transformation. Much is in motion, some is still unclear, a work in progress, with experimenting and researching, weighing up and prioritising.

This also applies to the role of battery storage for the energy transition. It is undisputed that they are indispensable for the switch to renewable energies. The current hype is correspondingly great. At the same time, it is becoming increasingly clear that the debate about the use of battery storage for the energy transition needs to be conducted more broadly, as there are still many blind spots, unreflective connections and unexplored possibilities.

This is where we come in with our Impulses for the Energy Transition.

This white paper focuses on the emerging topic of 'rightsizing battery storage'. It outlines the key points of a battery storage design that clearly goes beyond a mere 'less is also enough'. In addition, the relevant basics of battery design and life cycle assessment are conveyed in a practically relevant manner, as these are indispensable for a sustainability assessment of battery storage systems.

In this sense, the white paper is intended to contribute to the necessary debate on the use of battery storage for the energy transition in a technology-open and sustainability-oriented manner—as the key to an energy transition that is actually sustainable.

Prof. Dr. Günther Hambitzer
Managing Director of High Performance Battery Technology GmbH

Bonn, October 2021

01 Introduction

Battery storage systems are experiencing hype—but are they really sustainable?

Battery storage systems are experiencing enormous hype. They are being propagated as an essential component of a sustainable energy system. The spectrum of possible fields of application is broad: In addition to electric mobility, it is also stationary applications in industry and households that help to master the challenges of a renewable energy supply. Numerous gigafactories are currently being built, fueled by massive political support, which will bring an unprecedented amount of battery storage onto the market (CIC energiGUNE, 2021). And soon these batteries will begin their triumphal march in e-cars, industrial storage and household applications. A success story, then—for a sustainable energy supply of the future?

A real success story would have to be written differently.

The other side of the coin is that the production of batteries requires large amounts of resources and energy. This is accompanied by greenhouse gas emissions and other environmental pollution on a considerable scale. Today's battery hype could therefore turn out to be tomorrow's enormous resource and waste problem. In order to solve the sustainability problems of our current energy supply, new sustainability problems would have been created. A real success story would have to be written differently. Accordingly, the debate about the side effects of battery use is getting louder (Barske, 2020) (Flassbeck, 2020). Increasingly, approaches are being presented that could serve to align battery storage and its use more strongly than before with the requirements of sustainable development.

Oversizing consumes unnecessary resources, rightsizing corrects this in the right places.

Rightsizing is one of these approaches (Henßler, 2020). It is currently being discussed in the field of electromobility and essentially states that the development of traction batteries has actually led to oversizing. This is because most journeys made by car are over comparatively short distances. Many drivers do not need a vehicle that can cover 500 kilometres or more on one battery charge. So why lug around a battery pack that weighs several hundred kilograms and several thousand euros, and whose manufacture has a significant impact on the vehicle's environmental balance sheet? 'Less range is enough': that is the simple motto of the rightsizing approach in its current form.

It can involve much more than simply doing without—if it exploits the optimisation potential of battery technologies.

Rightsizing, however, can mean more—and do more. This becomes clear when one considers the dependency of battery size not only by the desired range (or other benefit), but also in particular by the available battery technology. Durability and specific energy, fast charging capability and deep discharge resistance are battery properties which, in combination, are decisive for the required battery size.

Thus, the battery technology determines the environmental balance of the respective applications, not least through its influence on the storage size.

A debate on battery rightsizing in this comprehensive sense is needed. On the one hand, this involves an understanding of the underlying interrelationships, and on the other hand, the associated sustainability potentials. Battery storage will only be able to make a real contribution to the energy transition if these sustainability potentials are systematically sought and exploited—as a central chapter of the success story that needs to be written.

This is the only way to exploit the sustainability potential of battery storage systems.

02 Battery rightsizing: More than sufficiency

'Less is more'—a central idea of the sustainability debate since the 1990s.

Installing smaller batteries for a shorter but still sufficiently long range is in line with the classic sufficiency approach to sustainability. Discussed since the early 1990s, this approach propagates a moderation of demands (Huber, 1994). More eco-efficiency would not in itself be sufficient for sustainable development: Efficiency gains often led to a more intensive use of the respective products, which nullified the originally intended resource savings. Therefore, it is important to stand up against excessive consumption demands and instead for a healthy, permanently environmentally compatible level of consumption.

However, sufficiency is not a foregone conclusion, and rightsizing can do more!

The approach is impressively simple: lower demands on range and thus on battery capacity lead to lower raw material and energy consumption for battery production, less weight and volume of the storage unit, lower costs and ultimately less waste. What more could you want? Indeed, sufficiency can contribute greatly to sustainable development (Bossert, et al., 2020). However, many people find it difficult to moderate their demands—not everyone, under current social conditions, will be enthusiastic about sufficiency measures. And: rightsizing batteries could make even greater contributions to sustainability if it involved more than simply downsizing batteries of a given technology.

The socio-technical complexity of battery use must be taken into account.

Moreover, the pure sufficiency approach does not do sufficient justice to the socio-technical complexity. For example, the range discussion is basically not only about the distance that can be covered with a single battery charge. Rather, everyday charging convenience and thus the battery's fast-charging capability play a decisive role in determining the range perceived as necessary. On the other hand, smaller battery storage units need to be charged and discharged more frequently compared to larger ones and therefore tend to be more affected by the negative effects of battery aging. Solving these practical challenges by oversizing batteries therefore seems simple at first, but will foreseeably lead to a significant resource and disposal problem. Ambitious rightsizing must also do justice to this complexity so that the energy transition can be financed in the long term (Bundesministerium für Wirtschaft und Energie, 2021).

Specific energy and its effects

A key parameter of battery storage systems is their specific energy: the maximum amount of electrical energy that can be stored in relation to the battery mass, expressed in watt-hours per kilogram (Wh/kg). While lead-acid batteries have specific energies of 30–40 Wh/kg and nickel-metal hydride batteries of 60–80 Wh/kg, values of 120–180 Wh/kg are often given for lithium-ion batteries—and even over 200 Wh/kg for electric cars. The specific energy thus varies greatly not only between different battery technologies, but also within the respective technology families. In fact, the range is much wider than the above values suggest. An analysis of the stationary lithium-based battery storage systems currently available on the German market, for example, gives the following picture (Figure 1):

The specific energy describes the ratio between storable energy and battery mass in Wh/kg.

