38th International Electric Vehicle Symposium and Exhibition (EVS38) Göteborg, Sweden, June 15-18, 2025

The HELIOS project – innovative hybrid modular battery systems for next-generation EVs

Farshid Naseri[1], Corneliu Barbu[1], Pedro Hernandez[1], and Tomas Jezdinsky[2]

[1]*Department of Electrical and Computer Engineering, Aarhus University, Aarhus, Denmark (fna@ece.au.dk; coba@ece.au.dk; pedro_hernandez@ece.au.dk*

[2]*European Copper Institute (ECI), tomas.jezdinsky@internationalcopper.org*

Executive Summary

HELIOS project has developed an innovative concept for a modular lithium-ion battery pack, combining a hybrid approach based on high-energy (HE) and high-power (HP) cells to improve overall performance and fast charging capabilities, while aiming for eco-friendly design for better circularity and life cycle assessment. Applying a holistic approach, experts in various fields from 18 consortium partners work together on HELIOS solutions combining innovative design ways to integrate battery management system, hybrid thermal management system, and DC-DC converter linked to new sensors to control and monitor the safety and behavior of the pack. This paper aims to present the HELIOS battery pack, its architecture and key innovations and breakthrough designs from dual-chemistry wireless Battery Management System (BMS) to hybrid Thermal Management System (TMS) and multi-sensing units for advanced pack monitoring.

Keywords: Electric Vehicles (EVs), Energy Storage Systems, Battery Management System (BMS), Modelling & Simulation, Energy Management

1 Introduction

Battery pack design is crucial for optimizing Electric Vehicle (EV) performance, as it affects weight, energy density, and thermal management [1, 2]. Lighter packs increase range and efficiency while maximizing energy density allows more energy storage in less space. Additionally, battery packs often contribute to the vehicle's structural integrity. Balancing these factors—weight, energy density, cooling, and structure—is key to improving EV range, efficiency, and overall performance [3]. While battery pack designs like Cell-to-Pack (CTP) or Cell-to-Chassis (CTC), try to increase energy density and reduce weight by directly integrating cells into the pack or even into the vehicle's chassis [4, 5], modular designs, meanwhile, group cells into smaller, easily replaceable modules, offering greater flexibility and ease of maintenance. One challenge is that EVs often require different power-to-energy ratios, which are difficult to achieve using modules made from only one type of battery cell. Cells are typically optimized either for energy, like Nickel Manganese Cobalt Oxide (NMC) cathode cells, or for power, such as Lithium Titanate Oxide (LTO) cells. Decoupling "energy" and "power" in battery pack designs can offer greater flexibility to meet diverse EV requirements [3]. In HELIOS, an innovative modular battery pack concept is proposed which is based on using High-Energy (HE) and High-Power (HP) modules in one pack enabling a flexible design with adjustable power/energy ratio to meet requirements for small to large-size EVs. The HELIOS battery pack's innovative design follows a holistic approach addressing all subsystems including the Battery Management System (BMS), Thermal Management System (TMS), and DC-DC converter. This paper aims to present the HELIOS battery pack concept and its beyond-state-of-the-art (SotA) functionalities, together with relevant preliminary results and assessments.

The HELIOS project (High-performance modular battery packs for sustainable urban electromobility services) is a four-year initiative funded by the European Union under the Horizon 2020 program [6]. The project brings together a consortium of 18 partners—including leading universities, research institutions, and industrial stakeholders—from eight European countries. Each partner contributes specialized expertise across various aspects of battery pack design, excluding the cells themselves. This includes the development of the BMS, TMS, electronics, sensors, contactors, mechanical enclosures, and overall system integration. HELIOS aims to deliver innovative hardware and software solutions for smart control of electrical and thermal subsystems, leveraging advanced materials, power electronics, and sensor technologies. Furthermore, the project integrates cutting-edge information and communication technologies (ICT), including cloud-based big data analytics, artificial intelligence, and Internet of Things (IoT) platforms. Figure 1 presents an overview of the HELIOS project, highlighting its work package (WP) structure and partner contributions.

