Pathways to the Next Stage of E-Mobility

- Affordable, safe and sustainable -

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ABSTRACT: Electromobility is considered a key contributor in the transformation towards sustainable mobility. Despite the clearly positive contribution battery electric vehicles provide to reducing CO_2 emissions **[1]** from road traffic, the take rate by consumers in the main markets is not in line with ambitious ramp-up targets for battery electric vehicle (BEV) deployment. This paper derives a prioritized set of challenges that need to be addressed to enable widespread e-mobility adoption. For these challenges in the order of their priority strategies are discussed and concrete examples of technical solutions given on vehicle side to enable a broader consumer adoption of electric vehicles.

1. INTRODUCTION

The adoption of e-mobility has fallen short compared with the expectations strongly driven by regulations. Consequently, the gap between projected electric vehicle sales and actual BEV adoption has widened in recent years. As shown in **Figure 1**, where bubble sizes indicate projected global production volumes for each main propulsion option (battery electric vehicle - BEV, range extender EV - REEV, plug-in hybrid EV - PHEV, full hybrid electric vehicle - HEV, mild hybrid electric vehicle - MHEV and pure internal combustion engine powered vehicles - ICE). The position of the bubble on the vertical axis represents the expected growth rate year-over-year. Filled circles show the projection from Q4/2024, dashed circles represent the projection from Q4/2023, one year earlier. Comparing these two forecasts, it can be observed that the 2023 prediction for 2025 and 2026 BEV growth was higher, for subsequent years lower than the forecast from the end of 2024. For 2027 and beyond the most recent forecast predicts higher growth rates than a year ago. This increase is necessary to offset previously reduced BEV shares towards meeting regulatory requirements for fleet average CO_2. Since already previous projections have not been met in terms of desired BEV shares, it appears that the gap between forecast and actual BEV shares is increasing and revised product strategies are needed to reduce the gap.

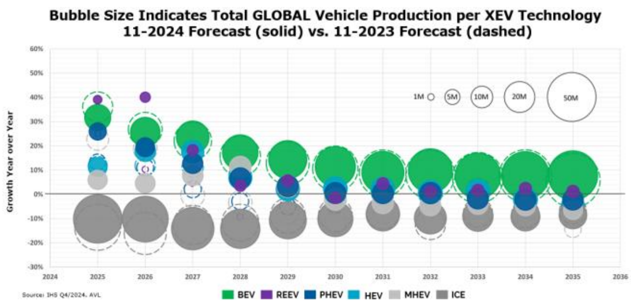

***Figure 1** Projected global passenger car production share by propulsion system technology*

Given the pivotal role battery electric vehicles (BEVs) are expected to play in achieving carbon-neutral transportation targets, the key question is: What steps are necessary to ensure BEVs are widely accepted in the mass market?

To address this complex question, we derive the priorities in product adaptation by applying Maslow's pyramid of human needs **[1]** to the consumer's view on electric vehicles. Like in Maslow's

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hierarchy, each layer of needs must be satisfied before progressing to the next level above. If we apply this analogy based on industry experience working in global markets as shown in **Figure 2**, we can deduce that the vehicle purchase price is the first obstacle towards adopting a BEV.

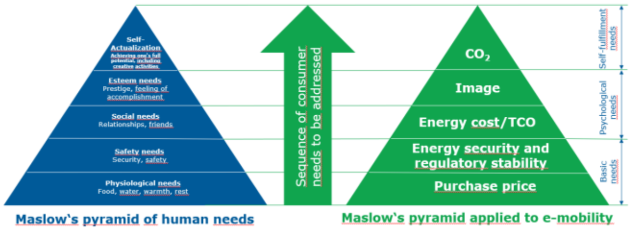

***Figure 2** Maslow's pyramid of human needs applied to mass adoption of e-mobility*

The next level is to be able to charge the vehicle when and where needed. If that is secured energy cost to operate the vehicle must support the business case for the consumer. The business case is of course also influenced by the resale price, insurance cost, taxation, finance cost, etc.

