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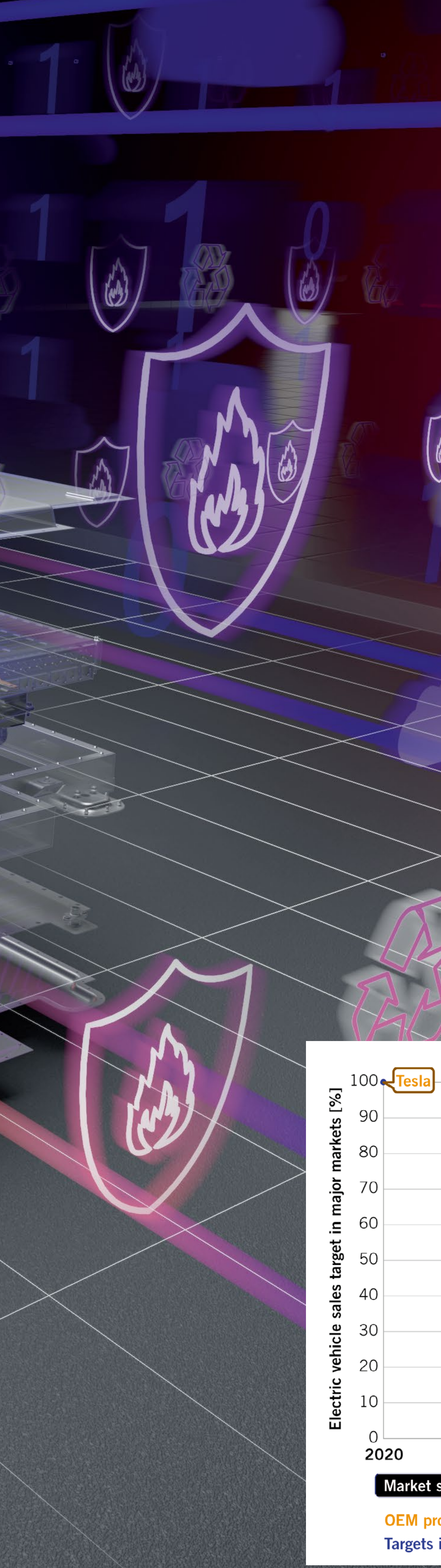
Technology Trends in High-voltage Battery Development

Key drivers for developments in automotive high voltage batteries are cost reduction, longer range, shorter charging times and improvements in lifetime, reliability and safety. More requirements for future battery generations are derived from government regulations and directions on energy efficiency, safety, and recycling, as FEV shows in the following.



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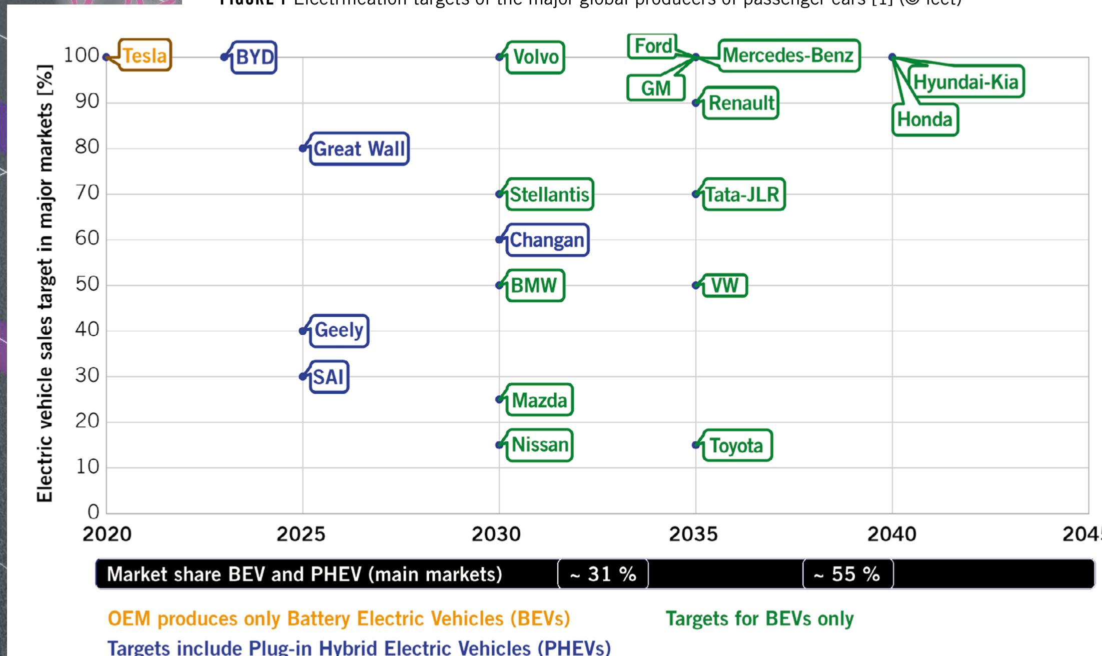
Cars, vans, buses, and trucks account for more than 20 % of global human-induced CO_2 emissions. Until October 2022, 19 out of the 23 major automakers have announced a stringent electrification strategy with up to 100 % zero-emission vehicles [1], **FIGURE 1**. To date, more than 20 nations have announced they would completely stop selling cars with Internal Combustion Engines (ICEs) during the next ten to 30 years. Meeting these targets demands a significant rise in the overall share of electrified vehicles globally. **FIGURE 2** shows the expected growth in two different scenarios, which are based on the following assumptions:

- constant market volumes in Europe, US, Japan, and South Korea market regions after 2025
- increasing market size for China, India and Rest-of-World (RoW) markets
- from 2019 to 2040, a global reduction of ICE powertrains in the accelerated and moderate scenarios by 66 and 44 % respectively
- growth of electric vehicles until 2030 mainly driven by Europe and China, after 2035 rapid growth in RoW countries.

Electrification of two- and three-wheel vehicles play a vital role in traffic decarbonization in Asia and Africa, especially

FIGURE 1 Electrification targets of the major global producers of passenger cars [1] (© icct)



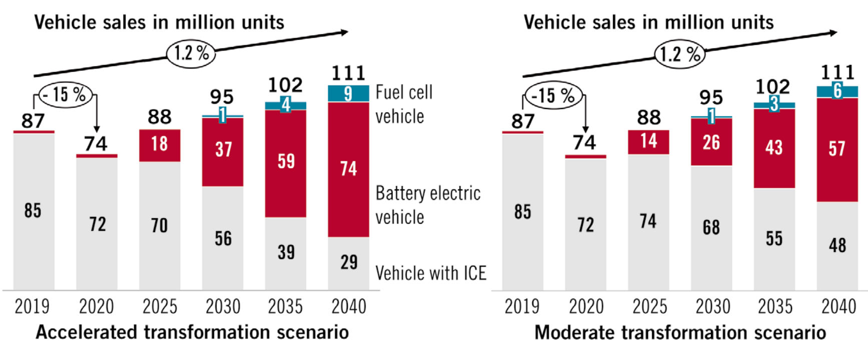


FIGURE 2 Projected development of vehicle sales with electric powertrain in two different scenarios (© FEV)

in big metropolitan cities. By 2050, the global fleet of motorcycles is projected to account for more than 400 million vehicles, a 50 % increase compared to today.

Ensuring battery safety with increasing energy density is one of the key enablers for growing market penetration of Battery Electric Vehicles (BEVs). Several countries have put regulations in place that require a 5-minute time window between warning of a thermal runaway event and potential endangerment of the vehicle occupants (for example China, India, Europe). More stringent requirements with higher time limit or even stop of propagation are under discussion.

ADVANCED BATTERY SAFETY

Thermal runaway is probably the worst hazard scenario for a Lithium(Li)-ion battery. Possible causes are, for example, faults internal to the cell or battery, such as internal cell short circuits, between cells, increased resistance, damaged electrical connections, or excessive current load. Cell overcharging, overcurrent or overtemperature can also trigger a thermal event. Decomposition of the Solid Electrolyte Interphase (SEI) starts above 60 to 70 °C cell core temperature. If the temperature rises further, separators out of polypropylene or polyethylene melt between 135 and 165 °C. The following internal short circuit initiates exothermal reactions, which in turn cause a rapid rise in temperature [2, 3]. As a result, the anode, electrolyte, and cathode decompose, releasing flammable hydrocarbon gases. These gases may spontaneously ignite if temperatures continue to rise while the oxygen accumulates.

During a thermal event involving a charged high-energy Li-ion cell containing liquid electrolytes, cell temperatures can reach up to 1000 °C and the release of up to 25 mol kW^{-1} h^{-1} (600 L kW^{-1} h^{-1}) of venting gases can occur [4]. The gas is mostly composed of CO_2, CO, C_2H_4, CH_4 and H_2, making it both poisonous and highly combustible.

Thermal propagation can be stopped or delayed using certain design strategies in the battery and the cell stacks, **FIGURE 3** [5]:
- sufficient dimensioning of vent channels to limit local pressure buildup
- heat shields made of special heat-resistant materials such as aerogels between cells or mica paper between cell groups as well as cell modules
- sufficiently dimensioned clearances and creepage distances between high-voltage-carrying parts to avoid short circuits caused by conductive parts in the escaping gases
- insulation of high-voltage conducting surfaces with heat-resistant insulating materials if the distance requirements are not met
- venting valves with temperature-resistant particle filters to prevent ignition of the escaping gases by the heated particles when they react with the ambient air.

Combined multi-physics and fluid dynamics simulation models calculate the pressure and temperature distribution in the battery, the distribution of the gas mixture, its flammability, and the propagation time between cells and modules.

