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Bipolar Technology: The Next Step in Battery Volume Optimization

- Opportunities and Challenges for New Vehicle Battery Platform Concepts -

Karsten Mueller [1)] Michael Clauß [1)] Alexander Fandakov [1)] Marc Sens [1)]

1) IAV GmbH, Carnotstr. 1, 10587 Berlin, Germany

E-mail: karsten.mueller@iav.de

michael.clauss@iav.de

alexander.fandakov@iav.de

marc.sens@iav.de

ABSTRACT: Despite significant advancements in the development of battery systems, which have enhanced volume utilization and vehicle range, sales in some regions are currently stagnating due to high prices and range anxiety. Over the past decade, IAV has been at the forefront of developing a compact bipolar Li-Ion battery system, designed to achieve driving ranges of up to 1000 km by integrating the battery directly into the vehicle chassis. The planar bipolar battery features plates with anodes and cathodes on opposite sides, connected in series to create a flat, space-efficient design. By eliminating the need for traditional module organization, this technology aims for high energy densities, low costs, and minimized internal resistance for improved efficiency. However, the bipolar concept also introduces unique technical challenges, such as the need for specialized electrical design and dedicated manufacturing equipment. This paper delves into the latest advancements in IAV's bipolar battery development, highlighting the potential for new platform concepts in vehicle applications.

KEY WORDS: Battery technology, bipolar battery, lithium-ion, energy density, space efficiency

1. INTRODUCTION

In recent years, substantial investments have been directed towards the development of specialized platforms for battery electric vehicles (BEVs), aimed at maximizing volume utilization and enhancing vehicle aerodynamics. However, despite these efforts, BEV sales in some key markets are stagnating and are not increasing at the pace necessary to meet ambitious legislative targets [(1)]. Surveys and analyses suggest that this stagnation is due to persistently high prices and, in some cases, range anxiety, even though vehicle autonomy has significantly improved. Additionally, the simultaneous tightening of CO_2 fleet limits is exerting further pressure on the automotive industry [(2)].

In 2014, IAV initiated the development of a bipolar Li-Ion battery system known as “EMBATT” Chassis-embedded Energy that addresses the mentioned challenges, marking a significant advancement in state of the art of battery systems for BEVs [(3)]. The objective of this concept is to create more efficient, next-gen battery systems capable of achieving electric driving ranges of up to 1000 km by maximizing the fraction of active material in the overall battery volume and reducing the space required for passive components to a minimum. The innovative bipolar technology emphasizes system-to-cell level integration and the elimination of interfaces, thus also introducing a handful of unique technical challenges.

2. THE BIPOLAR CONCEPT

Compared to state-of-the-art battery systems, the bipolar technology employs a fundamentally different structural design approach aimed at maximizing volume utilization at the system level. This is primarily accomplished by eliminating the need for cell housing and module organization with standard cell shapes (cylindrical, prismatic, or pouch), which typically result in significant amounts of unused space. Additionally, the bipolar approach employs chassis-embedded technology that integrates the vehicle chassis as the battery housing.

2.1. Concept overview

The primary component of the planar bipolar battery, as depicted in Figure 1, is the bipolar plate with active material. The electrode foils are assembled into a stack, with each bipolar plate featuring an anode on one side and a cathode on the other. All electrochemical cells are isolated from each other with a sealing to prevent ion flux. The electrical connection to the outside is made through two metal endplates (HV+, HV-). This structural organization allows the cells to be connected in series, achieving a higher system voltage and a very flat design. The traction system voltage is determined by the unitary cell voltage multiplied by the number of cells in the stack. The energy scale factor is the active area of the cell and the voltage level. Thanks to this compact design and the elimination of interfaces, such as cell connecting bus bars, superior utilization of the available volume can be achieved.

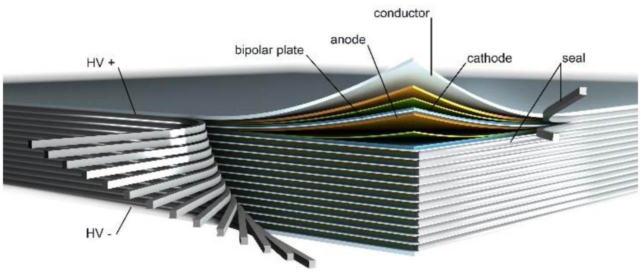

Fig. 1 Bipolar battery concept overview.

