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Sustainable development

A second life for used batteries from electric vehicles

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Society, politics, and industry are currently grappling with the omnipresent question of »What should be done with the old batteries of electric vehicles when they are no longer reliable enough or have reached the end of their lifetime?« Scientists at Fraunhofer LBF, led by sustainability expert Dr. Dominik Spancken and scientist Eva Stelter, have investigated this question in a structured way. In most cases, decommissioned batteries that are still fully functional can be given a second life in stationary energy storage systems, for example. This means that the resource-intensive battery cells remain sustainable and in use for as long as possible. However, the alternative use of batteries is usually not that simple and is strongly influenced by social, political, economic, and technical challenges. To enable a successful sustainable transformation process, all aspects must be carefully analyzed and considered to find a sustainable and economical solution that serves the common good. Read this study to find out how this can be achieved.

E-Mobility in Germany

Around 1.4 million purely battery electric vehicles are registered 2024 in Germany [1]. This corresponds to an installed battery capacity of around 50 GWh [2]. The growth rates for e-mobility are in the mid double-digit percentage range. The advantages of battery electric vehicles are that they are locally emission-free and climate-neutral when powered by electricity generated from renewable sources. There are currently still several financial incentives for users of battery electric vehicles, such as free charging with self-generated solar power, exemption from vehicle tax, GHG quota trading and lower operating costs due to significantly longer maintenance intervals compared to vehicles with combustion engines.

Motivation

However, there are also issues relating to E-mobility that have not yet been resolved in detail. One of these is: How will the large-volume recycling of the body, drive train and battery be managed in the future? Recycling the battery is currently the biggest challenge. At the end of their service life, the batteries have a state of health (SOH, degree of degradation and remaining battery capacity) of 80 to 90 %, depending on their use and the different power in- and output. As a result, the batteries have a lower capacity and slower power in- and output. This essentially influences the range and fast-charging capability. However, this does not mean that these batteries are not suitable for other applications in which energy density or fast-charging capability play a subordinate role. After the first life, these batteries can be converted into a 2nd-life application as stationary storage systems, where these used battery cells substitute new battery cells. The 2nd-life application as a stationary storage system is therefore a sustainable and a resource-saving solution. The potential of this sustainable solution has been investigated in this study based on expert interviews with stakeholders from politics, the energy industry, battery recyclers and manufacturers.

What is the current market situation?

Cell production in Germany currently amounts to 83 GWh per year (2023) and could be increased fivefold to around 400 GWh per year by 2030 [3]. This considers the increased production and registration numbers for battery electric vehicles. At the same time, a study by Goldman Sachs [4] shows that cell costs per kilowatt will fall by an average of 11% per year by 2030. This will be achieved through further technological development and more efficient use of materials, as in future the same power density can be achieved with a lower use of resources and raw materials. The so-called cell-to-pack design also increases the cost-effectiveness of the battery. The cells are arranged directly in the battery housing and connected to each other in a suitable series and parallel circuit, eliminating the need for an additional module housing.

Which cell chemistry is used?

Battery cells with the cell chemistry of Lithium-Nickel-Manganese-Cobalt (NMC) and Lithium-Iron-Phosphate accumulators (LFP) are predominantly used for mobility applications. The three phases (positive electrode, negative electrode, and electrolyte) contain Lithium Ions. The battery cells based on NMC or LFP have a high energy density of 100 to 250 Wh/kg and 1,000 to 2,000 charging cycles (LFP even 2,000 and more). The car manufacturers determine the choice of cell chemistry, for example, regarding economic (regional availability, local production, quantities), technical (range of applications, power density, service life) and company-specific aspects.

Which cell types are used for mobility applications?

The most economical way is to manufacture round cells. The most common formats are 18650 (diameter 18 mm and length 65 mm) to 46125 (diameter 46 mm and length 125 mm).

The 46125 cell has a higher capacity, shorter charging times, higher energy density and performs better than the 18650 cell in heavy-duty applications. In the future, the trend in battery electric vehicles will move away from many small cells towards fewer large cells. The cells will be connected in suitable series and parallel circuits and combined into modules that form the battery in a housing. The current trend is to move away from combining the cells into modules and to install them directly in the battery housing in a cell-to-pack design. This increases efficiency, reduces components and weight, and allows to install a higher energy density by volume. It is very difficult to repair the cells or transfer them to a second-life application using the cell-to-pack design. Through this the cells can only be separated or replaced without destroying them at great expense.