Heat barriers between modules can inhibit module to module propagation, **FIGURE 4** (left). The position of the barrier can have a major influence. The mica sheet placed between modules reduces the heat dissipation into the non-event module by about 20 % compared to a sheet mounted directly on the modules. **FIGURE 4** (right) illustrates the flame front propagation in case of combustion of the venting gas. Local temperatures of more than 2000 °C at the tip of the front can be reached. Fillers inside the battery can be used to min-

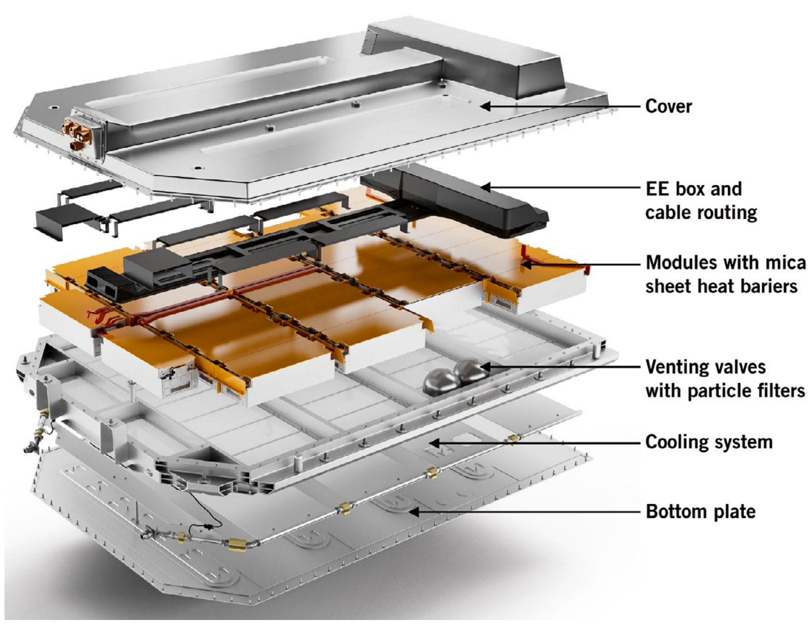


FIGURE 3 Exploded view of an exemplary high-voltage battery pack with design features to prevent thermal runaway (© FEV)

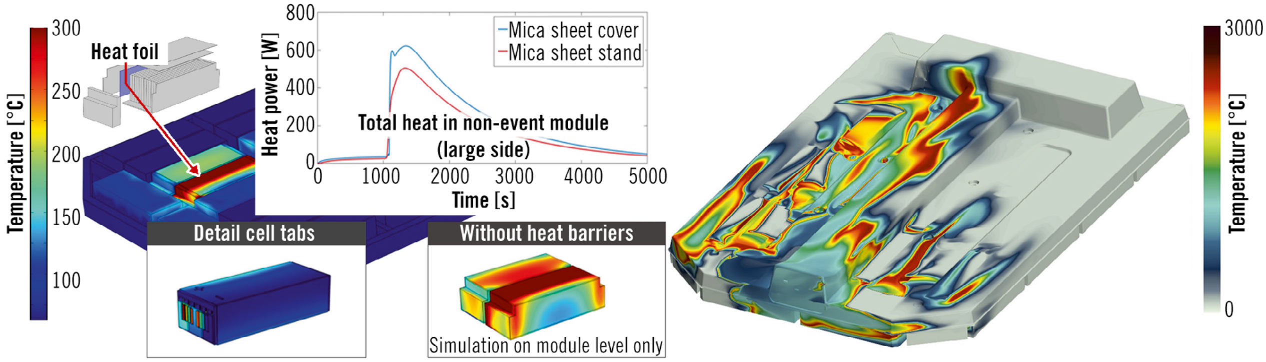


FIGURE 4 Thermal simulation result of a thermal cell event and CHT simulation of flame front considering ignited venting gas: influence of the heat barrier position on heat transfer to adjacent modules (left) and temperature distribution during venting gas combustion (right) (© FEV)

imize the amount of air and thus avoid the ignition of the venting gases or at minimum reduce the thermal reaction.

The maximum power density at the battery level is also limited by the thermal reactivity of the cell chemistry. In case of a thermal event, high energy cells with Nickel-Cobalt-Aluminum (NCA) or Nickel-Manganese-Cobalt (NCM) cathodes produce significantly more gas volume with higher temperatures than cells with Lithium Iron Phosphate (LFP) cathodes [4], which also have a higher thermal stability. This allows for tighter packing of LFP cells and thus enables higher volumetric efficiency.

INCREASE OF ENERGY AND POWER DENSITY

Driving range targets in 2025 for BEV span between 400 km for low-range vehicles, and > 900 km for long-range vehicles, typically in the premium car segment. Achieving these targets requires batteries with an energy content of more than 120 kWh with a corresponding volumetric and gravimetric cell energy density of up to 1000 Wh/l and 450 Wh/kg respectively.

Solid-state Li-ion batteries with solid electrolyte and metallic anode material (for example lithium or silicon) can significantly increase the energy and power density of the resulting battery system.