2.2. Concept targets

The goals of the planar bipolar battery technology are diverse and, compared to the current state of the art in battery systems, quite ambitious. Firstly, the technology aims to achieve an energy density of 500 watt-hours per liter (Wh/l) at the system level. This represents a significant enhancement of the value of 300 Wh/l, considered typical for state-of-the-art battery systems, and is achieved by maximizing the fraction of active material in the overall system volume while reducing the space required for passive components, as shown in Figure 2.

The maximized utilization of the volume available at the system level is enabled by combining an increased energy density at both cell (bipolar format and maximized single cell size) and system (chassis-embedded approach with platform and energy storage system integrated in a single unit) levels.

Secondly, the planar bipolar battery seeks to reduce overall system costs to approximately 100 euros per kilowatt-hour (€/kWh), making the technology more cost-effective and accessible, and thus suitable for the mass market. Lastly, the technology aims to decrease the internal resistance of battery systems to one-third of the levels found in current systems, significantly improving performance, efficiency, and ultimately vehicle range.

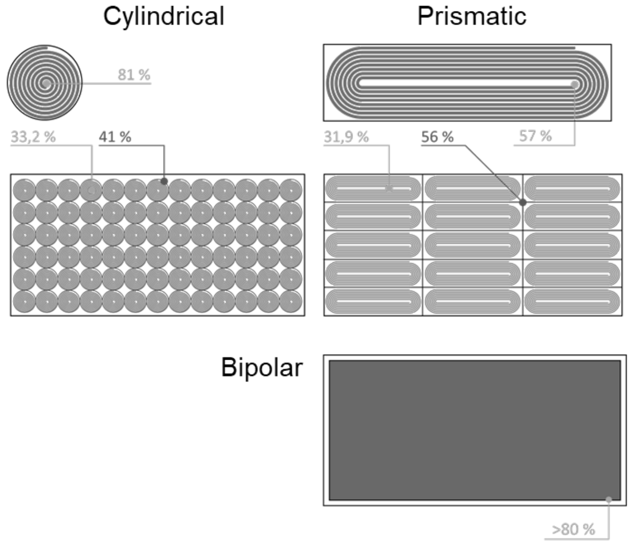

Fig. 2 Typical volume fractions utilized for storing electrical energy in the cells (grey) and at module or pack level (black) for common and the bipolar cell formats.

3. CONCEPT CHALLENGES

The specifics of the bipolar concept present unique challenges, with development heavily relying on reliably capturing the interaction between the electrical, chemical, thermal, and mechanical domains.

3.1. Electrical design

Battery cells are typically equipped with coated metal foils as voltage tabs, with aluminum used for the cathode and copper for the anode. However, bipolar batteries cannot use this typical setup due to the dissolving of aluminum and copper induced by the different electrochemical series, necessitating the use of a material with a higher electrochemical series for both active materials. Conductive polymer foil is an alternative solution since it works with both the voltage areas of the anode and cathode. A major disadvantage of polymer foil, however, is its low electrical conductivity in all dimensions. The goal is hence to reduce the voltage drop of the polymer foil, optimizing the current flow within the cell and minimizing losses. Alternatively, metal-based multi-material solutions can be employed as a compromise.

3.2. Load cases

While a typical battery cell requires only one load case because the current flows at a single point, the stacked architecture of the bipolar battery necessitates the consideration of two load cases. In the case of high current flow through the cell in the orthogonal-to-plane direction, Ohm’s law can be applied, and while the electrical conductivity can be low, the area is large. Balancing of the cells in the plane direction occurs when small potential differences are observed within cells, mostly due to manufacturing fluctuations and inhomogeneous cell aging. The important values in this case are the in-plane conductivity of the foil and its thickness. The ideal conductivity for a bipolar battery with a polymer foil has not yet been identified, with the use of innovative materials offering significant benefits (4).