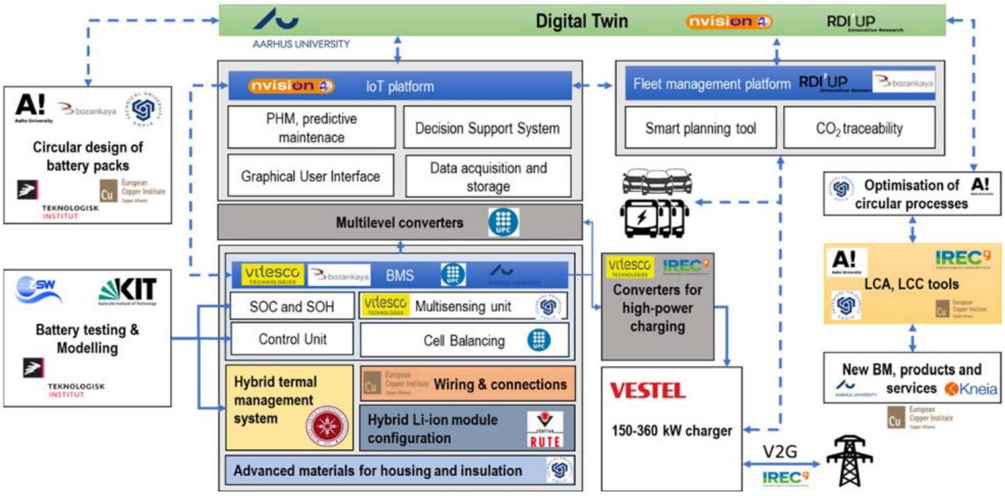


Figure 1: Overview of the HELIOS project and its WPs and participating entities

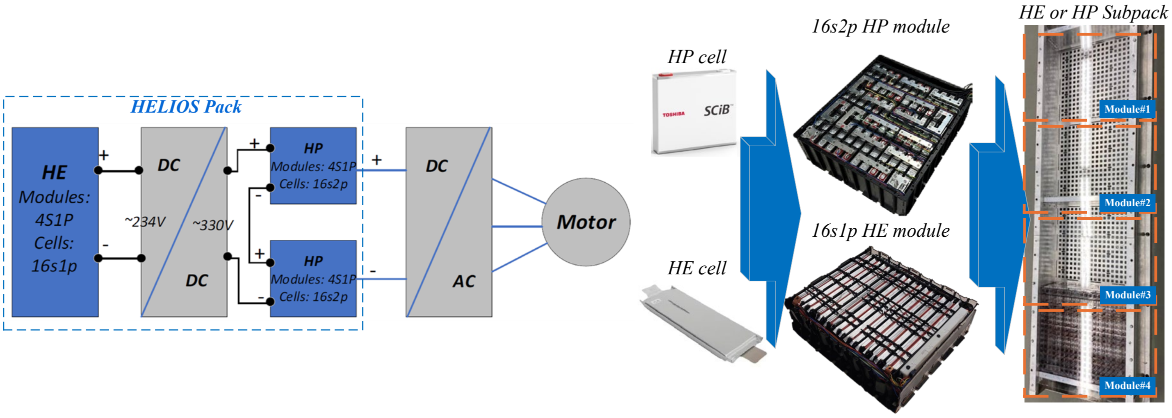
The manuscript is structured into several sections, each addressing key technologies developed within the HELIOS project. Section 2 provides a general overview of the HELIOS battery pack architecture and its main components. Section 3 focuses on the core hardware and software elements of the BMS, the Multi-Sensing Unit (MSU), and the bidirectional DC-DC converter. Section 4 presents the proposed solution for battery cooling and thermal management. Section 5 presents the DC-DC converter for the hybrid battery. Section 6 explores the digital twin concept and the integration of ICT technologies, including cloud connectivity and AI-driven analytics. In Section 7, based on simulations and partial prototype testing, the key performance results at the system level are presented. Finally, Section 8 concludes the paper.