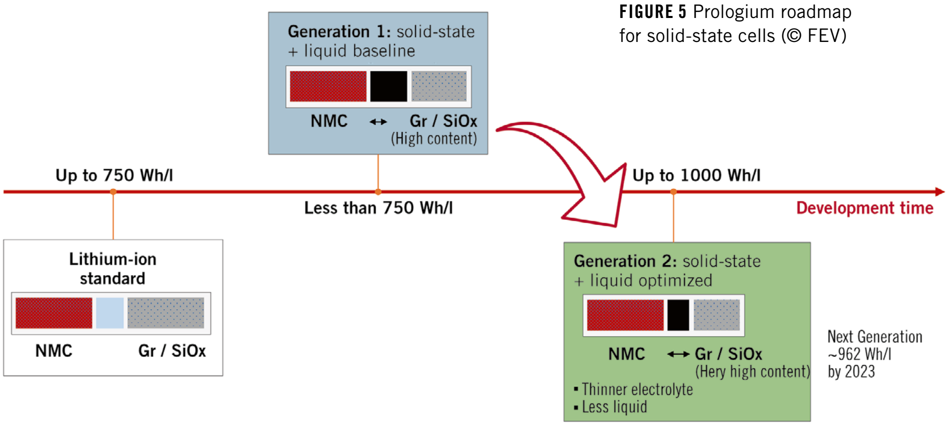


FIGURE 5 Prologium roadmap for solid-state cells (© FEV)

Metallic anodes have more than ten times the capacity of graphite anodes in conventional cells. Solid Electrolytes (SE) are used instead of Liquid Electrolytes (LE). Another advantage is that they are more thermally stable and less flammable, and no liquid can leak from them. Most Solid-State Batteries (SSBs) currently under development use polymer, sulfide, or oxide SE.

The volume change of the active materials during charge and discharge leads to mechanical degradation between the solid electrolyte and the anode and causes loss of the electrical contact. An optimized stack pressure is needed to maintain contact between the cell components. However, if the pressure is too high, short circuits can occur due to electrically conductive lithium bridges protruding through the electrolyte. Experiments suggest, for example, an optimum pressure of 5 MPa (approximately 50 bar) for sulfide-based electrolytes [6]. This is a much higher contact pressure than battery systems with LE cells.

Alternatively, liquid electrolyte can be added to the SSB to maintain contact with cathode active material components. This Hybrid Solid Liquid Electrolyte (HSLE) cell requires lower stack pressures. However, this approach reduces the thermal stability of the cell compared to All-Solid-State Batteries (ASSBs), but at the same time increases battery charging speeds and performance [7].

An example for a supplier of solid-state cells is Prologium, a Taiwanese cell manufacturer. **FIGURE 5** depicts Prologium's transition from traditional Li-Ion to ASSB cells. The first generation holds, besides the SE a little quantity of LE. With 28 % silicon in the anode, the cell energy density is 615 Wh/l. In the second generation (2023), the thickness of the SE layer and the LE content will be reduced, while the silicon content of the anode will be significantly increased. **FIGURE 6** shows the volumetric energy density at cell and battery level with Prologium's second generation cells (fourth quarter 2023, gray triangle) compared to the current first cell generation (gray square) and to conventional LE cells. At 950 Wh/l, the second generation will have more than 50 % higher energy density compared to the first generation. At the battery level, a higher energy density can be achieved with the second generation of cells at 350 Wh/l than with the best-in-class conventional LE cells currently on the market, shown as the benchmark line.

Compared to a battery with LE cells, the higher thermal stability of SE cells allows to increase the cell to pack volume ratio supporting an additional increase in energy density at the battery level. **FIGURE 7** depicts an optimized battery pack design for an SSB with eight modules of prismatic cells in a transverse orientation [8]. During a thermal event, SE cells produce fewer venting gases with lower temperatures than high-energy LE cells. This requires less thermal insulation between the cells or modules, which allows the insulation to be slimmed down. As a result, the SE cell module requires less material, less space, and weighs less than a comparable LE cell module. The cross-sections of the gas vent channels in the battery can be reduced, making the battery more compact.