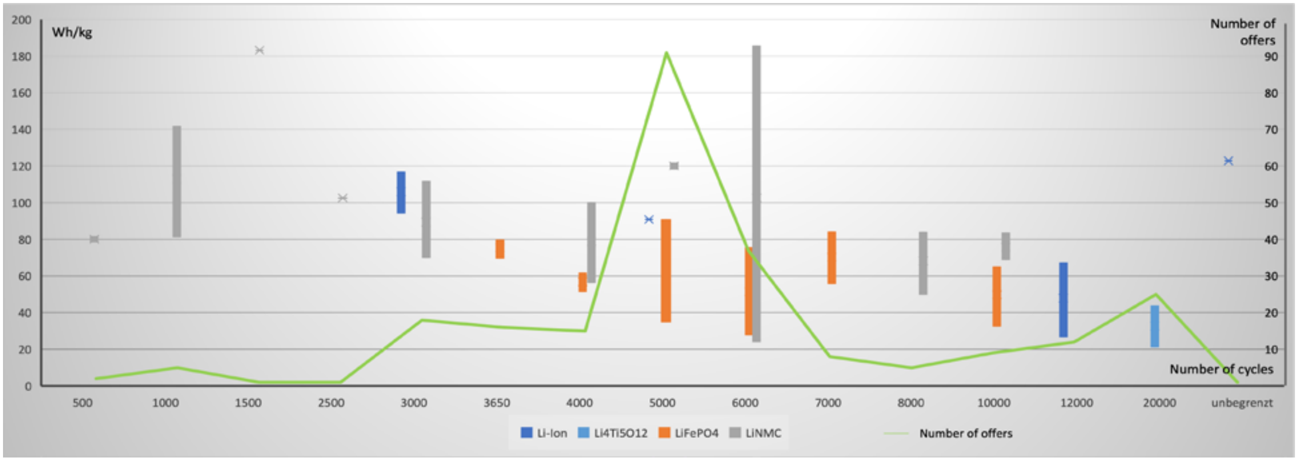


Fig. 1: Technology comparison for stationary lithium-based battery storage.
Source: Own calculation based on C.A.R.M.E.N. e. V. (C.A.R.M.E.N. e. V., 2021)

It can be seen that the specific energy of many of the batteries on offer is far below the range of 120–180 Wh/kg, namely in the range of 20–140 Wh/kg. This means that for an application requiring a nominal capacity of 10 kWh, depending on the specific energy, batteries with a mass of 56 kg (at 180 Wh/kg) up to 500 kg (at 20 Wh/kg) are required. All its components contribute to the mass of the battery storage: Electrodes such as electrolyte, separator and housing. Their material compositions and proportions of the total mass vary between the different technologies. For a well-founded, quantitative evaluation of the respective environmental effects—on the basis of an adequate, technology-dependent battery storage design—an ecological balance sheet consideration is therefore necessary.

The lower the specific energy, the heavier the battery storage—with consequences for resource requirements and the environment.

Nevertheless, as a rule of thumb, lower specific energies are associated with higher material requirements for a given application (i.e. a given amount of energy required, often referred to as 'capacity')—and this in turn tends to be associated with greater energy consumption, higher CO_2 emissions and greater other environmental impacts during manufacture. This is the simplest connection between the battery technology used, the 'size' (in terms of mass) of the storage device and the sustainability-relevant consequences of its manufacture.

Size matters—the size has a significant influence on the sustainability of the battery storage system.

Longevity: A decisive factor for sustainable battery storage systems

However, according to Figure 1, the current range of stationary battery storage systems harbours another, more important message: as the cycle life increases, the specific energy decreases. Storage with a relatively long lifetime of 7,000 or more charge cycles all have relatively low specific energies of less than 90 Wh/kg. Here, too, the links to sustainability are obvious: whenever batteries with a long cycle life are needed (for applications requiring frequent charging and discharging, for example), large, high-mass storage units with low specific energy are unavoidable according to the current market situation. In other words, battery size is the price that has to be paid for longevity, at least so far. And larger batteries have the disadvantages outlined above in terms of resource and energy consumption during manufacture.

With today's accumulators, longevity goes hand in hand with low specific energy.

The lifetime, however, has more far-reaching consequences for sustainability than the mere coupling to large storage units with low specific energy. It is, in itself, quite crucial to reducing the negative impact of battery storage on resource and energy consumption. When a battery reaches the end of its life—that is, when its capacity or performance is no longer sufficient for the given application—it must be replaced by a new battery. The production of a new battery requires a considerable amount of energy and resources, while the disposal of the old battery also creates a recycling or waste problem. Long-life rechargeable batteries therefore make a decisive contribution to minimising these production and disposal costs.

Durability reduces replacement and disposal and is the antithesis of the foreseeable recycling and waste problem.

If we look at the range of battery lifetimes in Figure 1, we see that their influence is enormous: a lithium iron phosphate ($LiFePO_4$) battery with a lifetime of 10,000 charge cycles, for example, only has to be produced and disposed of once, whereas two $LiFePO_4$ batteries with a life expectancy of 5,000 charge cycles are needed for the same application—which means that only part of the range in Figure 1 is considered.

The influence of longevity on battery sustainability is enormous.

The service life also has a decisive influence on the possible areas of application. The better the longevity, the more attractive the combination of different use cases on the same infrastructure (platform approach). This not only has a direct influence on the required storage dimensioning: this is significantly smaller compared to the individual case design. In addition, the platform approach also enables economic synergies that increase the overall attractiveness of storage deployment (Müller, 2018).

The longevity decides on possible areas of application and thus also on the economic efficiency of the battery storage system.

Fast-charging capability: Not only a question of charging comfort

The influence of battery characteristics on battery size is not always as obvious as in the case of specific energy and longevity. The property of fast charging capability is the best example of this. If it is given, a battery can be charged with large charging currents, i.e. within a relatively short time, without damaging the battery chemistry. In fact, this is not a matter of course: with current lithium-ion technology, fast charging generally exposes the battery to severe aging stress. For this reason, manufacturers usually recommend that batteries should only be fast-charged within a limited charging corridor—at most between state of charge of 20–80 percent. In this way, the negative influence of fast charging on battery aging can be kept within acceptable limits (Chargemap, 2021) (Sonnenberger, 2019).

Up to now, fast charging has been driving battery aging and thus reducing service life.

However, this procedure has a downside: If only part of the usable battery capacity can be charged quickly, only this part of the capacity is available for the application after fast charging. In the case of electromobility, this means that a comparatively short fast-charging stop can only extend the range of the vehicle by the said proportion. This is perceived by the user primarily as a limitation of comfort. In the current situation, in which long ranges play a central role in the debate about e-cars, this drives the manufacturers to a procedure that was already mentioned at the beginning: namely, the oversizing of the traction battery. If the capacity of the entire battery is increased by 50 percent, for example, the capacity of the fast-charging corridor is also increased by 50 percent.

In electromobility, a lack of fast charging capability leads to the ‘oversizing’ of traction batteries.

A lack of fast charging capability is thus a driver for the overdimensioning of batteries—at least in cases where fast charging capability is important. This is obvious in the case of electromobility, but also applies to other fields of application, such as grid balancing for primary control in the stationary sector. Here, a certain amount of power has to be supplied over a quarter of an hour when needed. The required storage size is essentially dependent on its maximum permissible charging or discharging speed. An example: For 1 MW of power

Stationary applications are also affected by oversizing.

over a power period of a quarter of an hour with a maximum permissible charging and discharging speed of 1 C (one-hour charging and one-hour discharging), the battery storage must have a size of 4 MWh. At twice the permissible charging and discharging speed (2 C, half-hour charging and half-hour discharging), 2 MWh would be sufficient for the same performance. Improved fast charging and discharging capability saves half the resources in this example under otherwise identical assumptions (Kompetenznetzwerk Lithium-Ionen-Batterien e. V., 2021).

Deep discharge resistance: The unrecognised potential

Conventional batteries must always be charged to a certain degree.