On the next level we find image, which includes the very important aspect of perceived safety. While several studies have proven battery electric vehicle fires have a lower occurrence than in other types of vehicles, a thermal event in a BEV is difficult to manage and, therefore, strong in the awareness of consumers. On top of the needs pyramid, we find the aspect of sustainability including carbon neutrality.

Derived from the needs pyramid, we can define the order of priority of challenges to be addressed for a widespread e-mobility adoption:

1. Product cost
2. Development of charging infrastructure and bridge solutions
3. Energy cost reduction, improve efficiency
4. Battery safety
5. The contribution to carbon neutrality

Achieving CO_2 neutrality is a global goal, with targets set by the European Union, Japan, China and many other legislators. It can be argued that the focus of e-mobility to date has been on the technology's impact on CO_2 emissions. While the pyramid may look different for consumers based on their personal preferences, economic situation, personal values and vehicle usage profiles, for the mass market the pyramid model appears applicable. This requires solving the underlying problems in the order as specified in the needs model, i.e. from the bottom to the top.

2. PRODUCT COST REDUCTION BY SYSTEM INTEGRATION

Product cost of electric vehicles is tackled on many levels. A lot of focus is put on the high-voltage battery since it is the single most expensive system. While smaller in magnitude, attention must be paid to every component in the high-voltage system. One approach to reduce component cost is to integrate multiple components both geometrically and functionally into a single unit, also known as x-in1 integration where multiple control units, power electronics and mechanical components are integrated into one unit.

It is current state of the art that an e-axle features a 3-in-1 architecture where the e-motor, transmission and power inverter are integrated into a common housing. In the constant search for cost reduction potential, the integration of other components such as the battery management system (BMS), DCDC converter, on-board charger, vehicle control unit (VCU) into a common housing is being pursued, as such a higher level of integration offers the potential to reduce packaging requirements and lower costs. The latter is further supported when the integration is extended to share microcontrollers, DC links and EMC filters.

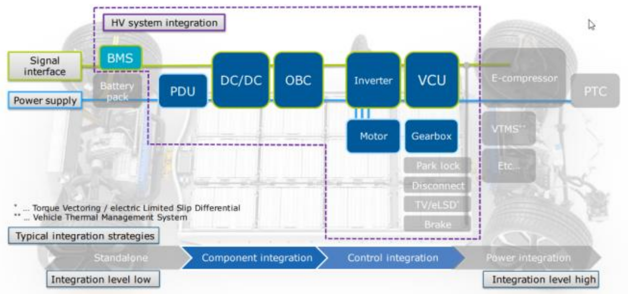

***Figure 3** 8-in-1 electric drive system, integration concept*

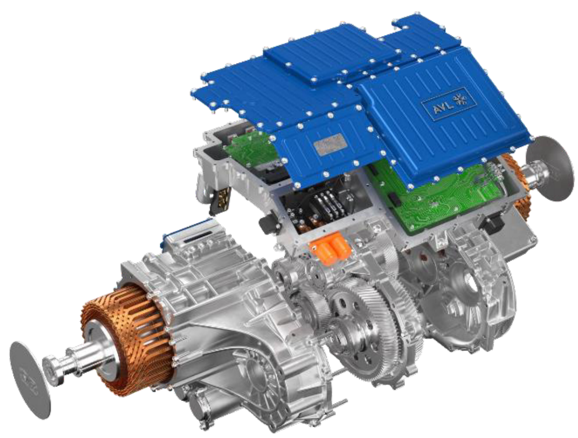

***Figure 4** 8-in-1 electric drive design*

According to our development results integrating all 8 components into a common housing, as shown in **Figure 3** for the concept schematic and **Figure 4** for the full design, shows the potential to

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reduce cost by 8-10%, packaging volume by 5-8% and mass by 9-12% **[3]**. However, it is important to note that this high level of integration also poses significant technical challenges, particularly in terms of electromagnetic compatibility (EMC) and noise, vibrations, harshness (NVH) characteristics.