Repurposing and recycling

If the battery of a battery electric vehicle can no longer be used for technical reasons, the following steps are usually taken:

- Deactivating and discharging the battery and removing it from the vehicle

Fig. 1: Arrangement of battery cells in the modules.

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- Dismantling the battery
  - Module level → 2nd-life application
  - Cell level → Recycling
- Mechanical separation processes for battery cells such as shredding, sieving and sorting to obtain the so-called Black Mass. Depending on the cell chemistry, the Black Mass contains high-quality cathode materials such as Lithium, Nickel, Manganese and Cobalt.
- Electrolyte recovery
- Hydrometallurgical processes for material separation of the Black Mass
- Pyrometallurgical processes for material separation of the Black Mass

When the battery is dismantled at the recycler, as many quality-describing parameters as possible must be available. Based on this, a decision can be made as to whether the modules are suitable for a 2nd-life application or whether they need to be dismantled down to cell level for recycling. In the future, the Battery Ordinance [5] will require every battery to have a battery passport. There should be information on the materials it contains, the SOH, the reparability, the reuse, the dismantling process, or the recycling process. Access to the battery management system (BMS) and the readability of important information is essential to be able to better assign cells to a 2nd-life application. This allows conclusions to be drawn about critical system states or the load profile in the application phase. At present, however, access to the BMS data is generally only possible through the manufacturer itself.

Among other things, research is currently being conducted into the development of a short-term assessment method for SOH based on physical parameters using artificial intelligence. There is also a lack of long-term experience as to which SOH is suitable for a second-life application and how the SOH continues to decrease in the second-life application. One method currently available for cell evaluation is to subject cells or modules to a capacity measurement. This involves carrying out three charging and discharging cycles at defined charge rates (C-rates). The duration of such a test is approximately 24 hours and must be carried out under elaborate safety precautions. As a result, the costs of such tests amount to between 500 Euro and 1,000 Euro and are therefore only economical for sufficiently large and valuable modules [6].

With electrolyte recovery, hydrometallurgy and pyrometallurgy, 90 percent of the materials contained in the cells, such as Copper, Aluminum, Graphite, Manganese, Nickel, Cobalt, and Lithium, can be recycled and recovered. However, hydrometallurgy and pyrometallurgy are very energy and resource-intensive processes. They require considerable amounts of energy, pressure, water, cooling water, and chemicals to extract the individual elements and separate them into pure materials. Despite the high energy and resource requirements, recycling and recovering materials is a more sustainable solution than smelting new material. In this way, for example, the habitats and cultures of the indigenous population as well as natural habitats worthy of protection are conserved at the respective potential extraction sites.

Various players (e.g. Umicore, BASF, Northvolt, Mercedes-Benz and Volkswagen) are currently building up recycling capacities and further developing recycling processes. It is assumed that the plants currently in operation will be working at full capacity from 2030 onwards with a higher volume of batteries to be recycled. At present, they only process the processing waste or by-products from the battery factories and only a few discarded batteries. A considerable proportion of cells are suitable for transferring to 2nd-life applications. As stationary electricity storage, these 2nd-life cells can contribute to the electricity storage strategy of the Bundesministerium für Wirtschaft und Klimaschutz der Bundesrepublik (BMWK) (engl. Federal Ministry of Economics and Climate Protec).

Storage technologies

In December 2023 [7], the BMWK published the fields of action and measures for a sustained expansion dynamic and optimal system integration of electricity storage in an Electricity Storage Strategy. The aim is to integrate the rapidly increasing shares of wind power and photovoltaics into the electricity grid. Electricity storage systems play a decisive role as energy storage systems and for the stabilization of the electricity system and the electricity grid. To this end, the BMWK is supporting the ramp-up and integration of electricity storage as short-term storage with its electricity storage strategy.