There is another battery property that must be placed in the context of rightsizing: Deep discharge resistance. Conventional lithium-ion batteries must always be charged to a certain degree; otherwise the battery chemistry would be irreversibly damaged. The proportion of the total capacity that falls out of use for this reason is usually up to 20 percent. This means that a significant portion of the battery capacity is basically unusable. Nevertheless, it must be produced and disposed of or recycled at the end of the battery's life—and, like the usable part of the capacity, it contributes to the energy and resource requirements of the entire battery storage system (Wikipedia, 2021).

With deep discharge resistant batteries, the same benefit can be realized with less battery.

The unusable capacity base of lithium-ion storage devices is rarely addressed in the context of battery sustainability. However, it is not certain that batteries will still have the same ageing protection requirements in the future as the rechargeable batteries available today. For in research and development there are already battery technologies based on lithium-ion, which are characterized by deep discharge resistance. Deep discharge resistant batteries allow the use of their entire capacity; deep discharge does not damage the battery chemistry here. The impact on battery size is obvious: the same usable capacity can be realized with less battery. The efficiency of the use of energy and resources is thus considerably increased.

It is the combination of properties that counts

The combination of the properties is decisive for the realisable sustainability potential.

When it comes to ambitious rightsizing of battery storage systems, four properties play a central role: specific energy, longevity, fast charging capability and deep discharge resistance. All of these have a decisive influence on the size of the storage system. However, they can only develop their full sustainability potential if they are combined with each other. However, this presupposes that they can actually be combined with each other. As already outlined, this is not the case with the batteries currently available: they are characterised either by (relative) longevity or by high specific energy, have only limited fast-charging capability and are not resistant to deep discharge. However, battery research is progressing rapidly. Technologies are on the verge of market maturity that promise great progress in the realization of all the above-mentioned battery properties. And even with batteries that are already available today, ambitious rightsizing is possible that goes beyond the mere sufficiency approach: precisely in that the available degree of longevity, specific energy, etc. is taken into account in the choice of technology and storage design in a sustainability-oriented manner.

The operating strategy of the use case provides the framework for the battery design.

The design of battery storage systems is not a trivial task. It requires precise knowledge of the application field as well as the operational strategy. On this basis, the required storage size can be determined in conjunction with the characteristics of the available battery technologies. In the case of large-scale applications, such as industrial storage systems, it is generally worthwhile to design the battery individually. The following applies: the better the battery properties, the more the operating strategy can be geared to operational use; the worse, the greater the importance of optimising the compromise between battery ageing and application.

The minimum size required as the basis for a comparable life cycle assessment results from the battery design.

Rightsizing of battery storage systems ultimately has a considerable influence on their life cycle assessment. Here, the environmental impacts over the entire product life cycle are taken into account, from the extraction of raw materials to the refinement, their installation and use, to replacement and disposal. Larger battery storage systems obviously consume more raw materials than smaller ones. Nevertheless, it is crucial to bring different technologies to a common denominator before comparing them. This is usually the application and the resulting battery design depending on the storage technology. A comparison of the environmental impacts at the level of the energy content measured in kWh, on the other hand, is regularly misleading in the case of otherwise different battery technologies. The life cycle assessment method, in conjunction with the battery design, allows a genuine comparison to be made between different storage technologies—even beyond battery storage.

In the future, the decision on storage technology will have to be much more oriented towards sustainability.

The final choice of storage system is ultimately made in an individual field of tension between partially diverging objectives. In view of the environmental impact of the energy transition, it is of relevance to society as a whole how well the requirements of battery design and the environmental balance can be met in a sustainable manner through ambitious rightsizing.

03 Design of battery systems

Battery storage systems are used in numerous applications in the context of energy systems. These include, for example, increasing the self-use of PV energy, reducing peak loads, grid-serving modes of operation (Hesse, et al., 2017) or combined approaches (Müller, 2018). In these applications, the correct design or dimensioning of the parameters of the battery system plays a decisive role in achieving the respective overriding objective—for example, cost-effectiveness, efficiency or emission reduction.

Battery storage systems have a wide range of applications. The right design is crucial for the achievement of the objective.

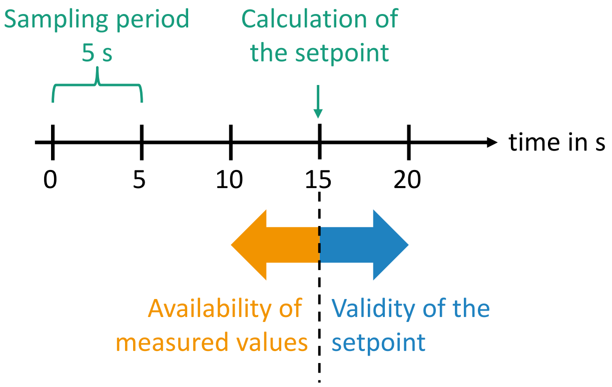
Each battery technology has specific properties that influence the design. A fundamental parameter is the capacity of the battery, which limits the energy content available to the application. The C-rate (the ratio of the charging/discharging current to the battery capacity) (Bergholz, 2015) also determines the maximum charging and discharging capacity of the battery system. It limits the available power. Further parameters, such as the operating point-dependent (i.e. dependent on the power called up) efficiency of the converters, the charge-state-dependent maximum power of the battery or also the self-discharge rate of the battery system, further limit the usable capacity and power in reality. These boundary conditions must be taken into account when designing battery storage systems.

An abundance of parameters influence the practical use and thus the design of battery storage systems.

Operating strategies must be considered

For the operation of a battery system, an operating strategy is necessary which calculates the power demand on the system according to the respective objective pursued. A further challenge arises in the operating strategy: While measured values from the energy system (for example, the electrical reference power) always refer to a time interval that has already passed, the target power of a battery system always lies in the future (see Figure 2). Whether the battery can also implement this power demand depends on the restrictions described above, especially the state of charge of the storage unit. Therefore, if a power demand is placed on the battery system, it must then be checked whether it could also be implemented in the desired manner and what the effects are on the controlled variable. When designing batteries, the operating strategy must therefore also be mapped.

The operating strategy is decisive for every design. It defines the framework for the requirements of the respective battery technology.



Description of the example

- Assumption: Calculation of the setpoint at 15 s
- The past measured values are available for the calculation
- For a sampling period of 5 s, the averaged value between 10 and 15 s is being used
- In contrast, the setpoint is valid from the time of calculation, in the example between 15 and 20 s

Fig. 2: Example of the availability of measured values and the validity of setpoints with a sampling time of 5 s

Use case peak load reduction

According to Section 17 (6) StromNEV (Electricity Network Charges Ordinance), industrial companies and larger consumers are not only billed according to the total energy purchased from the energy supplier. The annual—or, in accordance with Section 19 (1) StromNEV, the monthly if there is a very high, time-limited power consumption—load peak is also included in the billing. This corresponds to the highest 15 minute average power consumption during the billing period. For a load peak of 1.2 MW, corresponding performance-related costs of 120,000 € are incurred at a performance price of 100 €/kW. In order to achieve savings in the power-related costs, the load peaks must be reduced within a billing period. The relationship between the performance and energy-related costs depends on the underlying load profile: In the case of an annual load profile with a few very high load peaks and a low base load, the power price plays a much greater role than in the case of a more even annual load profile.