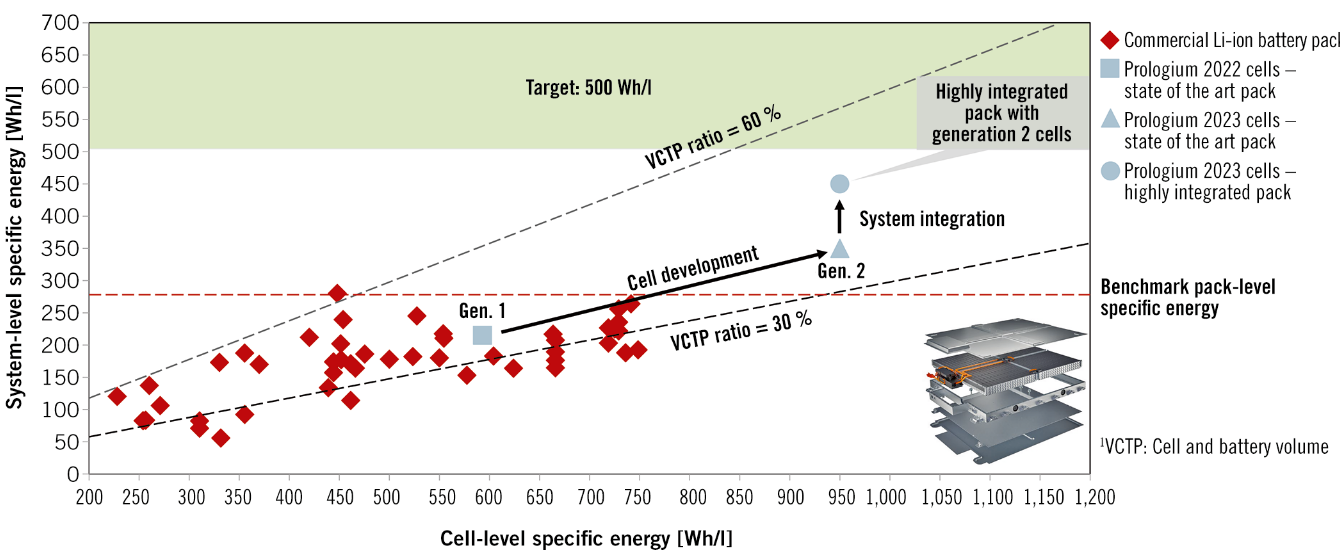


FIGURE 6 Volumetric energy density of various battery systems on cell level and system level, compared to Prologium's HSLB packs (© FEV)

The higher temperature stability of HSLE and SE cells allows the module lid to be welded. This allows the overall height of the module to be reduced compared to a bolted lid. Openings in the busbar holders allow free cell degassing to the top or to the bottom. The proposed design uses only a bottom cooling plate, which reduces the overall height of the battery. With current cell technology, this achieves a battery energy density of 215 Wh/l. With the second generation of cells, a battery energy density of 350 Wh/l is expected starting in fourth quarter 2023. Further improvements of the volumetric efficiency in the battery design enable an increase up to 450 Wh/l. As an outlook, it is expected that future ASS cells without LE content and a pure Li-metal anode will have an energy density of > 1000 Wh/l, with which an energy density of > 500 Wh/l can be achieved in the battery.

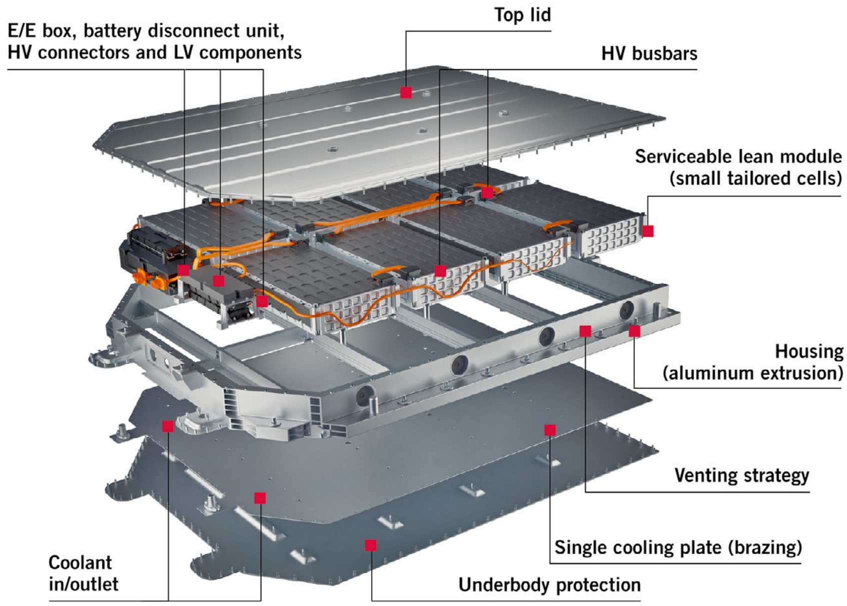


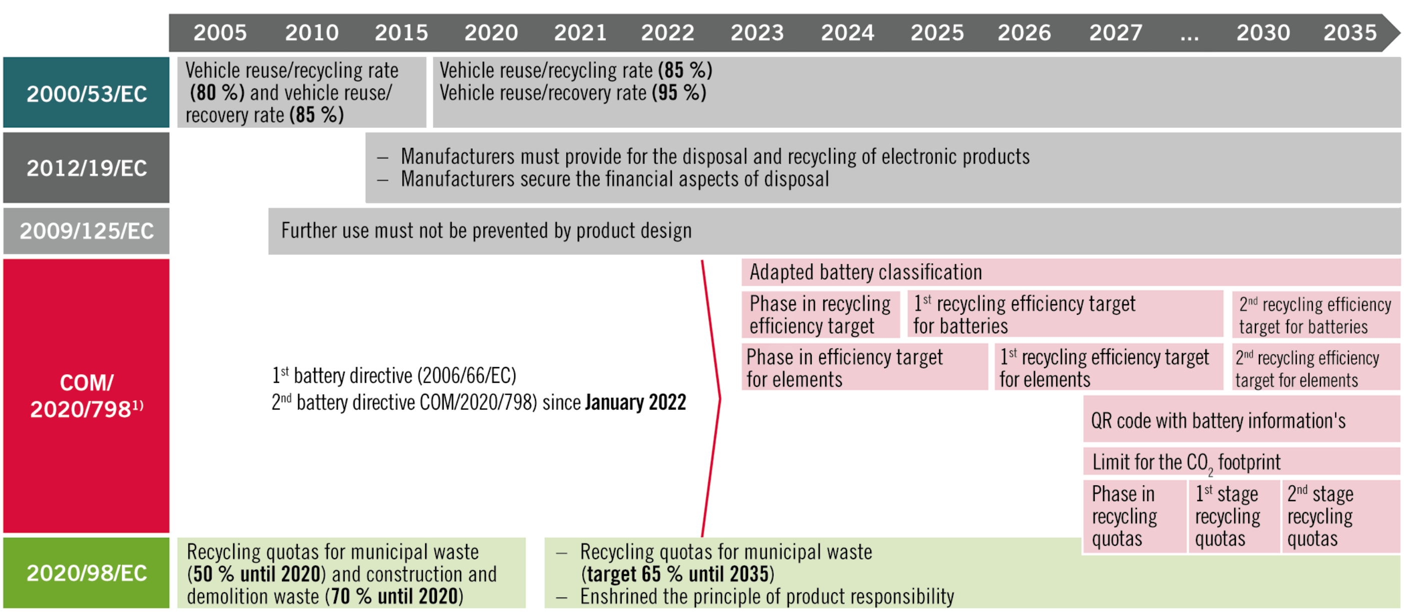
FIGURE 7 Optimized SSB concept design with eight cell modules with so-called 1S12P configuration (prismatic solid-state cells) (© FEV)