Another option to increase the level of integration and reduce product cost is to increase integration in the HV battery and cluster components related to electric energy management such as the onboard charger, DCDC converter (high voltage HV/HV, HV/LV low voltage), BMS and the power distribution unit, see **Figure 5**. In addition to the potentials stated above, this allows a reduction of mechanical devices needed for the pre-charge functionality by using the DCDC converter instead. These two approaches show that the choice of integration concepts must be considered early in the development of the vehicle architecture to find the best trade-off between packaging, cost, and serviceability of the overall system.

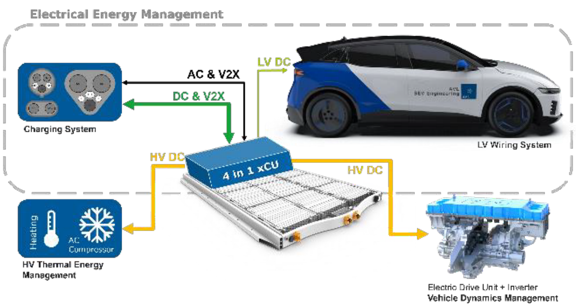

***Figure 5** HV System with 4in-1 xCU integrated in HV battery*

3. DEALING WITH CHARGING ANXIETY - REEV AS BRIDGE SOLUTION

Consumers appear to be hesitant to adopt to battery vehicles not only due to higher purchase prices vs. ICE-based vehicles but also because of concerns over vehicle range and charging infrastructure, which creates a major obstacle for broad consumer acceptance. While early adopters are willing to deal with the additional effort of searching for chargers and dealing with interoperability issues **[4]**, such inconveniences are not tolerated in the mass market, and therefore, need to be resolved. The deployment of available and reliable charging infrastructure takes place at a slower pace than BEV technology development **[5]** and market entry. A bridge solution may be required until the needed infrastructure which aligns to the EV sales and demand can be provided. This bridge solution may be a range extender vehicle, which can provide the consumer with a vehicle that can be operated electrically for every day commuting and offers the range extender for long distance travel and within regions with limited charging infrastructure availability. With respect to product cost, the range extender can provide scale to a BEV platform by extending the reach in the EV market. If the range extender variant and the BEV are co-developed based on a common platform, the potentially increased platform sales volume provides a very strong lever for cost reduction.

The CO_2 regulations in most develop markets allow for the use of range extender vehicles for many years to come. In Europe regulations are more challenging. A PHEV's homologated CO_2 value is strongly influenced by the electric range of the vehicle as shown in **Figure 6**. Here the scenario is shown for a C-segment baseline BEV with an 80kWh battery that is compared with a range extender powertrain with a 40kWh battery.

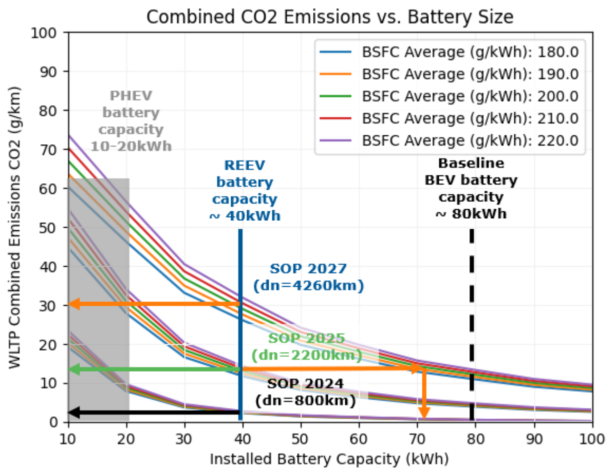

***Figure 6** Homologation CO_2 value for a C-segment crossover PHEV/REEV depending on the WLTP utility factor*

The curves show the homologation CO_2 values in the Worldwide Harmonized Light-Duty Vehicles Test Procedure (WLTP) cycle for the years 2024, 2025 and 2027, respectively. The curves are shifted upwards over time with for the same vehicle due to the utility factor which is used to calculate cycle CO_2. The utility factor weighs the electric range of an REEV. The weighting of the all-electric range is increased over time, which requires larger installed battery capacity to achieve constant CO_2 values.