Peak load reductions are economically attractive applications for stationary battery storage.

If certain conditions are met, the Electricity Network Charges Ordinance also allows ‘individual network charges’, which are regulated in Section 19 (2) StromNEV. These allow a reduction of the publicly tendered grid fee by up to 90 %. One application of this is atypical grid usage, in which peak load reduction only has to be implemented within predefined time windows (so-called high-load time windows). These are defined annually by the grid operator. In contrast to the determination of the general charge, in which the annual or monthly load peak is decisive, only the highest peak load within the peak load time window plays a role in atypical grid usage. The load peaks must be

Atypical and intensive grid use is worthwhile for both the grid operator and the electricity customer.

reduced by at least a specified minimum reduction (so-called materiality threshold). Another possibility for an individual grid charge is intensive grid use, where the aim is to achieve at least 7,000 annual hours of use. The prerequisite for this is an energy demand above 10 GWh (Bundesnetzagentur, 2011). If the expected energy demand is around 14 GWh, this annual usage period is achieved if the load peaks are reduced to 2 MW. In principle, the following applies: the more uniform the power consumption, the higher the resulting annual service life t_{Benutz}.

$$P_{max,15\,min} = \frac{E_{Bezug}}{t_{Benutz}} = \frac{14\,GWh}{7000\,h} = 2\,MW$$

If successfully applied on the consumer side, peak load reduction leads to savings in electrical energy costs. In addition, it also contributes to relieving the electricity grids and grid infrastructure, as these must be dimensioned for the maximum load case. The reduction of peak loads thus contributes to avoiding grid expansion (Rahmann, et al., 2017) as well as the connection of inefficient and expensive peak load power plants (Van den Bergh & Delarue, 2015).

Storage facilities can contribute to a reduction in the need for grid expansion and are therefore an important component of the energy transition.

Design of batteries for peak load reduction

In order to be able to use a battery system optimally for peak load reduction, dimensioning is necessary, taking into account the previously described boundary conditions. A higher reduction of peak loads does not necessarily lead to higher economic efficiency (Prasatsap, et al., 2017), which is why the price model must also be taken into consideration. The comparison of a conventional ('simple') design procedure, in which an ideal battery system and an ideal operating strategy are assumed, with a procedure in which all limitations are modelled and taken into account, shows battery capacities that are underdimensioned by up to 75 % and, in extreme cases, 43 % too low in nominal power (Lange, et al., 2020). The load profiles used (see Figure 3) represent different scenarios:

The economic efficiency and target achievement of the operating strategy depend to a large extent on the dimensioning of the storage facilities.

Load profile 1: A single load peak with a high output, for example due to the connection of a large consumer.
Load profile 2: Typical daily load profile, which is in part strongly influenced by PV self-generation.
Load profile 3: Typical daily load profile with periodic load peaks, for example due to repeated connection of a production plant.
Load profile 4: Several load peaks of different lengths with different power as a combination of load profiles 1 to 3.

The resulting design for the required capacity based on the outlined load curves is shown in Figure 4. The required battery capacity (y-axis) is shown depending on the selected reference limit (x-axis). The simple design procedure ('conventional') always shows too low capacities compared to the advanced procedure—in which all relevant boundary conditions of the battery as well as a real-time algorithm are taken into account. The operating strategies used here were implemented in a Real-world Lab for decentralized energy systems at Fraunhofer IISB (Oechsner, et al., 2019) and successfully validated (Lange & Kucera, 2019). Furthermore, the operating strategy is used in the context of a comprehensive load management system (Lange, et al., 2019).

Industrial storage facilities are often designed too small for target achievement. This endangers their economic efficiency.

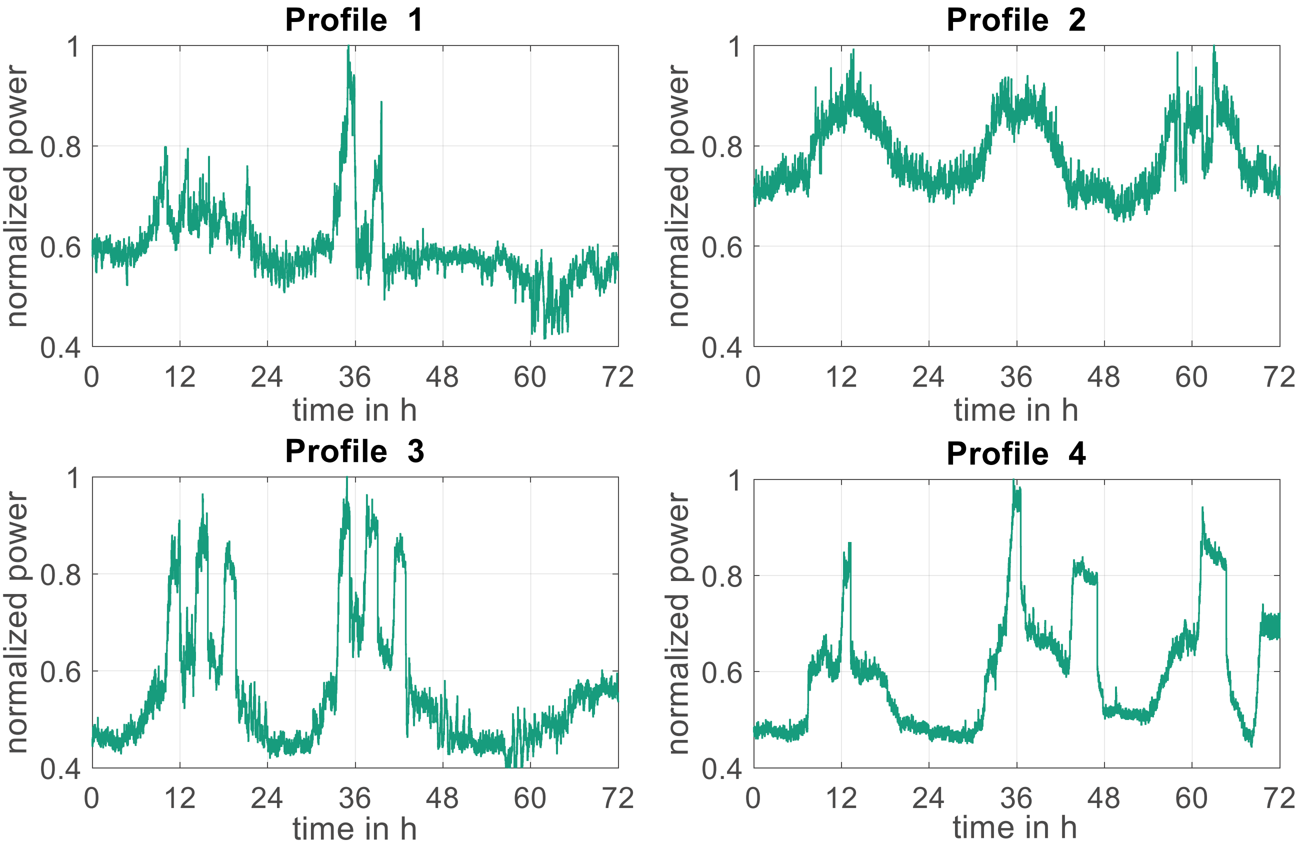


Fig. 3: Exemplary normalized load profiles as a basis for the design of a battery system for peak load reduction, representation translated from Lange et al. (Lange, et al., 2020)