RECYCLING AND CIRCULAR ECONOMY

The growing number of electrified vehicles creates environmental challenges in various aspects. Extraction and transport of the required materials, the production of components and batteries, and the disposal of used batteries are energy-intensive processes that must be optimized. The environmental footprint of a Li-ion battery is significant. The production of the battery accounts for 40 to 60 % of total emissions caused by the production of a BEV or electric. By 2030, there could be 11 million t of Li-ion battery waste from electric vehicles alone.

The European Commission (EC) has put several directives into force to set out measures to prevent and limit waste, and to ensure reuse, recycling, and recovery of battery materials. In December 2020, the EC adopted a proposal for a new regulation on sustainable batteries [9], which was provisionally agreed between the European Parliament and the EC in December 2022. From 2024 onwards, this framework will replace the existing

FIGURE 8 Timeline of waste/recycling directives for Li-Ion batteries (© FEV)



1) Adaptation of the 2006/66/EC since January 2022

battery directive 2006/66/EC, and will introduce higher collection targets, and stricter targets for recycling efficiency and material recovery for copper, cobalt, lithium and nickel. The recommendation set forth by the EC for Li-ion batteries and Co, Ni, Li, Cu are:

– recycling efficiency Li-ion batteries: 65 % at 2025, 70 % by 2030
– material recovery rate of 95 % for Co, 95 % for Ni, 70 % for Li, and 95 % for Cu in 2030.

FIGURE 8 shows the current EU legislation with relevance for Li-Ion batteries.

From January 2026, a digital battery passport will be introduced for every new electric vehicle. The battery passport will store essential battery data over the battery's entire life cycle. In particular, data describing sustainability and supply chains, such as CO_2 footprint or information on raw material extraction, will be retrievable. The determination of battery condition, reusability as well as recyclability shall be enabled.

State-of-the-art traction batteries of electric vehicles still have 70 to 80 % of their initial capacity when removed from the vehicle and can be reused for secondary applications such as stationary systems for seven to ten years. In the context of the circular economy for batteries, reuse is the most efficient way to avoid waste. Standardization of communication interfaces to read the battery's state of health and to retrieve diagnostic data for internal components help identify batteries that are safe for further use.

If repurposing for second life applications is not possible, recycling and recovery of the battery materials is the mandated choice to avoid waste. Dismantling the battery packs and modules into recyclable units is always the first process step preceding any other treatment. Examples for recyclable units are battery cells, busbars, wire harnesses, fuses, relays, and connectors. Today battery dismantling and disassembly is largely a manual process. The significant growth of End-of-Life (EOL) electric vehicle batteries during the next decade will demand automated dismantling processes and plants for battery packs and modules. One of the challenges is the large variation of possible pack and module designs even within one automaker across its different vehicle platforms and architectures. Automated disassembly strategies are subject of current research. Battery design for disassembly is an enabler for optimization of the disassembly process [10].

FIGURE 9 shows the principal schematic of an extended circular ecosystem for batteries, as well as joining methods in battery production, and the matching detachment methods. Key design principles for recycling are:

– standardization of components, especially of fixing types for module and cell connectors
– use of solid busbars with determined positions
– threaded or torqued connections
– bespoke, mechanically constrained push-fit connections
– accessibility of recoverable components [11].

Electrical safety during disassembly must always be ensured. Short-circuiting of cells, cell modules or flying sparks, which can all lead to a fire, must be prevented at all costs. Knowledge of the subsequent disassembly processes should therefore already be known in the development phase and considered in the design requirements.