With electricity storage systems, a distinction is made between short-term and long-term storage.
The aim of long-term storage of electricity is to use it to bridge the winter months. For example, surplus photovoltaic energy from the summer can be used by converting it into hydrogen and using it in various thermal power processes to generate energy. Charging this electricity in battery storage systems would require an immensely high number of storage units and is uneconomical due to the high-power loss caused by self-discharge of the cells.

In this context, short-term storage means using the surpluses generated during the day for peak loads or the dark phase at night. This requires stationary battery storage systems for private households, businesses and grid operators that respond to demand in real time with high dynamics. Pumped storage power plants are also suitable for this purpose but have reached their expansion limits in Germany due to the limited altitude and fragmentation of the landscape.

Stationary storage

Stationary electricity storage systems in private households have an average capacity of 8.8 kWh [8] and electricity storage systems used by industry (commercial or energy suppliers) have a capacity of up to 4,000 kWh [9]. The large-scale stationary industrial storage system is calculated to have a useful life of 10 years. In 2023, a stationary storage system with new cells of 500 kWh must be expected to cost between 1,000 Euro and 1,200 Euro per installed kilowatt for the entire battery system [10]. This includes all fixed costs such as site preparation, infrastructure, hardware (cells, inverters) and fire protection. Between 500 Euro and 600 Euro per kilowatt must be spent on the new cells alone.

Business models

There are different types of business models for private households, industrial companies, and energy suppliers.

Private households store the photovoltaic electricity generated during the day to use it for their own consumption during periods without sunlight. With sufficiently large photovoltaic systems, a high degree of self-sufficiency can be achieved, and costs saved.

Industrial companies with a high electricity demand report their forecast consumption and peak loads to the grid supplier on a daily basis, from which their electricity price is calculated. By operating a sufficiently large storage system, the peak loads can be covered by the company itself, resulting in lower costs. During the day, the storage system is charged with the customer's own solar power or at times when the electricity tariff is low.

There are several business areas for ***energy suppliers***. The storage system supplies households with electricity when there is no photovoltaic electricity generated. Given the high storage costs, this business area only pays for itself after a very long time [10]. Trading on the intraday market is much more economical. Furthermore, the highest economic returns are generated through license income for the provision of immediately available grid capacity to absorb peak loads and the sale of electricity.

Future development

A successful 2nd-life application is influenced by numerous factors. The modules must be dismantled, assessed regarding their condition, suitably combined (model, cell size, cell chemistry, year of manufacture, SOH, capacity) and integrated into a storage system. The 2nd-life cells must be significantly below the cost of new cells of 500 Euro to 600 Euro per kilowatt, whereby an annual cost reduction of 11 percent for new cells by 2030 must be expected and considered [4]. In addition, there are costs for the evaluation of the cells regarding their ageing condition and SOH. For 2nd-life cells to be used for economic reasons at present, the costs must be between 50 Euro and 100 Euro per kilowatt, depending on cell quality and module size. Otherwise, the risks of lower capacity, shorter service life, loss of performance or increased safety measures cannot be compensated.

Fig. 2: Dismantling the batteries of electric vehicles for a 2nd-life application.

In the future, the technological and more efficient development of cell production will mean that less raw material will be required to achieve the same power density. It is therefore advantageous from an economic and raw materials policy perspective to recycle a high proportion of cells. Furthermore, the draft of the Battery Ordinance [5] provides for recycling quotas and the use of recycled material (Lithium, Cobalt, Copper, Manganese, Nickel, and Lead) from old cells to produce new cells. For example, when recycling old cells, 50 percent Lithium is to be recovered in 2028 and 80 percent Lithium in 2032. The recycling rate initially stands in the way of 2nd-life applications. Furthermore, a 2nd-life application would mean that the material bound in the cells would not be available for the duration of the 2nd-life application. The Battery Ordinance creates the basis for bringing suitable cells into a 2nd-life application, particularly through the battery passport.

In the future, a different cell chemistry or even a solid-state battery may become established. For example, Sodium-Ion Batteries (SIB) have a lower energy density than Lithium-Ion batteries, but are more cycle-resistant, non-flammable and significantly cheaper. Furthermore, the use of Sodium makes them independent of global Lithium suppliers. Sodium-Ion cell chemistry is therefore potentially interesting for stationary storage systems. Research is currently being carried out into increasing the power density and efficient manufacturing processes. The first vehicles from Asia have already been equipped with batteries based on Sodium-Ion cell chemistry. The Chinese manufacturer JAC has been mass-producing the first electric cars with Sodium-Ion batteries since December 2023 [11].