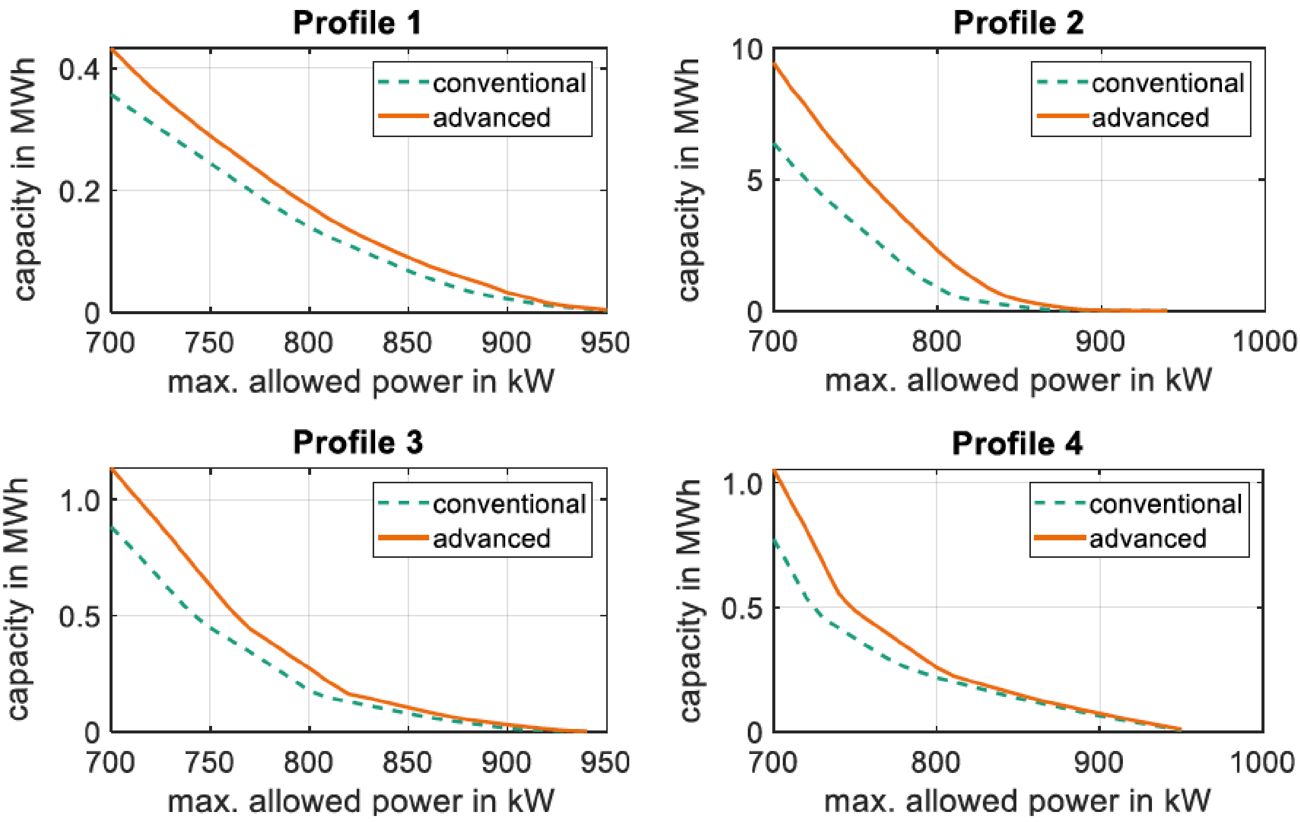


Fig. 4: Exemplary design of the required battery capacity for four load profiles based on a conventional and an advanced design procedure, representation translated from Lange et al. (Lange, et al., 2020)

Consideration of boundary conditions increases design accuracy

Only the consideration of all boundary conditions and specific properties enables a storage design in the economic optimum.

In the case of the described peak load reductions, insufficient battery capacity or performance can play against the efforts already made throughout the billing period if the decisive load peak could not be successfully reduced due to a lack of capacity. In extreme cases, this may result in no savings being achieved during the billing period. The results thus show that a suitable design for the application is absolutely necessary in order to achieve the desired goals in reality. For this purpose, all relevant boundary conditions have to be mapped and a comprehensive evaluation has to be performed. In principle, this can also be applied to other fields of application for battery storage systems and to combinations of different objectives. This consideration is also essential for applications such as self-supply optimisation with energy from PV and wind and opens up high potentials for an economic, but also environmentally friendly energy supply in the context of the entire energy system. Instead of a few large battery storage units, one approach is to use decentralised storage units (which can be implemented, for example, in the context of the charging infrastructure, keyword ‘virtual power plants’) in order to be able to optimally operate and use large-scale and ‘distributed energy systems’.

04 Life cycle assessment as a basis for sustainability assessments

Well meant is not necessarily well done: Only sound methods can lead to reliable sustainability assessments.

Battery storage systems for the energy transition must meet numerous requirements. Technical and economic aspects such as safety, durability and efficiency are fundamental. Since the energy transition is oriented towards the guiding principle of sustainable development, further requirements are coming into focus. The ecological sustainability goals of climate protection and resource conservation are often at the centre of public debate. The energy system of the future should not only help to alleviate the problematic consequences of the current energy supply, but also not create any new problems. This naturally also applies to the battery storage systems used.

The evaluation of new technologies may seem simple at first glance: Aren't quiet, (locally) emission-free electric cars obviously ecologically beneficial? On closer inspection, however, such statements prove to be very challenging. This is because technology impacts are often not obvious: They can occur far away in time or space, or they can arise as a result of a complex interplay of factors. Battery raw materials are extracted in distant parts of the world, sometimes with serious environmental consequences; effective recycling processes have yet to be developed for the future disposal of the storage devices. Against this background, it is understandable that sustainability assessments must be scientifically sound in order to produce reliable results.

Life cycle assessment enables a comprehensive consideration of all relevant environmental effects and is scientifically recognized.

The life cycle assessment method provides such a scientific basis for sustainability assessments (Umweltbundesamt, 2018). A life cycle assessment claims to determine all relevant environmental impacts of an object under investigation. This includes two aspects: Firstly, the entire life cycle of the object under investigation is considered 'from cradle to grave', i.e. from production to disposal or recycling. Secondly, for each stage of the life cycle, the associated material and energy flows are traced back as far as they are relevant and decisive. This means that not only the use phase of an electric car, for example, is relevant, but also its production and disposal; and not only the greenhouse gas emissions during the production of the traction battery are taken into account, but also those that occur during the extraction of all relevant preliminary products.

Life cycle assessments serve different purposes. First of all, they can ensure that people are aware of the relevant environmental impacts of a product in the first place. This is—and therein lies the second application purpose—an important prerequisite for making production processes and modes of use more sustainable: If it is known at which points particularly high (or particularly easily avoidable) emissions occur, improvements can be achieved in an efficient manner. Thirdly, life cycle assessments are used to compare products and processes. They ensure that assessments do not stop at the obvious technological consequences, but are comprehensive in the truest sense: scientifically sound, taking into account all relevant consequences over the entire life cycle.