DIGITAL BATTERY TWIN

Reliable and accurate estimation of the battery condition pertaining to safety, reliability, capacity, performance, and health status requires highly sophisticated Battery Management System (BMS) algorithms and standardized diagnostic and data interfaces. The impressive proceedings in AI-based data analytics and the nearly unlimited computational power in cloud systems have unlocked an immense potential for modeling real-world systems in a virtual environment. Digital twins of physical systems allow predictive analytics, identification of patterns and anomalies, and thus improve decision-making. Recent research has proven that a digital battery twin based on an Equivalent Circuit Model (ECM) can deliver accurate results for state of charge and state of health estimation [12]. Reliable estimation of remaining life requires analysis of large amounts of historical battery data from test or fleet operation [13].

The subject of current work is the development of flexible and adaptable battery twins for field and fleet operation. **FIGURE 10** shows the integration of a digital battery twin into the battery development process. The quality of the database significantly influences the accuracy of subsequent AI-based analytics. Accurate mapping of design, test, and field data to an individual battery is necessary to create a digital twin of that very battery. Of critical importance is the selection of data sets that are representative of the tasks at hand. The data is pre-processed by means of standardization, plausibility checks, and elimination of outliers amongst other things. The AI algorithm is then trained with the cleaned and appropriately classified data.

The digital twin is expected to provide reliable information on battery and

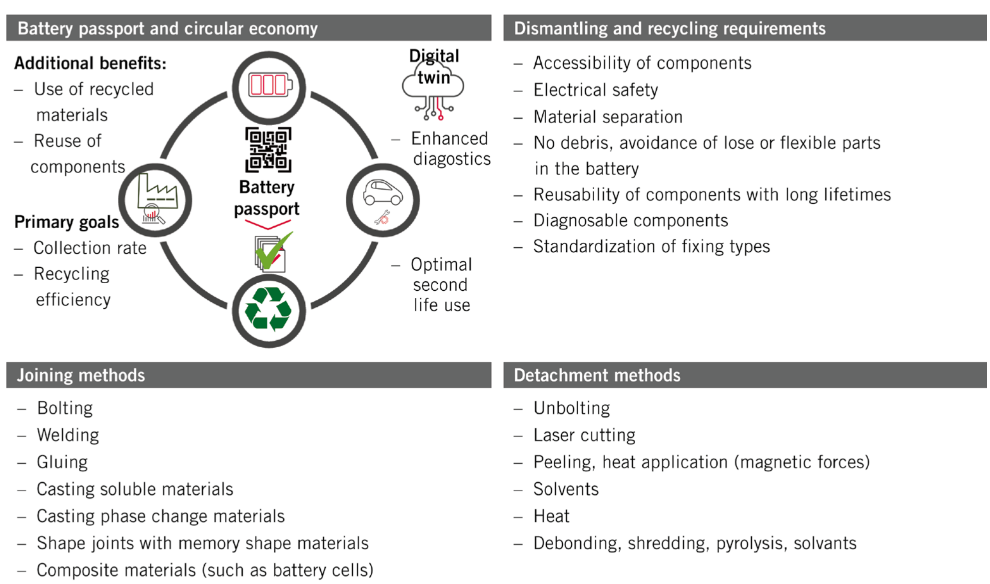


FIGURE 9 Joining and matching detachment processes; requirements for dismantling and recycling (© FEV)