3.3. Homologation and safety

Batteries must undergo critical safety tests for homologation, adhering to various regulations. These tests are categorized as mechanical (e.g., crush, vibration), electrical (e.g., short circuit, overcharge), and thermal (e.g., over-temperature, thermal propagation). UNECE R100 is mandatory in the European Union, while global regulations like UN38.3 and GTR are partially integrated into regional standards (5). In addition, the thermal propagation test prescribed in GB 38031 simulates a defect leading to thermal runaway, observing the spread to adjacent cells (6). The goal is to ensure passenger safety by maintaining an emergency egress time of over five minutes, with an imminent significant increase expected with further legislation (7). As the released energy in a thermal propagation case can be 10 times higher than the stored electrical energy, this poses a considerable challenge for the bipolar battery with its highly compact design and only a thin foil separating a cell in thermal runaway from neighboring cells.

3.4. Design, manufacturing, and vehicle application

The bipolar battery concept necessitates the use of specialized manufacturing equipment tailored to its unique needs. Additionally, the coating processes must be redesigned to accommodate the specific requirements of bipolar batteries. High-fidelity simulation approaches extensively validated based on measurement data are further essential to accurately model and optimize the performance of these batteries in the design process. Ultimately, employing a bipolar battery for vehicle applications requires the development of completely new platform concepts.

4. DEVELOPMENT OF A BIPOLAR CONCEPT FOR PASSENGER CARS

The potential for advancing the state of the art in battery systems with the application of bipolar technology is explored by developing a passenger car bipolar battery system concept with a chassis-embedded platform integration. This combination maximizes volume utilization and the proportion of active material, resulting in exceptionally high energy densities and extended vehicle ranges. Starting with an overview of the developed passenger car concept, the following sections delve into the solutions implemented to address the unique challenges associated with this innovative design.

4.1. Passenger car concept overview

The concept of a bipolar battery system for electric passenger cars is designed to deliver high performance and efficiency. The system is based on a concept study featuring a 115 kWh capacity and operates on a 400 V system with a configuration of 112 series and 9 parallel cells (112s9p). The innovative design integrates the platform and bipolar battery into a single unit (chassis-embedded technology), optimizing space and functionality, Figure 3 top. The battery format measures 1000 x 1900 x 115 mm³, consists of 3 modules housing 3 stacks each, thus yielding 9 stacks in total, with dimensions of 950 x 590 x 34 mm³ and a capacity of 31 Ah per stack. Additionally, each module incorporates four cooling plates to provide two-sided contact of each stack with the thermal management system, ensuring a uniform temperature distribution.

One bipolar battery cell is composed of a conductor made from bimetallic foil (copper and aluminum, each with equal thickness), a separator, an electrolyte solution, and active materials. To prevent electrolyte leakage and potential short circuits resulting from electrolyte mixing, each cell must be individually sealed. Each stack is capped on both sides with a collector plate (copper on the anode side and aluminum on the cathode side) and is fully enclosed with a pouch film. For the electrodes, the concept utilizes a graphite anode and NMC cathode (C/NMC), combined with a liquid electrolyte. Already with these state-of-the art materials, it achieves an impressive energy density of over 450 Wh/l. This high energy density results from the volume utilization rate of over 75% achieved at Begin of Life (BOL) and including the E-Box, that has not been optimized for this application. The battery system is compressed using a dedicated tensioning system applying constant force while compensating volume changes resulting from variations in the cells' state of charge and state of health.

In terms of sustainability, the ecological footprint of the battery system is estimated to be 66 kg-CO_2-eq. per kWh, reflecting a commitment to reducing environmental impact. The system is also cost-effective, meeting the specified target with estimated total costs amounting to 105 €/kWh, of which 80% are attributed to material costs with the cathode being the major contributor. Thus, the developed bipolar battery concept is characterized by a good balance of performance, efficiency, and sustainability.

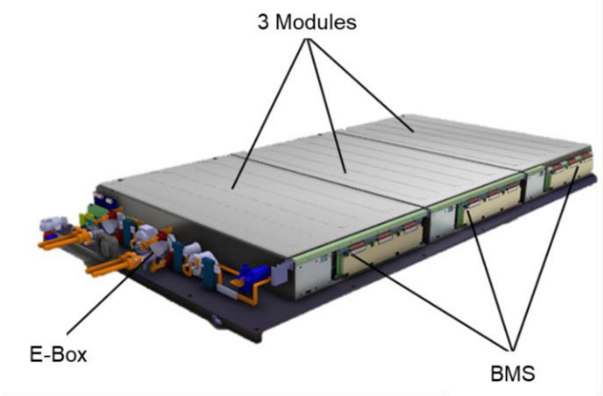

Fig. 3 Chassis-embedded platform for passenger cars with fully integrated (top) bipolar battery system design (bottom).