Final sustainable consideration

The use of previously used battery cells from former traction storage systems in 2nd-life applications is a complex transformation process. To master this, a transdisciplinary approach is required to discuss the relevant challenges and issues in all their complexity. The different perspectives of various scientific disciplines regarding economic, ecological, and social aspects must be considered. In turn, the transformation process must be adapted through dynamic development to meet new or current challenges. In this sustainability transformation, technical and social aspects must be harmonized to achieve a solution that is oriented towards the common good.

Economy
Economy: From an economic point of view, battery cell production is continuing to develop towards more efficient processes, making it possible to increase energy density and use significantly less raw materials. Research is also being carried out into new cell chemistry to reduce cell costs and make do with more readily available materials. At the same time, recycling processes are being further developed so that as many raw materials as possible can be recovered in high quantities and ideally in high quality. It may therefore be more interesting from an economic point of view to preferentially recycle cells with uncertain performance behavior or ageing status and to use the raw materials more efficiently elsewhere in new cells. Furthermore, it is currently questionable whether and how cells from the current »cell to pack« structure will be transferred to a 2nd-life application at all. Nevertheless, there will be individual niche applications in which business models that use 2nd-life cells will become established.

Ecology
From an ecological point of view, it makes sense to keep the battery of a battery electric vehicle in use for as long as technically possible. Ideally, the battery should reach the end of its life at the same time as the rest of the vehicle and all components should be recycled efficiently. If the battery is replaced during the life of the vehicle and still has sufficient SOH, it should be transferred to a 2nd-life application. These can be used, for example, in stationary electricity storage systems that store surplus solar and wind energy and release it at peak times or during periods without photovoltaic energy production. This is an important contribution to the sustainable expansion and conversion of the energy infrastructure.

Recycling old cells is of key ecological importance to keep materials in circulation. Sufficient high-quality recycled material on the market reduces the quantities of new material to be extracted. The energy required for the extraction and smelting of new material is usually many times higher than recycling. Furthermore, the reduced exploitation of mineral resources and the reduction of extraction sites protect natural habitats and cultures.

By optimizing and increasing the efficiency of manufacturing processes, it will be possible in future to produce cells with the same energy density using significantly less energy and resources. Technological developments over the next few decades will bring cell technologies to market maturity that can be produced with significantly fewer resources and therefore lower costs.