This makes life cycle assessments a valuable tool, especially for social discussions and political decisions. Another advantage of the method is that it has been used since the 1970s and has long been internationally standardised in ISO standards 14040 and 14044 (DIN EN ISO 14040, 2009) (DIN EN ISO 14044, 2018). This means that LCAs that comply with these standards have a high degree of comparability, as the approach and data basis are shared. This does not mean, of course, that LCA comparisons can show which product is indisputably the better one in every respect. As their name suggests, they only concern the ecological assessment dimension, not technical, economic or other aspects. In particular, however, assumptions and presuppositions must be made for each LCA, which have a decisive influence on the result.

Embedded in an argumentative framework, life cycle assessments are valuable tools for social discussions and political decisions.

Main features of life cycle assessment

Every standard-compliant life cycle assessment comprises four steps: (1) definition of the objective and the scope of the study, (2) preparation of the life cycle inventory, (3) estimation of environmental effects and (4) interpretation and evaluation.

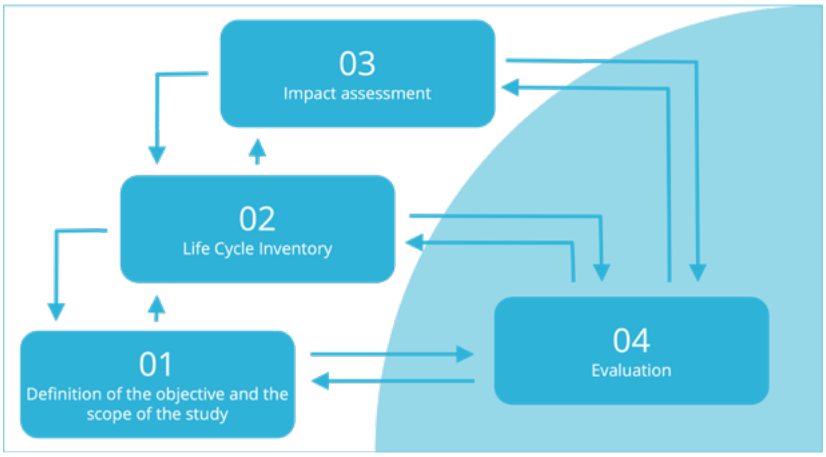


Fig. 5: Phases of a life cycle assessment (based on DIN EN ISO 14040, 2009)
Source: Own

(1) The definition of the objective and the scope of the study has a considerable influence on the entire course of the study—it must therefore be carried out with particular care. The linchpin of comparative life cycle assessments is the so-called functional unit. This is a quantitative reference value against which the alternative products or processes are examined and ultimately compared with each other (Graubner & Pohl, 2015). If, for example, the ecological advantage of cloth or disposable diapers is being examined, the functional unit would be 'a diaper' or 'a childhood with diapers'. The difference is considerable: Children with cloth diapers become 'dry' considerably earlier, and the number of diapers per childhood is correspondingly lower. Here, as always in LCAs, it must be reflected and justified which functional unit is reasonable or even obligatory for the application of the study.

The definition of the objective and the scope of the study significantly influences the following steps of a life cycle assessment.

Furthermore, it is a question of the system boundaries of the LCA: What is within, what is outside the scope of the analysis? Does the analysis end with the disposal of a product, or should recycling and (partial) reuse be included? The choice of cut-off criteria also has a limiting effect: Which inputs and which outputs can be neglected and which cannot? If a factor no longer has a significant influence on the LCA statement, effort can be saved. Due to their formative function for the entire study, transparent documentation of all these settings is essential.

(2) The life cycle inventory quantifies all relevant input and output flows over the entire life cycle of a product system (Umweltbundesamt, 2018). These input flows include the raw and basic materials for all parts of the product. Output flows consider not only greenhouse gas emissions, but also waste and other environmental impacts. This inventory of the object under investigation leads to the calculation of the corresponding life cycle inventory results.

'From cradle to grave': The life cycle inventory provides an inventory of the object under investigation over its entire life cycle.

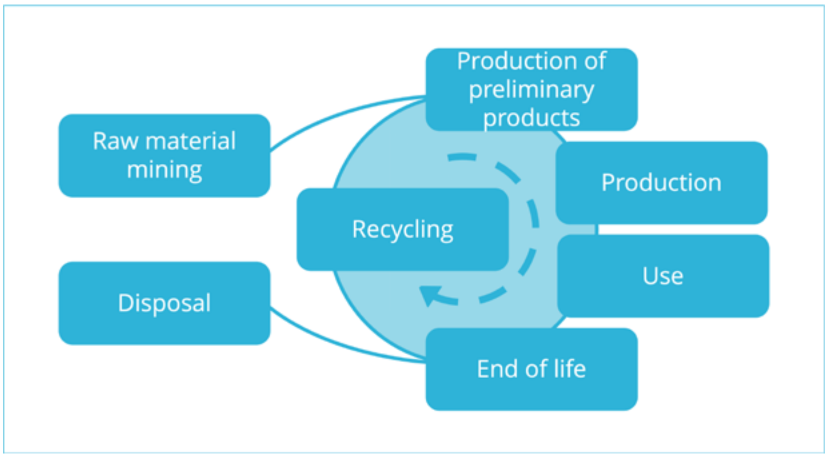


Fig. 6: Holistic balancing based on the life cycle assessment cycle (Fraunhofer Institut für Bauphysik (IBP), 2020)
Source: Own

(3) In the impact assessment, the quantified life cycle inventory data are assigned to specific ecological impact categories. Common impact categories include in particular:

The impact assessment assigns the life cycle inventory results to specific environmental impacts. Recognised data sets ensure comparability.

- Primary energy non-renewable (PEne): Sum of the primary energy consumption of non-renewable energies (hard coal and lignite, oil, natural gas and uranium) in connection with the production, use and disposal of an economic good.
- Primary energy demand renewable (PEe): Sum of the primary energy consumption of renewable energies (biomass, solar radiation, geothermal energy, hydropower and wind power) in connection with the production, use and disposal of an economic good. Together with PEne, this results in the total primary energy consumption of an economic good.
- Global warming potential (GWP): Sum of gas emissions that contribute to the greenhouse effect.
- Ozone depletion potential (ODP): Sum of the ozone-depleting potentials of ozone-depleting substances (including halocarbons such as CFCs and nitrogen oxides (NOX)).
- Photochemical ozone creation potential (POCP): Sum of the potentials of certain trace gases (e.g. nitrogen oxides and hydrocarbons) to form ground-level ozone under the influence of UV radiation. They are formed preferentially during incomplete combustion, during the handling of petrol and when organic solvents enter the air. The resulting effect is also referred to as summer smog.
- Acidification potential (AP): Effect of emissions (including sulphur dioxide and nitrogen oxides) on soil acidification through leaching from the atmosphere.
- Eutrophication potential (EP): Sum of the input of emissions (including phosphorus and nitrogen compounds) as nutrients into soils and water bodies.