The CO_2 curves in **Figure 6** are calculated for assumed average brake specific fuel consumption (BSFC) values of 180-220 g/kWh for the considered ICE. These BSFC values are in line with modern engines. The resulting tolerance band represents engines that can be found in REEVs on the roads today. In addition, the curves show the homologation value based on the utility factors regulated for 2024, 2025 and 2027, respectively. This means if we now look at the intersection of the 40kWh battery capacity line

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with the 2024 utility factor lines, we end up with a homologation CO_2 value of approximately 3g/km in 2024, see black arrow in **Figure 6**. The green arrow indicates that the same REEV will be homologated with approximately 14g/km with the utility factor that is regulated for 2025. If we now look at the regulation for 2027, we follow the orange arrow pointing to the left and see that by then the CO_2 homologation value of the same vehicle will be increased to over 30g/km. If the 14g/km from 2025 should be maintained also for the 2027 utility factor, we need to follow the orange arrow pointing to the right, which means that a battery capacity of 72kWh would be needed. This is not feasible economically or from a packaging standpoint.

The gray box in **Figure 6** shows a typical PHEV battery capacity of 10-20kWh in a C-segment vehicle, where the upper end of the capacity range is limited by packaging in such an ICE-based platform. The homologation CO_2 value of such PHEV ranges in 2027 from ~ 50 g/km with a 20kWh battery to ~65 g/km with a 10kWh battery, which are much higher CO_2 value than an REEV can achieve in the same vehicle.

By 2030, the fleet average CO2 value must be reduced by 55% compared to the 2021 limit, or to an average of about 55 g/km by 2030, with the actual value depending on the OEM's fleet. Therefore, the leverage for REEVs to reduce fleet average CO_2 levels in Europe will diminish over time, with zero tailpipe emissions being required by 2035 according to current regulations. Therefore, if an OEM decides to launch an REEV into the market, the sooner the product comes to market, the better the chances are to recover the investment in view of the regulations. In other markets such as the US, China, Japan and India REEVs may play an important role for more years to come. With on board monitoring of actual electric vs ICE operation combined with optimized ICEs to minimize the detrimental impact of the missing mechanical drive during ICE operation, the REEV may offer an attractive bridge technology.

3.1 Integration

When adapting a BEV platform to accommodate a range extender, automakers must coordinate multiple technical domains, from structural design to software controls and NVH management. A successful REEV configuration hinges on integrating the ICE, battery, and vehicle body in ways that preserve BEV driving characteristics while adding the flexibility of operating based on fuel when needed. Development and testing show that meeting these requirements demands thoughtful modular design and precise packaging trade-offs.

3.2 Platform and Packaging Requirements

Adapting a dedicated BEV platform for the installation of an ICE, fuel tank, and exhaust system typically involves reworking front or rear substructures, underfloor layouts, and coolant circuits. It has been observed that critical design items include the length of the front (or rear) overhang, underbody structure for exhaust routing, and space to position a small fuel tank (20 to 30 L) while avoiding intrusion on battery volume. These modifications necessitate structural changes to the body in white (BIW) since most BEV platforms rely on the battery housing to carry loads. Shifting battery mounts and integrating new reinforcement elements can be costly if not planned early in development. Early collaboration between vehicle designers and powertrain engineers can minimize expense by ensuring the base platform accommodates future REEV options.

3.3 Production Flexibility

OEMs that have modular assembly stations gain more versatility in installing either a purely electric or an ICE-supported powertrain on the same line. By contrast, non-modular manufacturing processes may need extensive redesign to handle new interfaces and workflows introduced by the REEV architecture. Adopting flexible, modular “stations” are recommended so that integrating REEV components impose minimal disruption to existing body-assembly processes. This approach also helps preserve future options if market conditions shift and demand for either BEV or REEV variants change rapidly.