In the final bipolar battery system concept, the Battery Management System (BMS) is positioned on one side, while the cooling connection is located on the opposite side, Figure 3 bottom. Each cell is connected to the BMS via a flexible printed circuit board, allowing for the balancing of each individual cell. The current-carrying capacity is designed to be 100 mA, ensuring sufficient passive balancing. The discussed use of aluminum and copper for the conductors guarantees the current-carrying capacity. The integration of advanced balancing and cooling mechanisms supports the system's overall robust energy management and thermal regulations.

4.2. Bipolar battery cell design

Addressing cell-related challenges unique to the bipolar concept is a major prerequisite for the development of the passenger car battery pack presented in Section 4.1. A bipolar battery cell, Figure 1, is composed of active materials, a conductor, a separator, and an electrolyte solution, with each cell being individually sealed to avoid electrolyte leakage. The development of bipolar cell samples involves several key stages, starting with material development topics focusing on the conductor. Various conductor materials and manufacturing methods have been evaluated, including metal-based multi-material solutions, polymeric conductors with chemical refinement (Ni plating) for improving the conductivity, galvanic coatings, inkjet plating, and screen printing. The assessment focused on electrochemical stability, utilizing cyclic voltammetry to identify potential side reactions within the relevant voltage window. Among the tested materials and compared to copper foil serving as a reference (as typically used at the anode of conventional battery cells), the plated aluminum-copper variant has demonstrated superior performance. Additional advantages in terms of availability in large quantities, porousness, thickness and costs have resulted in its selection as conductor material for the bipolar cells (8).

Based on this, sample stacks in different formats have been mechanically fabricated, Figure 4, based on a newly developed process aiming to improve the consistency of the manufactured battery stacks and to facilitate scalability in production, considered a critical factor for commercial viability. The developed stack manufacturing process has been continuously improved based on insights from evaluations of various manufacturing technologies performed for the A4 format, including electrode production, de-coating of active material, laser cutting and joining, stacking, sealing, and electrolyte filling. In addition, by employing a combination of pre-drying at 110 °C and vacuum drying at 110 °C for 24 hours respectively, the residual moisture could be cut in half compared to vacuum drying at 90°C. All sample stacks include pouch bags in addition to the individual cell seals to protect against leaking electrolyte.

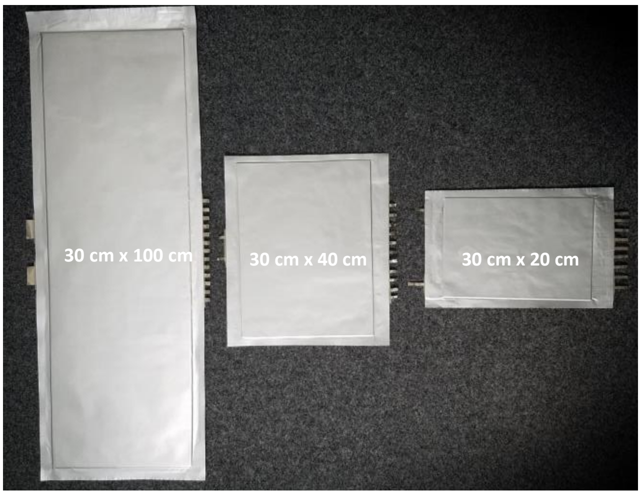

Fig. 4 Manufactured bipolar cell sample formats.

The integration of sense contacts for stack voltage monitoring and cell balancing has been meticulously designed to ensure minimal transition resistance and effective handling. Here, the challenge lies in the connection technology with the conductors and in the implementation through the pouch bag [9]. Based on an evaluation of weld image, adhesion, and surface, nickel-plated steel foils with 25 µm and 67 µm thickens emerged as the preferred choice for the battery management system connection due to their favorable processing and sealing properties.