2 Overview of the HELIOS battery pack

HELIOS adopts a dual-chemistry, or hybrid, battery structure that combines two distinct cell types—each optimized for a specific performance attribute. HE cells are designed for energy storage and extended range, while HP cells are optimized for rapid power delivery. The HE cell utilizes a NMC cathode paired with a graphite anode, while the HP cell features a Lithium Manganese Oxide (LMO) cathode combined

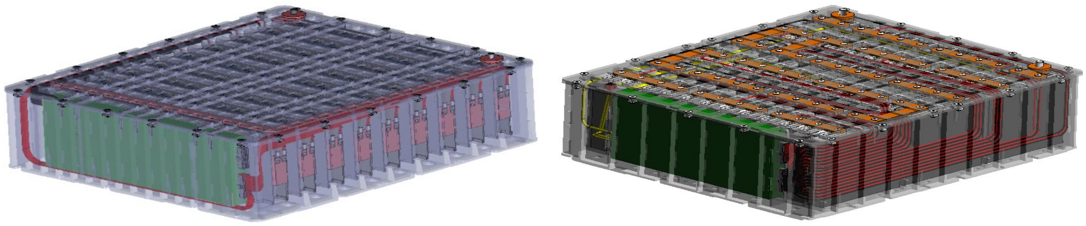
Table 1: Specifications of the cells in the hybrid pack

Parameter	**HE cell**	**HP Cell**
Nominal voltage	*3.65V*	*2.3V*
Rated capacity	*73 Ah*	*20 Ah*
Minimum operating voltage	*2.75V*	*1.5V*
Maximum operating voltage	*4.2V*	*2.7V*
Cell chemistry (cathode-anode)	*NMC-graphite*	*LMO-LTO*
Cell format	*Pouch cell*	*Prismatic cell*
Gravimetric Energy density	*286.51 Wh/kg*	*85.19 Wh/kg*
Gravimetric Power density	*859.52 W/kg*	*1192.59 W/kg*



(a) (b)

Figure 2: (a) High-level schematic of the HE and HP pack electrical connections to the motor drive (b) Modular design approach for the HE and HP subpacks.



(a) (b)

Figure 3: CAD design of the modules (a) HE module (b) HP module

with a LTO anode. As the fundamental building blocks of the battery pack, these cells are integrated using a modular hybrid approach, enhancing the system's flexibility and scalability to meet diverse power and energy demands across various applications. The specifications of the HE and HP cells are summarized in Table 1.

The hybrid battery pack consists of multiple HE and HP subpacks. Each subpack is composed of four modules of identical size—four HE modules form an HE subpack, and four HP modules form an HP subpack. Using modules of similar physical dimensions offers advantages in terms of mechanical integration, manufacturing efficiency, and thermal management, enabling a common housing and assembly process regardless of the cell chemistry. The architecture of the hybrid battery pack is shown in Fig. 2. The modules are fabricated using a so-called "egg-box" design, which enhances structural rigidity and facilitates efficient thermal management through improved airflow and heat dissipation. The HE modules are configured in a 16s1p arrangement, while the HP modules follow a 16s2p configuration to meet their respective energy and power requirements. Due to the different electrical characteristics of the HE and HP subpacks, they are operated at distinct voltage levels. Two HP subpacks are cascaded in series and are directly connected to the DC link of the motor drive to reach a voltage of ~330 V (the DC-link required by the vehicle demonstrator Mitsubishi i-MiEV), whereas the HE subpack is rated at ~234 V and is interfaced with the HP subpacks via a bidirectional DC-DC converter. The DC-DC converter is designed to have bidirectional power flow to both charge and discharge the HE subpack as needed. This architecture enables independent control and optimized utilization of both chemistries, ensuring flexibility and performance across diverse operating scenarios. The DC-DC converter is controlled using an energy management strategy embedded into the BMS. Fig. 2(b) shows the HELIOS modular approach.