3.4 Battery Adaptation and Trade-offs

Investigations of the impact on battery by switching to an REEV configuration indicate that pairing a medium-sized battery pack (30-60+ kWh, depending on vehicle size) with a range extender engine can satisfy most consumer use cases while reducing overall battery capacity compared to a dedicated BEV. A design for a REEV battery with the main design features is given in **Figure 7**, where modularity with the BEV variant battery was a key focus for maximum cost effectiveness.

Selecting a slightly lower-energy but higher-power battery chemistry (e.g. LFP) can yield cost savings that offset the added complexity of the ICE system and its integration. Thermal management is also crucial with REEV batteries as they experience higher load variability. A robust cooling design, with either water-glycol or refrigerant cooling, helps to maintain performance and to extend battery life.

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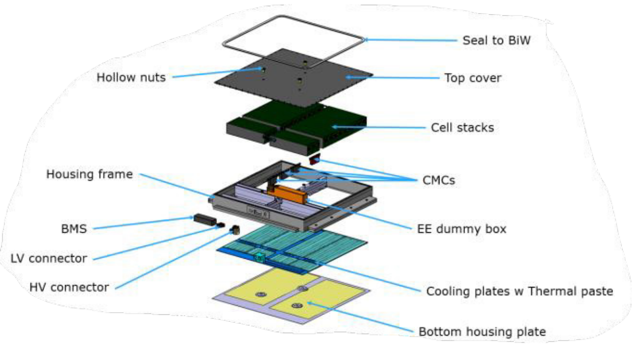

***Figure 7** Modular range extender battery design*

3.5 NVH

Because many consumers expect near-silent operation from vehicles marketed as electric, range extender engine noise and vibration can be highly disruptive and must be avoided. To make the ICE imperceptible in the REEV installation, we have concluded that an effective NVH package requires:

• A stiff and well-balanced ICE, with a tuned control strategy for smooth starts

• Strategic decoupling of the range extender engine from the EDU (electric drive unit) to reduce direct vibration paths

• Intake and exhaust systems with resonators or other attenuation measures to contain airborne noise

• Predictive operating strategies to run the range extender engine during higher ambient background noise or at stable loads that minimize harsh transients

3.6 Software and Controls Integration

Implementing a range extender demands an expanded supervisory control unit that accounts for battery state of charge, the aftertreatment temperature window, and performance demands. Predictive controllers that factor in navigation data and traffic forecasts to optimize range extender activation have been developed. These controllers help maintain a sufficiently high temperature in the exhaust aftertreatment system, reduced number of cold starts, and avoid intrusive noise events. This coordination across propulsion and thermal domains becomes a key enabler of a seamless “extended EV” driving experience.

3.7 Key Conclusions and Outlook

• *Modular Platforms*: Early planning for both BEV and REEV variants avoids late-stage redesign and saves cost, particularly in BIW structure and assembly line investment.

• *Balanced Battery Sizing*: A moderate battery capacity is sufficient when combined with an efficient range-extending ICE; this often yields cost benefits over large-battery capacity BEVs. Battery lifetime must be paid special attention to since an REEV will experience up to twice as many SOC swings over its lifetime if external charging is used predominantly.

• *NVH as a Differentiator*: Minimizing perceptible engine operation remains one of the greatest challenges. Advanced decoupling, packaging, and predictive engine-run strategies are critical.

• *Regulatory and Emissions Strategy*: Legislation for hybridized powertrains continues to evolve. Engines used in a REEV setup must meet the same emissions standards as conventional hybrids or PHEVs, including added OBD complexity and stringent aftertreatment performance.

• *Market Flexibility*: Given the volatility of electrification targets, having a platform that can pivot to both ICE-based range extenders and pure BEV helps OEMs hedge against uncertain consumer demand and shifting regulatory timelines.

4. IMPROVED EFFICIENCY

Battery electric vehicles are inherently more efficient in terms of energy consumption compared to ICE vehicles since much less waste heat is produced by the propulsion system. Nonetheless, in times of high energy prices in general in many parts of the world and high cost for using public charging, more focus is put on a BEV’s energy consumption to create a positive business case. In this context a high-efficiency e-axle system that achieves an average WLTP cycle efficiency of 94% has been developed.