Tests dedicated to establishing the optimal tensioning force have been performed with a 48 V stack, Figure 5. This bracing condition is essential because the stack experiences changes in thickness both from cell aging and during charging and discharging cycles. Without proper tensioning, delamination of the electrodes could occur, leading to an increase in internal resistance. The tests performed have revealed the best performance with a force of 0.8 N/cm^2. However, it should be noted that the optimal value strongly depends on both the bipolar cell size and cell swelling performance at end of life.

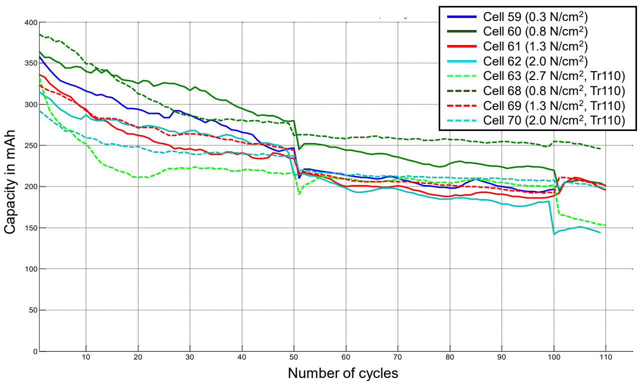

Fig. 5 Impact of stack tensioning on capacity after 100 cycles.

In a last step, the manufactured stack samples have been employed for comprehensive testing of their function and cycle stability, with tests of up to 100 cycles having been conducted successfully with different active samples. Results from cycling of a 10-cell stack conducted with a current of 0.9 A are shown in Figure 6. The curves demonstrate a highly consistent behavior following the formation phase. Notably, there are hardly any voltage deviations observed between the individual cells within the stack, indicating uniform performance and stability across the system. This consistency is crucial for ensuring the reliability and efficiency of the stack in practical applications, as it suggests a well-balanced electrochemical environment within each cell.

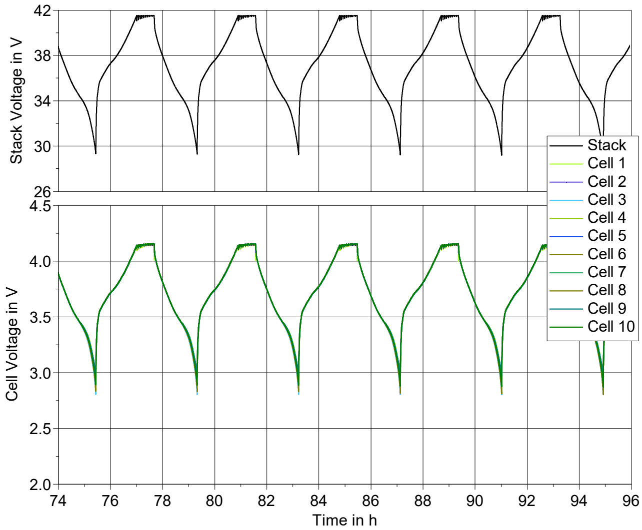

Fig. 6 Cycling of a stack with 10 cells (cycles 25 - 30).

4.3. Thermal and mechanical challenges

The cooling system of the bipolar battery concept is integrated as intermediate layers within the battery modules, with the cooling medium directed to the stacks through the base structure, Figure 7. This integration strategy aims to maintain optimal temperature levels by providing each stack with direct contact with two cooling plates. It should be noted that this strategy implies a direct correlation between the number of stacks and the necessary number of cooling plates, ultimately impacting the achievable volume utilization rate.

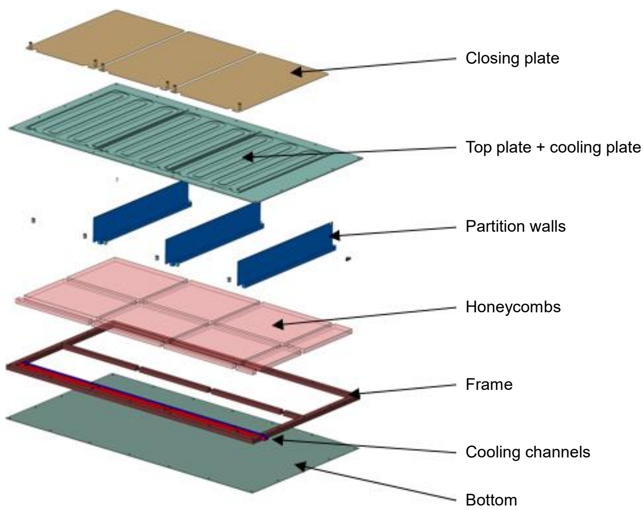

Fig. 7 Exploded view of base structure with cooling connection.