The CAD designs of the HE and HP modules are shown in Fig. 3. Both modules have identical outer dimensions—390 × 340 × 120 mm (L×W×H)—resulting in a volume of ~16.5 liters. This uniform sizing simplifies mechanical integration and packaging within the battery system. The HE module weighs approximately 18 kg and provides a nominal voltage of 58.4 V with an energy capacity of around 4.3 kWh. Likewise, the HP module weighs about 22 kg, has a nominal voltage of 36.8 V, and delivers an energy capacity of approximately 2.9 kWh.

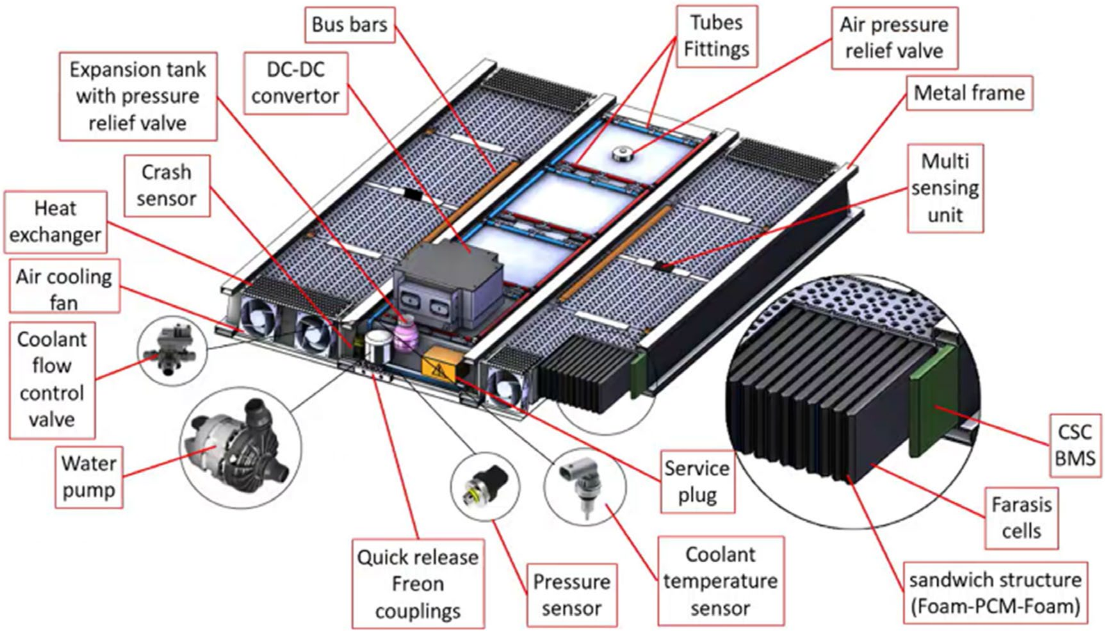


Figure 4: Schematic of the overall battery pack concept and major components

As part of the HELIOS project, a prototype hybrid battery pack is currently being developed for integration into a Mitsubishi i-MiEV. The demonstration pack will consist of two HP subpacks connected in series to achieve a combined voltage of approximately 300 V, aligning with the DC-link requirements of the vehicle's motor drive. In parallel, an HE subpack will be connected to the same DC-link via a bidirectional DC-DC converter. The overall battery system is designed to deliver a rated energy capacity of approximately 41 kWh, corresponding to a gravimetric energy density of around 166 Wh/kg and a volumetric energy density of approximately 208 Wh/L. The system also achieves a gravimetric power density of about 1.4 kW/kg, enabling rapid charging of approximately 65% of the battery within just six minutes. The schematic of the battery pack and its main electrical, thermal, and mechanical components are shown in Fig. 4.

The following subsections provide further details on the main components of the battery pack, highlighting their key features and technological innovations.