The detailed layout process, design features, and operating strategy to achieve this result are presented in the paper titled 'Sustainable EDU Solutions' by Wilhelm Vallant, AVL List GmbH scheduled for presentation in Session B32-EP: System Design for BEV and HEV at EVTeC2025.

5. BATTERY SAFETY

Battery safety has a strong impact on consumer perception and, hence, on the willingness to move to a BEV. While regulations regarding battery safety are getting stricter, OEMs are targeting to exceed regulatory required targets. For instance, UN ECE R100 (Rev. 5) has a proposed update to regulate that for a period of two hours from a single cell thermal runaway, there shall be no thermal propagation. By now the latest achievements in battery development have allowed for great strides in safety and even exceed present regulatory standards. Whereas just a few years ago,

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these high levels of safety were only envisioned. Today, these targets have been realized with highly volatile chemistries by improved health monitoring and early warning anomaly prediction combined with design measures resulting from advanced simulation methods, strategic integration of new materials, proper gas channeling, and particle capture.

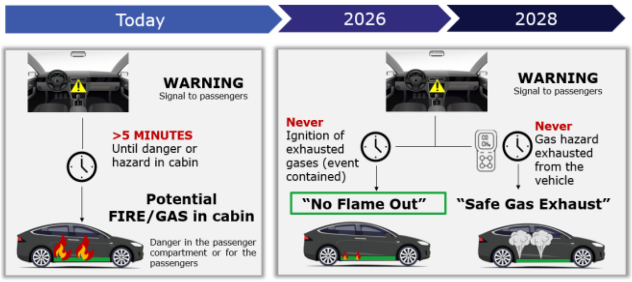

Figure 8 *Evolution of battery safety standards*

GB/T 38031-2020 is one of the primary Chinese standards governing the safety requirements and test methods for lithium-ion traction battery packs and systems in electric vehicles. It builds on earlier GB/T standards (such as GB/T 31485) and incorporates a variety of mechanical, thermal, and electrical safety tests.

A central requirement is that the battery pack must not cause danger to the passenger compartment within a minimum time window after the onset of a thermal event. This window in many markets and standards worldwide refer to a minimum of 5 minutes (often described as the time needed for occupants to exit safely), Chinese regulatory discussions have recently been evaluating an update to define that no fire or explosion is present for a minimum of 5 minutes upon the triggering of an event alarm. These increases in requirements are not only intended to increase safety but also enable sufficient time for first responders to arrive and address issues before a hazard is present.

As electrified powertrains continue to advance, there will be expanded requirements for combined system testing, including how battery packs behave with the vehicle's thermal management and structural subsystems during extreme events.

The demand coming from regulation, OEMs, and consumers is expected to increase with the overall technology advancement ultimately requiring new passive and active measures such as; advanced heat shielding, strategic and dynamic venting, particle filtering, and predictive battery management algorithms, in order to prevent flames or ignited gas from escaping the battery system.

5.1 Implications for Latest Battery Safety Trends

Recent advancements in battery safety underscore the importance of integrating improved materials, more robust design strategies, sophisticated sensing systems, and increasingly rigorous validation methods. For instance, fire barriers and intumescent coatings, which expand in high-temperature environments, have emerged as effective techniques to isolate damaged cells and minimize the propagation of thermal events. At the same time, researchers have made strides in refining volatile chemistries, such as nickel-rich nickel–manganese–cobalt (NMC), by optimizing electrolytes, separators, and additives to reduce the likelihood of internal short circuits.

On the monitoring side, enhanced Battery Management Systems (BMS) incorporate prognostic algorithms that swiftly detect local temperature, voltage, and resistance behavioral anomalies, allowing predictive intervention to avoid catastrophic failures. These algorithms draw upon continuous data streams that inform real-time assessments of battery health, enabling timely maintenance or mitigation actions. In tandem, advances in thermal management have led to the introduction of both passive and active countermeasures.