Various cooling technologies have been explored to identify the most effective solution for the bipolar concept, Table 1, ensuring sufficient performance without compromising the utilization of the available volume. A liquid cooling approach utilizing four cooling plates per module results in an overall inadequate cooling performance. This shortcoming is largely attributed to the absence of cooling plates with geometries specifically optimized for the bipolar application. This highlights the necessity for further refinement in the design of liquid cooling system layouts to meet the specific performance requirements of this application.

As an alternative, a direct evaporation of refrigerant can be considered, with a feasibility study conducted to assess the risk of refrigerant overheating within a module. While this method shows potential, the dissipation of heat to ambient at high power loss conditions remains a challenge. In addition, a feasibility study on the implementation of heat pipes has resulted in further exploration of this technology to be halted due to space constraints within the design, limiting the practical application of this technology in the bipolar concept. A two-phase cooling using refrigerant, employing four cooling plates, has been examined as well. Although the cooling performance within the battery is estimated to be sufficient, the system's ability to transfer heat using automotive-compatible components, such as chillers and pumps, appears limited.

	Liquid cooling	Direct refrigerant evaporation	Heat pipe	2-phase cooling (refrigerant)
Status	Insuff. cooling performance	Optimization loops necessary	Technology not applicable	Feasibility study completed
Required flow rate	> 50 l/min (Target: 15-25 l/min)	~ 300 kg/s	-	27 l/min
Temperature distribution (cooling plate)	11 K (Target: 5 K)	17 K (Target: approx. 1 K)	-	3 K
Temperature distribution (stack)	t.b.d.	21 K (Target: 15 K)	-	Approx. 15 K
Max. temperature	t.b.d.	56°C (Target: 45°C)	-	45°C
Total height of cooling plates (per module)	16 mm	12 mm	12 mm	12 mm

Tab. 1 Cooling technology performance assessment results.

Overall, the cooling system faces challenges with low thermal conductivity within the stacks, leading to critical temperature differentials at stack heights exceeding 30 mm, even at charging power levels of only 100 kW. Without a dedicated cooling plate design, liquid cooling is anticipated to result in very high temperatures and uneven cooling due to fluid heating. Furthermore, the necessary flow rate for liquid cooling to support fast charging, along with the expected pressure loss, is currently considered unattainable. On the other hand, the refrigerant mass flow needed for fast charging with up to 125 kW is feasible. To achieve effective cooling, distributing the refrigerant across 12 cooling plates and controlling at least three expansion valves may necessitate a higher overall mass flow. Thus, direct refrigerant evaporation emerges as the preferred cooling strategy, offering a promising solution to the challenges identified. This approach, while still requiring further optimization, is considered a viable path forward in enhancing the thermal management of bipolar battery systems. Alternatively, dedicated, highly optimized cooling plate designs are expected to provide sufficient for the most cases, although compromised, performance.

Beyond cooling, the tensioning of the battery stack is a critical aspect of the bipolar battery design, necessitating thorough investigation due to the specific requirements of the concept. As discussed in Section 4.2., tensioning is essential for ensuring no delamination of the electrodes occurs. Based on the design and cell characteristics, it is estimated that approximately 10% of the available space must be allocated for stack tensioning. Thus, the tensioning system is designed to apply a force of 0.3 N/cm² at the beginning and approximately 2.7 N/cm² at the end of the stack's life.

To address this, two types of spring elements have been considered: one made of steel and an alternative made of foam. In the steel variant, the individual legs act as leaf springs, which have been meticulously designed and simulated. The residual thickness of the steel spring at the end of its life is approximately 1 mm. The foam variant, designed with similar considerations, has proven to be significantly lighter, with a total system-level weight of approximately 250 g compared to nearly 10 kg for the steel version. However, it remains to be tested whether the foam can endure the cyclic loads throughout the entire lifetime of the battery system.