Society

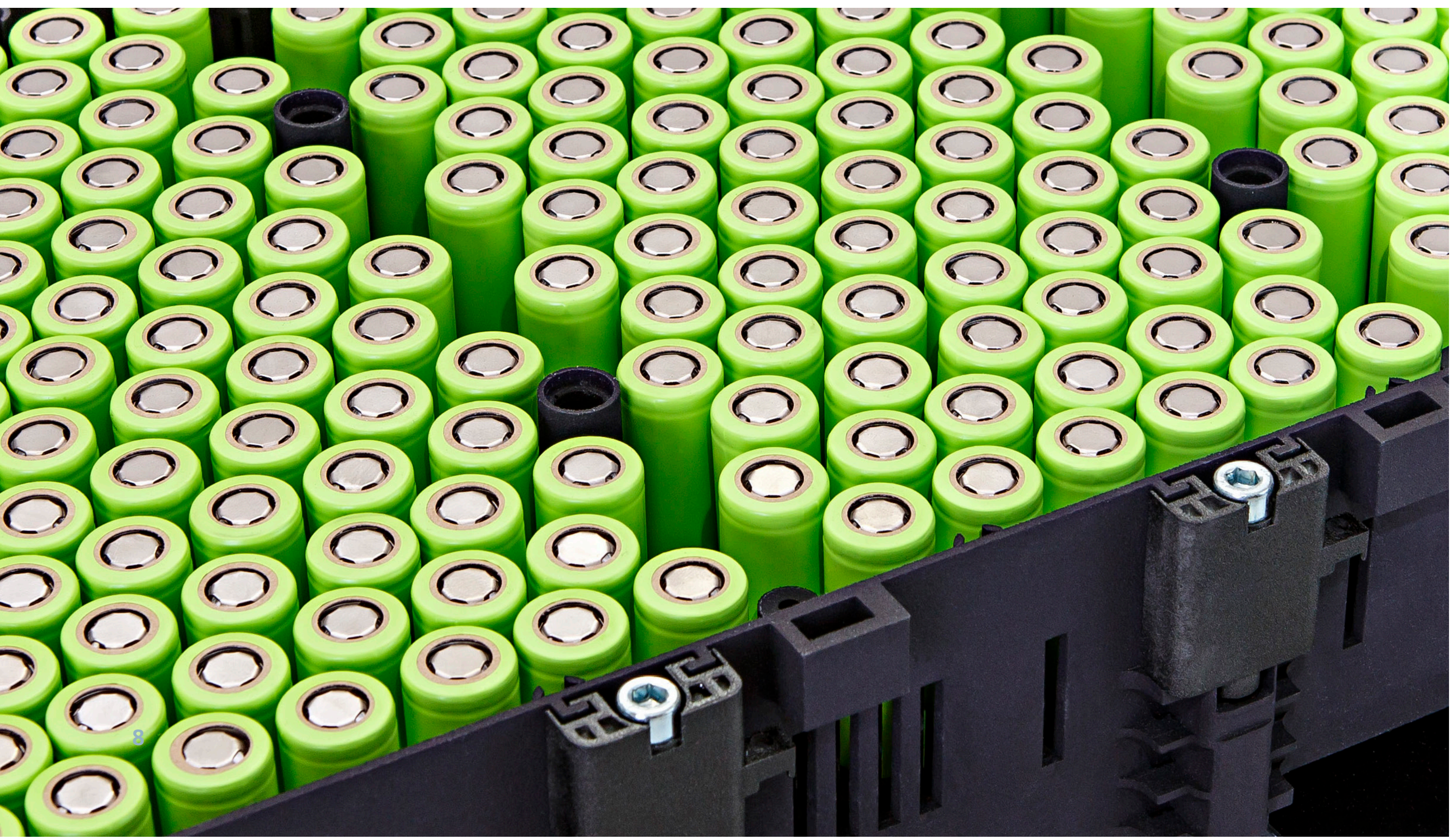
Society expects battery electric vehicles to be emission-free and, if powered by renewable electricity, climate-neutral. Similarly, an efficient recycling or repurposing concept is expected for components that are still functional at the end of the vehicle's life. Various stakeholders such as users, manufacturers or politicians often decide against the use of 2nd-life applications due to insufficient economic or technical aspects. Political intervention at this point, such as the Battery Ordinance, provides a framework with numerous degrees of freedom that can be used to ensure the long-term development of various sustainable 2nd-life applications.

The conversion of the electricity grid and the needs-based integration of electricity generated from renewable sources is a social challenge that we will have to overcome in the coming decades. Stationary electricity storage systems can make a major contribution to making surpluses available at times of demand. If functional 2nd-life cells are used in the electricity storage systems, this is a sustainable and thoroughly economical alternative to the use of new cells.

It is of particular interest to recycle the raw materials from old battery cells and reuse them in new cells. This reduces dependency on raw material suppliers. In the future, cell technologies will be developed that are based on locally available raw materials and require highly efficient and climate-neutral manufacturing processes.

In summary, the 2nd-life application of already used battery cells in stationary energy storage systems is a preferable sustainable and resource-saving solution. Cells for which a 2nd-life application is not possible from a technical point of view should be fed into an efficient recycling process. In the long term, more efficient manufacturing processes will reduce cell costs. At the same time, energy density will be increased, and cell ageing and utilization properties will be improved. New resource-efficient and sustainable cell chemistries will also be developed to such an extent that they can replace established, resource-intensive cell chemistries in terms of their performance.

Fig. 3: Arrangement of the battery cells in the cell holder in modular design.