Passive containment strategies often rely on compartmentalized housings, which guide vented gases and flames away from sensitive areas, or material and device integration which are intended to permanently alter during an event. Active systems, like spanning liquid, refrigerant-based, or immersion cooling, maintain cell temperatures below critical thresholds under heavy loading or during high-rate charging to address potential abuse to the cells, and in the case of immersion cooling, the technology can also help to contain energy and particle release during an event thus protecting neighboring cells from continued propagation. Furthermore, thermal management systems need to consider design robustness to maintaining functionality during certain triggering events to aid in heat extraction which also helps to mitigate propagation. Venting systems which re-seal after a pressure pulse are also being brought into today's designs to help contain ignitable gases as well as provide a resistive barrier for oxygen to enter the battery compartment. The development of these passive measures is strongly guided by advanced multi-physics simulation, see **Figure 9**.

Increasingly strict validation protocols further bolster battery safety by emphasizing the predictive and iterative nature of system development. High-fidelity multi-physics simulations enable engineers to design and identify potential failures and validate solutions before physical testing – or even first sample builds – commence. These tools help anticipate the behavior of cells under abuse conditions such internal shorting, penetration, side-impact collisions, and thermal propagation, ensuring that

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countermeasures are in place long before a battery reaches the final production stage. Regulators and OEMs alike now incorporate more exhaustive test profiles, including partial state-of-charge evaluations and aggressive crash-intrusion scenarios, thereby aligning scientific innovation with real-world performance expectations.

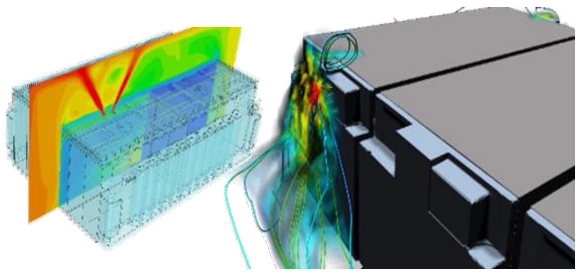

Figure 9 Multiphysics simulation of battery thermal event

6. $CO_{2}e$ EMISSIONS

Step-by-step $CO_{2}e$ emission regulation is evolving from tank-to-wheel via well-to-wheel to a life-cycle perspective. For example, Japan's well-to-wheel (WTW) regulations for CO_2 emissions are set to come into force in 2030. These regulations will include assessments of the entire lifecycle of energy consumption, from generation and transmission to consumption **[6]**.

As part of the Green Deal the EU is setting several regulations to achieve the net-zero CO_2 target in 2050. As shown in **Figure 10** the EU is breaking down the targets for vehicle products and components.

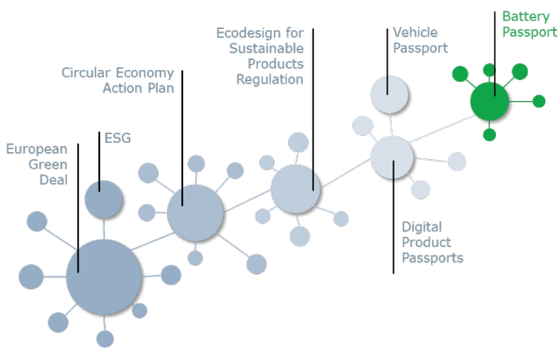

Figure 10 EU Regulations for increased sustainability

The EU Battery Regulation is first in line, which will come into force.

6.1 EU Battery Regulation

Several regions have robust regulations for battery safety and environmental impact, none match the EU's comprehensive approach, which includes monitoring, CO_2 footprint declarations, and a digital product passport.

6.2 $CO_{2}e$ Reduction - Example Battery Cover

The battery cover requirements include cost, weight, fire resistance, and $CO_{2}e$ footprint. Three materials were evaluated in depth: steel, aluminum, and fiber composite plastic (SMC).

While steel is cost-effective, aluminum offers clear weight advantage, and SMC balances $CO_{2}e$ footprint and weight. As shown in **Figure 11** no single material meets all criteria optimally, making selection complex **[7]**.