4.4. Chassis-embedded platform design

The developed bipolar concept employs a chassis-embedded technology that integrates the vehicle chassis as the battery housing. The integration of the 115 kWh bipolar battery into a passenger car vehicle platform is shown in Figure 8. While being highly efficient in terms of material and space usage, this approach presents challenges that require specific measures to enhance structural integrity and ensure compliance with regulations such as UNECE R100, Section 3.3. In this context, the development goal is for the design to not only meet safety standards but also to surpass established safety and performance benchmarks.

Two material concepts, resulting in two distinct designs, have been explored for integrating the bipolar battery - one utilizing steel and the other aluminum. Initially, these designs undergo acceleration verification, with the system tested to withstand an acceleration of 60 g in the Z-direction. Additionally, a load path examination is conducted using an exterior frame model to ensure the vehicle's structural resilience, particularly during front crash and pole test scenarios, Figure 9.

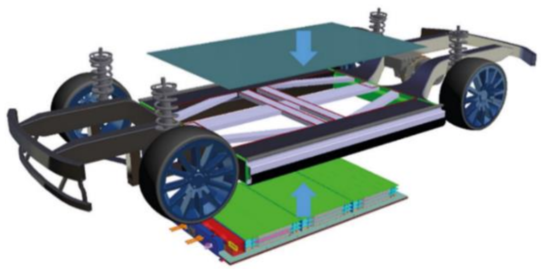

Fig. 8 Bipolar battery integration in chassis-embedded platform.

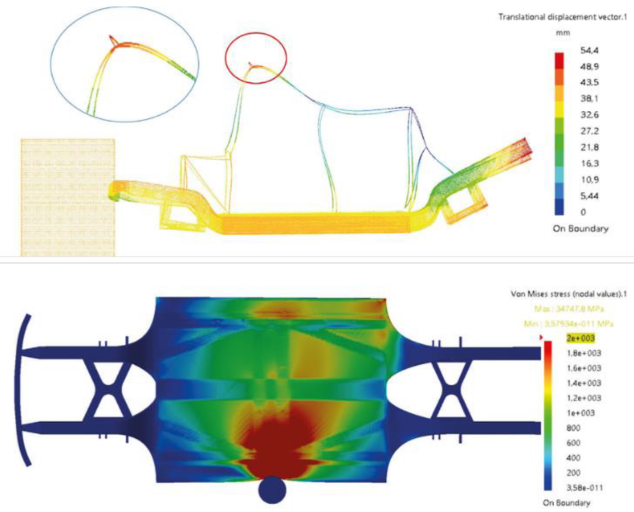

Fig. 9 Load paths in front and side pole crash tests.

Achieving a torsional stiffness of 50 kN/deg is a critical aspect of the target design, ensuring the vehicle maintains structural integrity under various driving conditions. The final design exceeds this target, achieving a torsional stiffness of 51 kN/deg. Structural cohesion during operation is further supported by the mechanical preload applied to the battery system, as detailed in Section 4.3. Overall, the design complies with current regulations, thanks to a streamlined development process that saves iteration loops through the early application of body replacement models.

The final platform concept design emphasizes the synergy between the platform and the battery. Achieving a lightweight index of 1.52 kg/(Nm/deg*m²) underscores the achieved balance between weight and structural performance, marking a significant advancement in electric vehicle platform design. By eliminating the battery housing typically required in conventional integration approaches, a mass saving of approximately 30 kg is achieved, with future amendments to regulations anticipated to accommodate the specifics of advanced battery technologies.

4.5. Perspectives with advanced electrode materials and solid-state electrolyte

Integrating solid-state electrolytes into the existing bipolar battery concept presents a promising approach for further significant enhancements of energy density, resulting in more space-efficient battery systems. The potential is assessed with calculations dedicated to estimating the achievable energy densities by incorporating a solid-state electrolyte, combined with different anode materials and electrode thicknesses, with these being a function of the number of stacks. The evaluation is performed with the bipolar concept presented in Section 4.1. as a basis, the number of stacks within each module ranging between 3 and 5, and with the maximum installation space for the system remaining constrained to 1900 x 1000 x 115 mm.