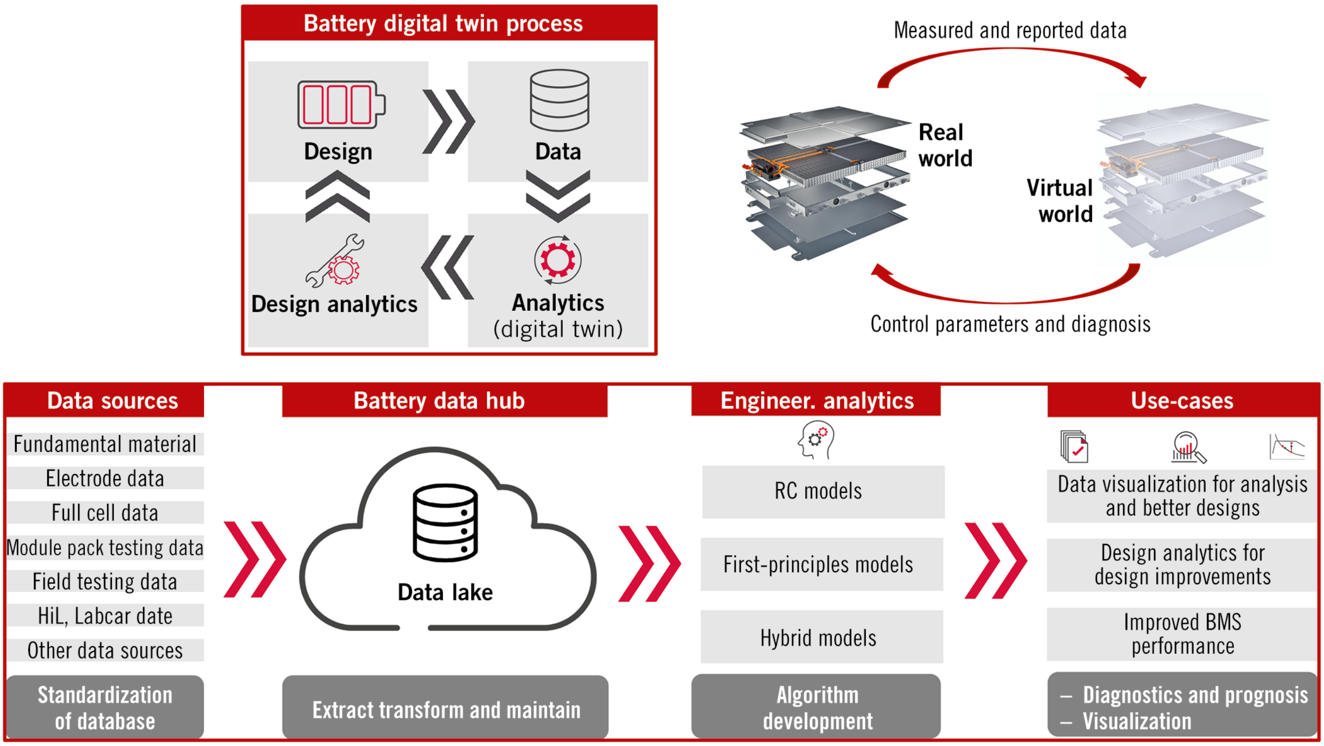


FIGURE 10 The battery digital twin: process and implementation steps for field data analysis (© FEV)

component status as well as expected remaining lifetime. This will allow preventive maintenance and repair measures to be planned, and battery reliability and safety to be increased. The aim is also to improve the accuracy and robustness of the BMS algorithms, to find weak points in the design and to identify improvement measures.

CONCLUSION

The share of electric vehicles must be increased significantly in the coming years to further decarbonize the transport sector. Battery electric vehicles are less complex in design and thus require less maintenance than vehicles with internal combustion engines, but battery technology still comes with some disadvantages. The use of solid-state technology, reduction of fire hazards through design and simulation measures, and design for recyclability, combined with cloud and AI technologies, are enabling the development of safer, more reliable, and more sustainable batteries.

The development of battery cells and systems is largely driven by the automotive industry. Many of the technological leaps achieved there also have a positive impact on adjacent industries, for example stationary energy storage systems, heavy-duty vehicles and industrial applications.

REFERENCES

[1] Yang, Z.: Beyond Europe: Are There Ambitious Electrification Targets Across Major Markets? Online: https://theicct.org/global-oem-targets-cars-ldvs-nov22/, access: April 12, 2023
[2] Ma, S. et al.: Temperature effect and thermal impact in lithium-ion batteries: A review. Online: https://www.sciencedirect.com/science/article/pii/S1002007118307536, access: April 12, 2023
[3] Golubkov, A. W. et al.: Thermal runaway of large automotive Li-ion batteries. Online: https://www.researchgate.net/publication/329330660_Thermal_runaway_of_large_automotive_Li-ion_batteries, access: April 12, 2023
[4] Golubkov, A. W. et al.: Thermal runaway of commercial 18650 Li-ion batteries with LFP and NCA cathodes – impact of state of charge and overcharge. Online: https://www.researchgate.net/publication/279069810_Thermal_runaway_of_commercial_18650_Li-ion_batteries_with_LFP_and_NCA_cathodes_-_Impact_of_state_of_charge_and_overcharge, access: April 12, 2023
[5] Sauer, A.; Beykirch, R.; Hosseininasab, S.; Bauer, L.: Detection and Prevention Measures of Thermal Propagation. In: MTZ 5-6/2021, pp. 80-83
[6] Doux, J.-M. et al.: Stack Pressure Considerations for Room-Temperature All-Solid-State Lithium Metal Batteries. In: Advanced Energy Materials 1/2022
[7] Guo, Y. et al.: Solid-state lithium batteries: Safety and prospects. In: eScience 2/2022, pp. 138-163
[8] Stapelbroek, M.; Sauer, A.; Teuber, S.; Pampel, F.: Solid-State battery pack design: simply exchanging the cells? 31. Aachen Colloquium Sustainable Mobility, 2022
[9] EU Commission: Proposal for a Regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020. Online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX-%3A52020PC0798, access: April 12, 2023
[10] Thompson, D. L. et al.: The importance of design in lithium ion battery recycling – a critical review. In: Green Chemistry 10/2020
[11] Baazouzi, S.; Rist, F. P.; Weeber, M.; Birke, P.: Optimization of Disassembly Strategies for Electric Vehicle Batteries. Online: https://www.researchgate.net/publication/355993447_Optimization_of_Disassembly_Strategies_for_Electric_Vehicle_Batteries, access: April 12, 2023
[12] Sauer, D. U. et al.: Digital twin for battery systems: Cloud battery management system with online state-of-charge and state-of-health estimation. In: The Journal of Energy Storage 8/2020
[13] Wang, W. et al.: Application of Digital Twin in Smart Battery Management Systems. Online: https://cjme.springeropen.com/articles/10.1186/s10033-021-00577-0, access: April 12, 2023

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