Variant	Cost [€]		CF [kg CO_{2e}]		Weight [kg]	
Steel	70	▲	66	●	18	◆
Aluminum	117	▲	85	●	7	◆
SMC	147	▲	67	●	10	◆

Figure 11 Battery Cover - Material Variation

Ease of maintenance, reusability, and recyclability are key optimization targets. Product safety requirements now include measures for thermal runaway and electromagnetic shielding, alongside crash impact behavior. **Figure 12** shows the impact of the material selection for the battery cover on six product requirements that need to be harmonized in a holistic design approach.

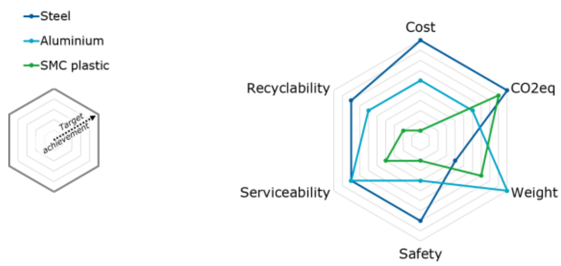

Figure 12 Balanced Product Approach in Design

Understanding the relationship between product requirements, material choice, and production processes is essential. Future research focuses on advanced materials, innovative manufacturing techniques, and comprehensive lifecycle analyses to enhance sustainability and performance.

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6.3. Impacts on Safety and Vehicle Integration

The risk of thermal runaway and its effects are significantly influenced by the design of the battery pack and the cell chemistry used *(see chapter 5. BATTERY SAFETY).*

The battery cover plays a crucial role in preventing flame propagation outside the battery pack during a thermal runaway event. The choice of material greatly affects the burn-through behavior, and the time required for burn-through. Additional measures, such as the selection of base material, reinforcement at key points, sealing, and the inclusion of fire-resistant material layers, can further enhance fire resistance.

A comprehensive understanding of material properties and their possible combinations is essential for optimally defining the parameters required for safety. This knowledge enables the development of battery covers that effectively balance safety, weight, cost, and environmental impact.

6.3. Outlook: Battery materials from biological sources

Future regulatory boundary conditions on reducing CO_{2e} footprint while increasing recycling quotas in battery raw materials for material scientists to find alternative solutions.

As an example the research project SMaDBatt aims to develop sustainable materials and designs for battery housings in electric vehicles, focusing on wood-steel hybrid structures to enhance recyclability and energy efficiency[8].

That includes:

- *Material Innovation:* Utilizing underused materials like recycled wood and bark for higher-value applications.
- *Design Optimization:* Improving the recyclability and energy efficiency of battery housings through disassemble-friendly designs.
- *Environmental Impact:* Promoting circular economy principles by selecting environmentally friendly raw materials and innovative construction methods.

As manufacturing techniques advance, we will see more approaches like SMADBATT in the future.

7. CONCLUSIONS

While the industry is facing headwinds by consumers regarding adoption of battery electric vehicles, regulations and the need to reduce the detrimental environmental impacts of traffic keep driving the need to enable sustainable mobility solutions. Addressing product cost is the key enabler to overcome the barrier to adopting e-mobility in the mass market and needs to be addressed on many levels, starting on component or sub-system level while always targeting for an overall gain on complete vehicle level.

Until charging infrastructure and the supply of electricity from renewable sources can be guaranteed, the range extender vehicle may be a viable bridge technology and can deepen market penetration of a vehicle platform, thus, also providing a cost benefit.

Battery safety can be managed through state-of-the-art health monitoring combined with passive measures to achieve "no gas out" behavior even with highly volatile chemistries, effectively eliminating all battery safety concerns for the consumer. Since this goes well beyond legislative requirements, this concern, which is often cited by consumers, can clearly be managed with the advanced development and validation methods that have been developed in the industry.

Driven by upcoming regulations and CO_2 emission trading schemes, which will influence product cost, methods have been established to be able to find the best trade-off between product cost, performance, serviceability and CO_{2e} footprint in the design process. Since most of the later footprint is defined in early product development stages, these considerations must be taken into account from onset of the development process to support the transformation towards sustainable mobility.

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