This process of linking life cycle inventory data with impact categories is also known as classification. The greenhouse gas potential, for example, includes not only CO_2 emissions, but also methane and some other greenhouse gases. The impact categories are then translated into adequate impact category indicators in the course of so-called characterization. For example, the greenhouse potential is expressed in CO_2 equivalents (CO_2-eq.). This indicator thus encompasses all climate gas emissions, brought down to a common denominator.

Indicators can bring different effects of the same impact category to a common denominator.

For example, the GWP of a kWh of electricity according to the German electricity mix is characterised by the relevant life cycle assessment dataset as 0.54 kg CO_2-eq. per kWh (Bundesministerium des Innern, für Bau und Heimat (BMI), 2020). There are now generally recognised environmental product declarations (EPDs) for many products that contain this characterisation for use in LCA.

(4) The final evaluation and interpretation of an LCA primarily serves to derive conclusions and present the results in a comprehensible way. Reporting and critical review as integral parts of a LCA are important for the communication of LCA results and their integration into decisions for action.

Evaluation, interpretation, reporting and critical review are integral parts of a life cycle assessment and important for the communication of the results.

Life cycle assessment of battery storage systems

If battery technologies are to be compared with each other, the functional unit must take into account the specific properties of the technologies under consideration. Challenges arise primarily from the different aging effects: Each technology has specific maximum achievable cycle numbers, degradation mechanisms, and charge and discharge losses. Thus, it can make a decisive difference in terms of life cycle assessment whether the intermediately stored energy per charging cycle or the intermediately stored energy over the entire lifetime of the battery storage system is considered.

A functional unit that can bring all these factors down to a common denominator is the effective energy stored over the entire use phase, measured in kWh (kWh_{eff}). It allows a comparison of environmental impacts not only between different battery technologies, but also between different storage technologies. The question is how much energy (net) can actually be extracted from the storage system for the application under consideration. When comparing a fuel cell vehicle with a battery electric vehicle (BEV), it is not a matter of comparing the range of a tankful. Rather, the environmental impacts result from all the steps that are required for the effective mileage achieved—from the raw materials through production and use to disposal.

The effective energy stored over the utilization phase (kWh_{eff}) is suitable as a functional unit to make different technologies comparable.

Before defining the scope of the study (and thus also the process steps to be analysed), it must be decided which use case is to be considered at all. There can be no general life cycle assessment for all applications of a storage technology: The assembly of a large number of individual storage cells into storage modules, the integration of the required storage management system and the installation in the application (e.g. in a vehicle or in a property) must always be considered for the specific application. For comparisons, it makes sense to go to the level of the storage cells. These are specified and can be used in different storage setups. In conjunction with appropriate modelling of the entire life cycle, the cell level can thus serve as a universal reference basis for technology comparisons on a life cycle basis.

The use case determines the scope of the investigation, the individual battery cell is then the focus of the technology comparison.

The ISO standards for life cycle assessment only provide a very rough classification of life cycles. For the application in studies, for example for the analysis of energy storage systems, it is expedient to go into more detail. For this purpose, it makes sense to use a structure that has been developed in the field of life cycle assessment of buildings. It also represents a recognised reference framework (see Fig. 7). In addition, a wealth of detailed basic data sets can be taken from the work of the construction industry (DIN EN 15978, 2012) (DIN EN 15804, 2020).

The construction industry is an important pioneer of LCA: It provides a recognised frame of reference that can also be used for technology comparisons of battery technologies.

The manufacturing phase is the first life cycle phase to be considered. This includes (1) the extraction of all raw and basic materials required for the storage cell, (2) their transport to the production site and (3) the further processing and assembly into the finished cell. Basic data for life cycle assessments are available for both raw material extraction (e.g. nickel, lithium, etc.) and transport routes (sea and inland waterways, rail, air and road, including load factor and empty runs). In addition to the list of ingredients of a battery technology, its energy density and deep discharge resistance also influence the quantities of raw materials required. They therefore have an effect above all in the manufacturing phase. With regard to the process step of assembling the storage cell, the necessary use of energy and operating materials (inputs) as well as the creation and disposal of by-products (outputs) such as waste are taken into account.

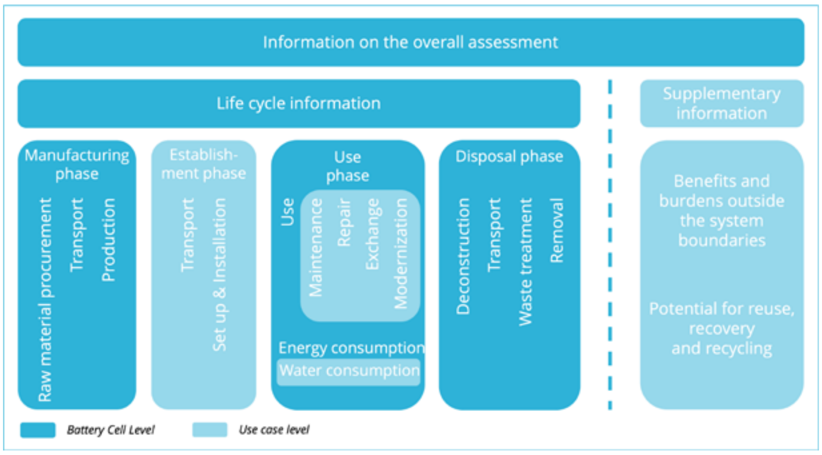


Fig. 7: Life cycle phases (based on DIN EN 15978, 2012 and DIN EN 15804, 2020)
Source: Own representation

The raw materials used as well as the battery properties of energy density and deep discharge capacity have an effect particularly in the manufacturing phase.

The use phase is the second and central life cycle phase to be considered. Here, the energy consumption during operation of the battery storage unit is considered above all. Capacity reduction, increase in internal resistance, fast-charging capability and cycle stability have an impact on the ageing behaviour of the battery and thus primarily affect the energy consumption in the use phase. The longer the period under consideration, the more dominant the effect of the use phase on the life cycle assessment. Even for short life cycles, the comparison of storage technologies shows that the use phase is the main driver of the environmental impact—not the much-cited ‘backpack’ with which the technologies emerge from the manufacturing phase.

The battery characteristics capacity decrease, increase in internal resistance, fast-charging capability and cycle stability influence the ageing behaviour and determine the energy consumption in the usage phase.

Finally, the disposal phase models the end of the life cycle of the storage cells: This includes (1) the removal and dismantling of the batteries, (2) the transport to the collection point, (3) the actual waste treatment and finally (4) the landfilling of the components that cannot be recycled.

If the storage cells considered so far are installed in a specific application, this makes it necessary to extend the life cycle analysis. In addition, there is, for example, the construction phase, which includes transport to the installation site of the storage facility and its assembly. The use phase is extended to include the components (1) inspection, maintenance and cleaning, (2) repair, (3) replacement and exchange, and (4) modernisation. Additional water consumption is also included.

For the comparison of technologies, the decisive question is how much capacity of the respective storage technology is effectively needed to achieve the same intermediate storage result. Flammability and explosion hazard only have an effect in case of damage.