3 Battery management system (BMS)

The HELIOS BMS is designed as a modular and scalable system capable of managing a hybrid dual-chemistry battery pack composed of both HE and HP modules. The architecture supports separate monitoring and control of HE and HP subpacks, with a bidirectional DC/DC converter acting as a power exchange interface between them. A central Battery Management Controller (BMC) serves as the primary decision-making unit, coordinating communication and control across all battery modules. The system architecture of the battery pack is depicted in Fig. 5. The BMS mainly comprises cell supervision circuits (CSCs), a battery management control (BMC), and a current sensing module (CSM). The CSCs monitor 16 series connected cells and each HE and HP module is equipped with one CSC board, which additionally measures up to 5 temperature spots within the module. The main role of CSC is to measure individual cell voltages and temperatures within the battery module. The boards can detect abnormal situations such as over-voltage and under-voltage conditions. The CSCs have an embedded passive balancing option with switched resistors to balance the state-of-charge (SoC) for the series-connected cells. To enhance scalability and reduce wiring complexity, wireless communication is implemented between the BMC and individual CSCs located in each module. Likewise, the CSCs are upgraded with extended boards enabling faster passive balancing by increasing the balancing current to reduce cell balancing time. Communication with the Current and High Voltage Measurement Module (CSM/HVCM) is handled separately, isolating high-voltage measurement functions from the BMC and ensuring compliance with automotive safety standards