The evaluated electrode materials include a graphite anode, graphite-silicon (10% by weight yielding a specific capacity of 705 mAh g^{-1}), and lithium metal with a specific capacity of 3860 mAh g^{-1}. For the cathode, NMC811 is selected as a representation of the state of the art. Among the electrode materials investigated, lithium metal emerges as a particularly promising candidate due to its very high specific capacity, which can enhance the energy density by almost 100% compared to typical liquid systems when the same stack amount is used, Figure 10 top. Increasing the number of stacks, while resulting in thinner electrodes and being beneficial for incorporating a higher number of cooling plates, hence considered an enabler for the application of plate-based liquid cooling, results in a reduction of energy density, Figure 10 middle. This trade-off highlights the importance of optimizing stack amounts and electrode thickness to balance energy density and thermal management. Notably, with comparable cathode thicknesses, the use of lithium metal increases the energy density at the system level by only up to 60%, Figure 10 bottom.

The integration of solid-state electrolytes combined with lithium metal into bipolar battery concepts not only promises improvements in energy density but also offers potential benefits in terms of safety and longevity. Solid-state electrolytes can mitigate issues related to liquid electrolyte leakage and sealing of the stacked cells as well as evaporation and combustion during thermal runaway, thereby enhancing the overall safety profile of the battery system. Additionally, the use of solid-state electrolytes can potentially impact the cycle life of the battery by reducing degradation mechanisms associated with liquid electrolytes.

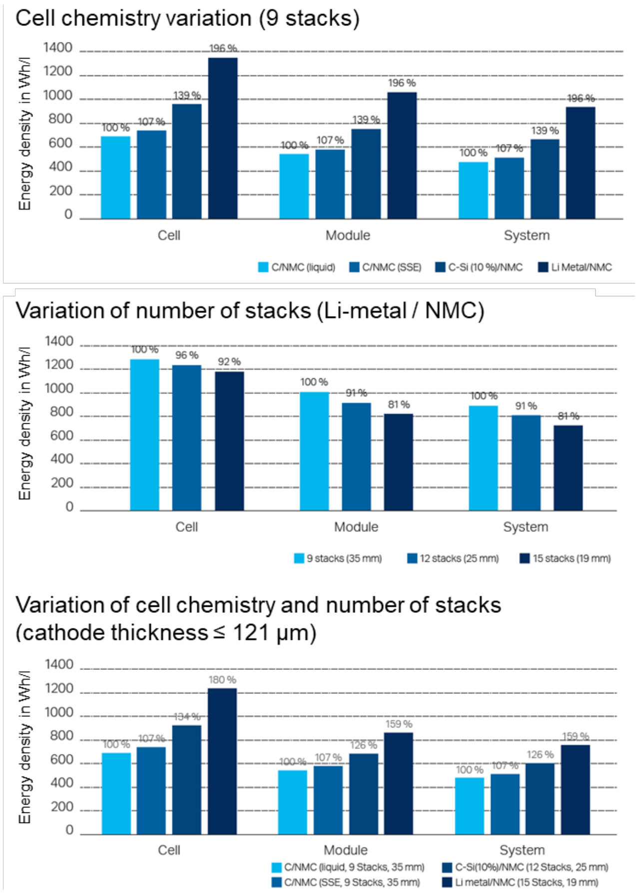

Fig. 10 Impact of cell chemistry (top), number of stacks (middle) and the two parameters combined (bottom) on energy density for liquid and solid-state electrolytes.

5. CONCLUSIONS

This contribution focused on a planar bipolar battery design connecting anodes and cathodes in series, thus eliminating traditional cell housing and module organization to achieve high energy density, low costs, and reduced internal resistance, aiming for driving ranges up to 1000 km. This innovative approach, however, presents unique technical challenges, requiring specialized electrical design and manufacturing equipment.

Still, the presented latest advancements in the development of IAV's bipolar battery system integrated into the vehicle chassis reveal huge potential for new, space-efficient battery platform concepts in vehicle applications that can be further boosted by the application of advanced electrode materials. Overall, compared to a state-of-the-art passenger car battery system design, the presented bipolar concept offers a significant reduction in internal resistance by 30%, considerably enhancing efficiency. It also increases capacity by 20% and improves the energy density by 17% (volumetric) and 9% (gravimetric) respectively. Additionally, it reduces the specific CO_2 footprint by 9%, contributing to environmental sustainability, while reducing costs by 1%. By employing lithium metal combined with solid-state electrolyte, the capacity is expected to be boosted by 70%, yielding a further substantial improvement in energy storage capabilities.

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