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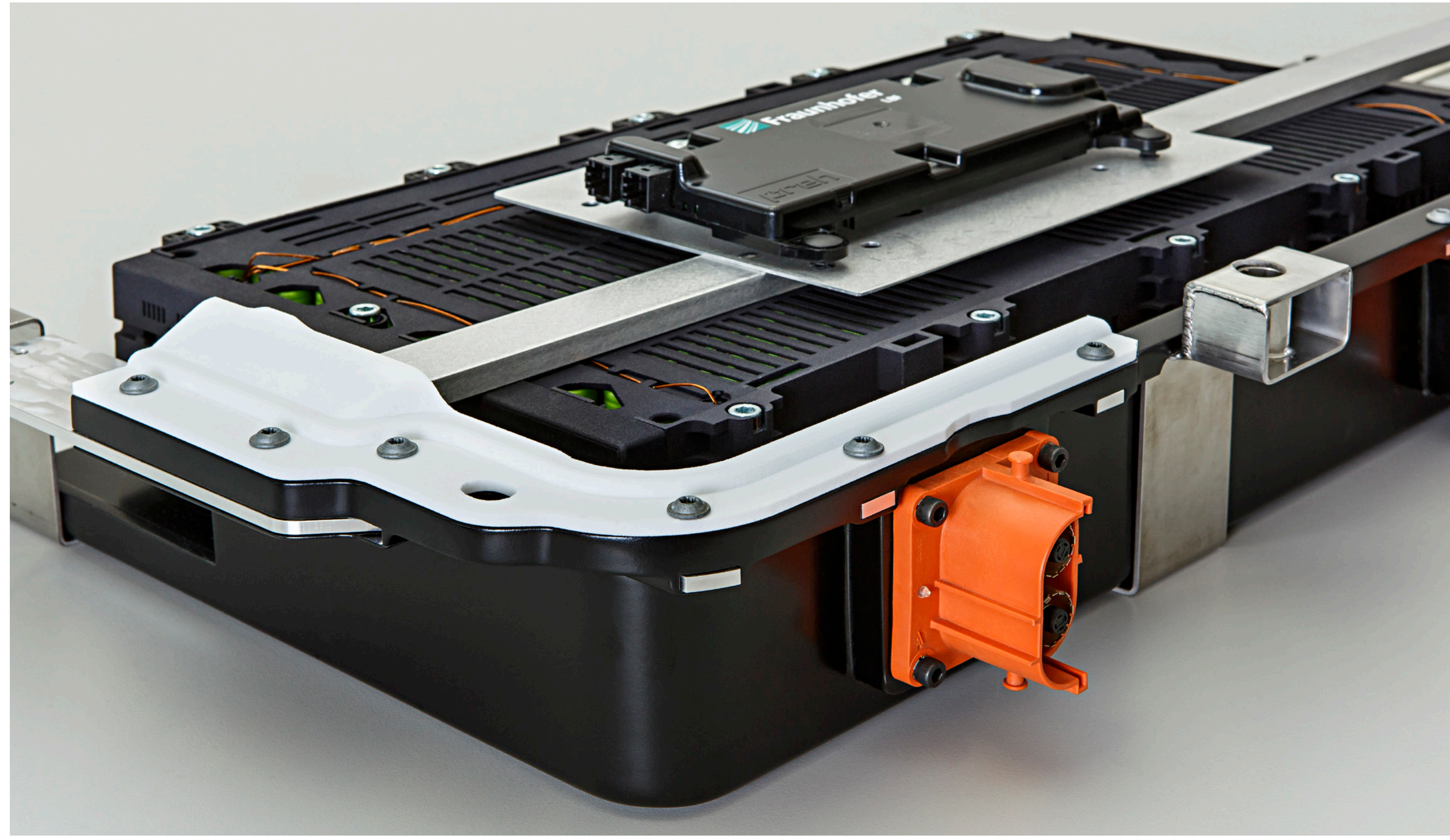

Fig. 4: Structure of the battery in modular design with crash struts, battery management system and electrical connections.

"In the future, the number of battery cells used in second-life applications will increase. At the same time, however, enough old battery cells must also be recycled to utilize the raw materials in more efficient and new cell technologies."

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More information about CIRCULUS-Project

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doi:10.24406/publica-3054