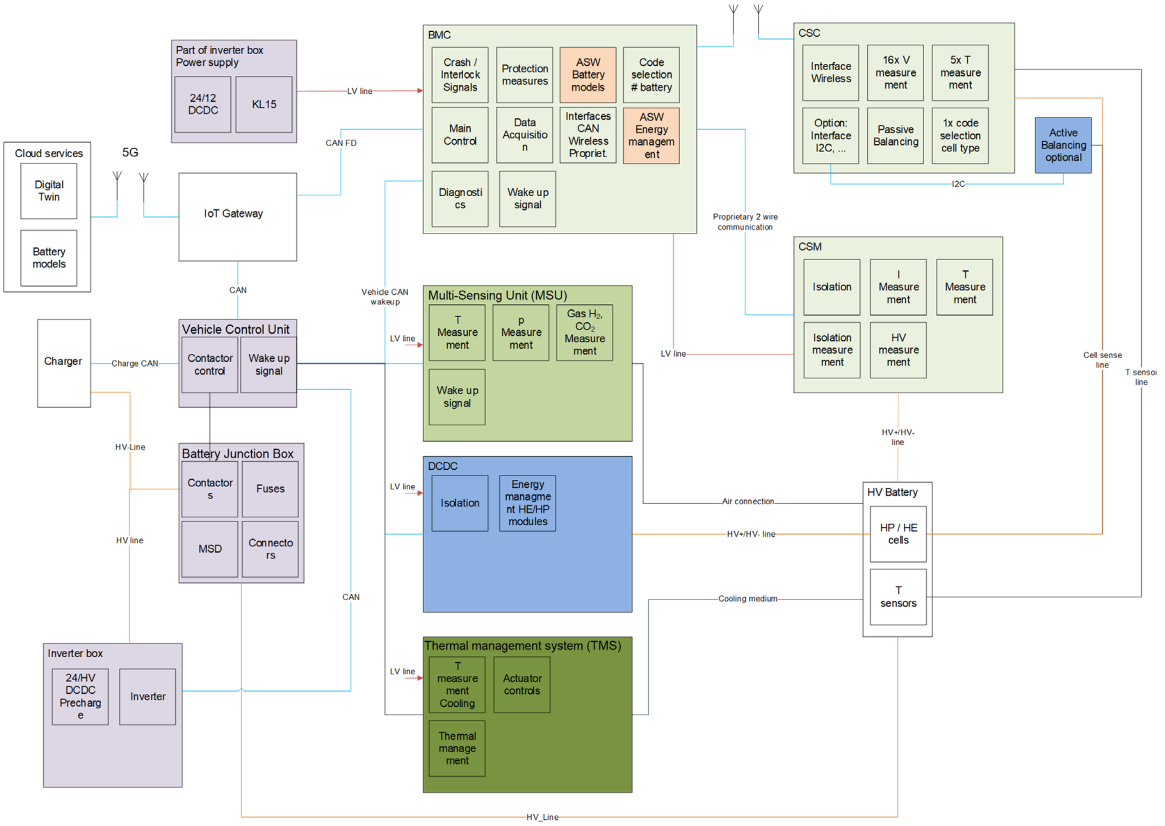


Figure 5: Electrical architecture of the main pack components in HELIOS

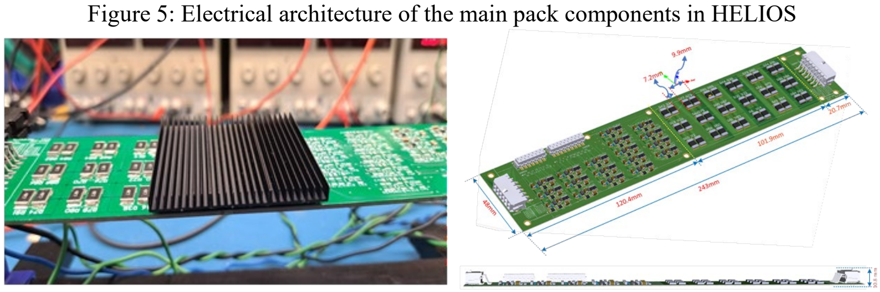


Figure 6: Schematic view and the fabricated extended passibe balancing board

(e.g., ASIL D for overcurrent protection). The hardware innovations of the HELIOS BMS lie in the wireless communication system and extended passive balancing system. The wireless system reduced BMS weight by 2% due to the removal of the communication harness. Likewise, extended passive cell balancing enables balancing currents up to 1.75 A using power resistors (from conventional ~300 mA) as depicted in Fig. 6, yielding faster cell balancing during fast charging scenarios. The BMC externally communicates with the vehicle control unit (VCU) using a dedicated CAN bus. Key battery measurements are also streamed to an exclusive data bus toward IoT gateway using CAN-FD protocol. The IoT gateway is the communication bridge to send data to the cloud services, including the digital twin and fleet management platform (FMP) which facilitate advanced battery analytics.

Another beyond-SotA feature of the HELIOS BMS is its dual-chemistry compatibility, enabling simultaneous monitoring and management of two different cell types. A set of universal State-of-X (SoX) algorithms has been developed to estimate key battery states—Charge (SoC), Health (SoH), Power (SoP), and Energy (SoE) [7]. These algorithms are embedded within a scalable and flexible software architecture that allows straightforward calibration to accommodate new cell chemistries. The SoC estimation is fulfilled using an Extended Kalman filter (EKF) combined with a Thevenin-based equivalent circuit model (ECM) [7]. For SoH estimation, both internal resistance growth and capacity fade are considered as key aging indicators to be estimated. The resistance estimation is fulfilled using the least-squares (LS) algorithm with a sliding window while the capacity is estimated using the Total Least Squares (TLS) technique [8]. The SoP estimation is determined using a model-based approach and considering limits on maximum charge and discharge currents, allowable SoC ranges, and voltages [9]. Different experimental studies were conducted on both LTO and NMC cells to characterize their distinct dynamic behaviors. The SoX estimation models were accordingly tailored to support both chemistries, incorporating appropriate model structures and leveraging an online Recursive Least Squares (RLS) algorithm to continuously update model parameters during operation taking into account nonlinearities [10].