In particular, taking into account the different ageing behaviour of different storage technologies over the period of use may reveal that replacement and exchange are required. If one normalises the consideration on this basis, the question arises as to how much capacity of the respective technology is effectively required to achieve the same intermediate storage result. For example, if one compares battery technologies that are similar except for aging, it is obvious that more short-lived than long-lived batteries are needed to achieve the same storage performance. Accordingly, the LCA of the rapidly aging technology must consider more storage cells for the same use case. For the concrete replacement requirement in the technology comparison, the following applies: The more intensive the use of the battery storage system, the higher the replacement requirement for the battery cells with the less favourable properties. Flammability and explosion hazard only have an effect in case of damage and are not considered further in the logic of a life cycle assessment due to the large number of preventive measures.

Finally, there are further credits and burdens outside the system boundary: Any secondary and/or energy raw material potentials from reuse, recovery and recycling are no longer within the system boundaries and may have to be allocated to a new product or process in life cycle assessment terms.

The results of life cycle assessments are controversially discussed. It is therefore all the more important to set the premises carefully when defining the objectives and the scope of the study.

The importance of the final evaluation and interpretation of a life cycle assessment can be seen in the debate about the mobility of the future. A good example is provided by the study of the German economist Hans Werner Sinn and his co-authors on the comparison of diesel engines and electric mobility (Buchal, 2019) and the controversy that followed (Diethelm, 2019) (Hajek, 2019). Criticism was mainly voiced regarding the selection of vehicles, the laboratory value procedure, the assumed battery lifetime, the end-of-life scenario, the consideration of components and the energy sources used (Schwierz, 2019). The discrepancies between these and the results of other studies underline the importance of careful selection and transparent communication of the premises for any technology comparison (Agora Verkehrswende, 2019).

Life cycle assessments as a seal of quality

A life cycle assessment can provide decisive competitive advantages: The environmental impacts associated with a product are increasingly relevant to decision-making.

Life cycle assessment is not an end in itself. It not only has the task of enabling a comprehensive environmental assessment and making the statements comprehensible and thus verifiable. It is also increasingly becoming a differentiating factor and a unique selling point in the competitive comparison of technologies. Are hydrogen-based or purely battery-electric drives more suitable for truck transport from an ecological point of view? And, with regard to purely battery-electric drives: Which battery (technology, raw materials used, production process, etc.) is the most advantageous from an ecological point of view? These types of questions can be answered comprehensively and scientifically with the help of life cycle assessments. This allows generating unique selling propositions that can be used on both the supplier and consumer side.

Storage technologies can also adopt life cycle assessment in the form of a seal of approval—even at the level of the same technology: If a manufacturer uses raw materials from critical sources, this means a disadvantage compared to a competitor who obtains his raw materials from more sustainable sources. With a mandatory life cycle assessment, technology providers thus have an important design element in their hands to influence the energy transition in a sustainable manner in every respect.

The construction industry can also be a role model for storage technologies in the use of quality labels.

Here, too, the construction industry can serve as a role model: The German Sustainable Building Certificate has become the leading certification system for sustainable buildings. This involves the evaluation of buildings, e.g. with regard to their ecological sustainability—a topic that can be assumed to have a certain proximity to a large number of applications of storage technologies.

05 Conclusion and outlook

Rightsizing is an important building block for the sustainability-oriented use of battery storage. However, in order to exploit its full potential, rightsizing must go beyond mere sufficiency—by reflecting the role of specific energy, longevity, fast charging capability and deep discharge resistance for battery dimensioning and taking them into account in practice. This is already possible and desirable for batteries available today. In particular, however, it should be a matter of assigning due importance to these very properties in battery research and development.

Ambitious rightsizing can help to significantly reduce energy and resource requirements from cradle to grave. At the same time, the practical and economic attractiveness of the battery technology used increases considerably: The reduction in the size and mass of the battery storage is a decisive advantage for numerous (not only mobile) applications. And new fields of application and possibilities (such as the bundling of different use cases on a shared infrastructure, platform approach) can be developed.

The automotive industry's demand for batteries at a price of 60 USD/kWh is a clear counter to this in the current technological environment, as such prices are primarily at the expense of longevity. At the same time, this price does not include compensation for environmental impacts. Rather, the costs are transferred to the general public (Deloitte, 2020).

However, the realisation of the technical and economic synergy potential of the platform approach is often hindered by current regulation. To date, storage facilities have been classified as consumers and thus charged grid fees for both charging and discharging—a situation that urgently needs to be remedied for a successful energy transition. For storage technologies to be used adequately, they must be accepted as the fourth pillar of energy supply. This is the only way to balance generation and consumption as the share of renewable energies in the energy mix grows, thus ensuring affordable security of supply (Bundesverband Energiespeichersysteme e. V. (BVES), 2020).

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07 Author profiles

Dr. phil. Marc Dusseldorp, Dipl.-Geoökol., has been a research associate at High Performance Battery Technology GmbH since January 2020. There, he is primarily concerned with issues relating to the sustainability of battery storage systems for the energy transition. Previously, he was employed at the Institute for Technology Assessment and Systems Analysis (ITAS) of KIT and at the Office of Technology Assessment at the German Bundestag since 2004, among others as coordinator of an international graduate school on energy futures. Since 2005, he has been a lecturer at KIT. Besides his employment, Marc Dusseldorp works as a freelance scientist. His work focuses on the methodology of sustainability assessments, as in his dissertation on the topic of 'Sustainability Goal Conflicts', as well as on sustainability transformation.

Dr. rer. pol. Sebastian Heinz, MSSc Human Geography, has been Chief Sales Officer of High Performance Battery Holding AG since June 2018. Previously, he was responsible for the Internet of Things (IoT) in business customer sales at Telekom Deutschland. With his dissertation on market development in a cooperative model, he developed an alternative strategy for the voluntary introduction of smart metering systems in Germany. The approaches developed therein are also suitable for the use of battery storage systems and thereby tap the potential of platform models for the energy industry. In 2018, he also founded the Institute for Innovation and Cooperation Management (Incoom), which specialises in business model development that are sustainable in every respect.

Dr.-Ing. Christopher Lange, M.Eng. in Electrical and Microsystems Engineering, has been a research associate at Fraunhofer IISB in Erlangen since 2014, where he works on the automation, simulation and optimization of sector-coupled energy systems. His focus is on the development and implementation of intelligent operating strategies for the optimal use of energy technology components (e.g. battery storage, CHP, heat/cold storage, H_2 components) to reduce peak loads, optimize self-sufficiency and/or increase efficiency. These operating strategies are used, for example, in energy management systems, building control systems or plant control systems. As part of his scientific work, Christopher Lange wrote his doctoral thesis on the topic of peak load reduction across energy sectors.

Dr.-Ing. Sebastian Pohl, Dipl.-Wirtsch.-Ing., DGNB Senior Auditor, WiredScore AP, Auditor GEFMA 160, has been a member of the management and shareholder of LCEE, a spin-off of TU Darmstadt, since 2015. There he deals with issues of sustainable construction, especially in the building materials and construction supply industry. In particular, he accompanies life cycle assessment and certification projects of construction projects according to national and international systems and advises clients from the real estate industry. After studying industrial engineering, he initially worked for a well-known management consultancy and in 2010 moved to the TU Darmstadt as a research assistant, where he also completed his doctorate in 2014. He is the author of numerous specialist articles and a lecturer at the TU Darmstadt and the FH Münster.

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