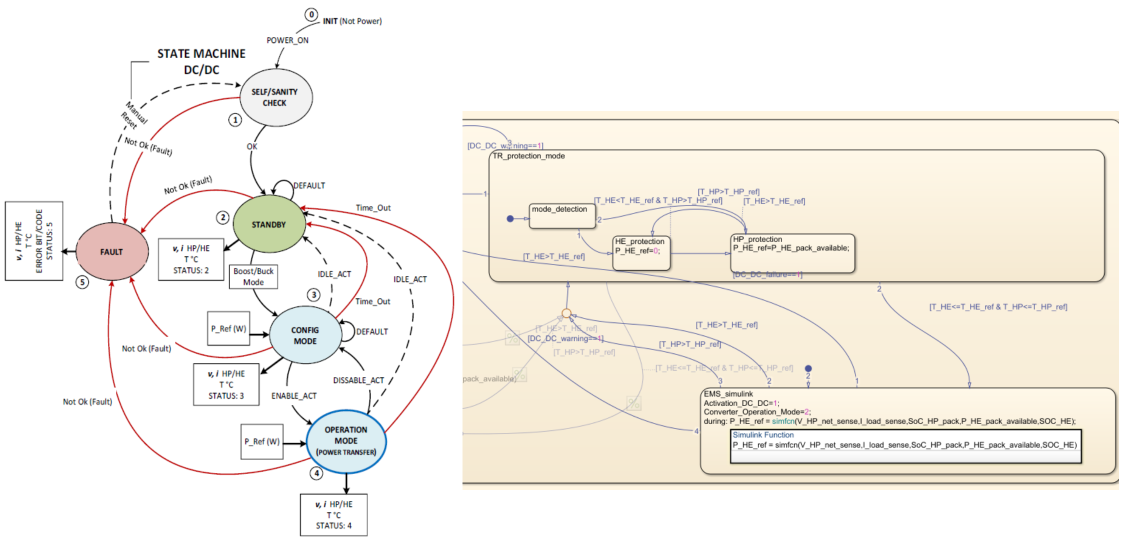
The algorithms were validated using a custom dynamic driving cycle developed to replicate real-world driving conditions in Aarhus, Denmark—referred to as the Aarhus Driving Cycle (ADC). Validation results at 25 °C for both cell types are summarized in Table 2, demonstrating the robustness and versatility of the SoX framework.

Table 2: RMSE of SoX co-estimation under ADCP at 25°C

	SoC	SoH_R	SoH_C	SoP_{Ch}	SoP_{Dch}
NMC	~0.008	~0.041	~0.015	~ 10 W	~ 8W
LTO	~0.012	~0.052	~0.021	~15 W	~ 18W

Software development in the automotive industry adheres to the Automotive SPICE® framework. Within this process, a dedicated architecture tool is employed for software architectural design (SWE.2), which generates an AUTOSAR-compliant container. This container is then synchronized with the detailed software design and unit implementation stages (SWE.3), as well as verification activities (SWE.4), all carried out in the MATLAB/Simulink® environment, which is also used for algorithm development and implementation. Following successful simulation and validation, the production code is automatically generated according to AUTOSAR standards and integrated into the software project targeting the automotive microcontroller. The software is architected with scalability in mind, enabling all key variables to be configurable. This allows the same automatically generated codebase to be reused across multiple system configurations, significantly reducing development effort and enhancing modularity and flexibility.

A key innovation in the HELIOS BMS software lies in the integration of an Energy Management System (EMS) designed to regulate power flow between the HE and HP subpacks. The EMS is implemented as a Stateflow® model with hierarchical states and operational modes enabling optimal utilization of the hybrid battery architecture under various driving and charging scenarios. The EMS dynamically allocates power between the HE and HP subpacks based on real-time conditions such as the SoP of each subpack [3]. In general, the HE subpacks, based on NMC cells, are used as range extender by providing a smooth continuous power, while the HP subpacks, composed of LTO cells, are utilized to handle major share of



(a) (b)

Figure 7: (a) schematic of the stateflow logic of DC-DC converter (b) schematic of the stateflow model of the EMS

power demands and transient spikes. This strategy leverages the superior power density and cycle life of LTO cells, thereby extending the overall battery lifespan. The EMS operates across three primary modes: Parking, Charging, and Driving. Within each of these, additional sub-modes are defined to handle specific use cases, including limp-home mode (to drive with reduced performance in case of a faulty pack), critical mode (de-rating a specific subpack if its temperature goes above a safety threshold), and cold start mode. During the cold-start conditions, the system prioritizes the HP subpack to avoid stressing the more temperature-sensitive NMC-based HE cells, thus reducing their degradation. In charging mode, activated when a charging session is scheduled or initiated, the EMS may pre-condition the battery by discharging the HP subpack into the HE subpack. This strategy increases the SoC margin in the HE subpack, enhancing charge acceptance and reducing overall charging time, particularly under fast-charging conditions. The EMS also functions as the upper-layer control logic for the bidirectional DC-DC converter, determining the operating mode (buck or boost) and issuing power references based on real-time energy distribution requirements. The DC-DC converter itself is governed by a separate Stateflow® model, ensuring a coordinated control strategy based on the EMS and the DC-DC converter control. The EMS function is implemented in the BMC unit. Figure 7 provides a snapshot of the hierarchical Stateflow® implementation of the EMS and the DC-DC converter control logic.

In addition to the basic protection functionalities provided by the CSCs and the BMU such as over-charge and over-discharge protections, a novel MSU has been developed and integrated into each subpack of the HELIOS battery system [11]. The MSU is designed to provide advanced diagnostic and protection capabilities by monitoring a range of critical physical parameters that extend beyond conventional voltage, current, and temperature measurements. Specifically, the MSU tracks the evolution of critical gas concentrations (H2), internal pressure, and localized temperatures at key locations within the subpack and across individual modules. The primary goal of the MSU is to reduce the risk of thermal runaway (TR) and fire propagation, especially considering flammable electrolytes. Such events can pose significant hazards to vehicle occupants and result in substantial property damage to surrounding infrastructure. The MSU provides an added layer of safety by enabling early detection of pre-runaway conditions, thereby allowing the system or the VCU to take preventive action before a critical failure occurs or to issue an evacuation alarm before a fire starts. The development of the MSU involved a comprehensive sensor selection and validation phase, during which multiple sensing modalities—pressure, gas concentration, strain, and temperature—were evaluated. Of particular note is the use of strain sensors that measure mechanical deformation (i.e., cell swelling) caused by internal chemical reactions. This mechanical response often precedes thermal events, offering a valuable early-warning indicator for impending failure. The MSU's effectiveness was rigorously validated through a series of abuse tests, including nail penetration, thermal overheating, overcharging, and external short-circuit scenarios [11]. These tests confirmed the robustness and reliability of the sensing architecture. Notably, during one validation scenario, the MSU successfully detected gas generation within ~11 seconds, clearly demonstrating its capability for rapid hazard identification and early intervention.

4 Thermal management system (TMS)

A hybrid TMS has been developed for the HELIOS battery pack, integrating liquid cooling (using a serpentine), air cooling, and phase-change materials (PCMs) to provide robust and adaptive thermal regulation. The inclusion of PCMs plays a critical role in buffering sudden temperature spikes and absorbing excess heat during high-load or fault conditions [12]. This thermal buffering effect extends the response time available to the active cooling components, significantly enhancing thermal runaway protection and overall system safety [13]. The thermal solution is integrated within a thermo-mechanical "egg-box" structure, which provides dual benefits: high thermal efficiency and mechanical robustness. This structure enables uniform cooling and minimizes thermal gradients across the cells, while also enhancing the structural integrity of the battery module. The core components of the TMS include 1- the serpentine cooling channels to circulate water-ethylene glycol coolant mixture for heat extraction, 2- fans with PWM control to enable active air cooling, 3- thermal actuators and flaps to regulate airflow paths within the housing to manage heat dissipation, and 4- TMS controller to orchestrates the system by interpreting sensor data and adjusting coolant flow, fan speeds, and flap positions, accordingly. The TMS is governed by a closed-loop control algorithm implemented in MATLAB/Simulink, utilizing a dynamic thermal model of the subpacks for real-time management. The control architecture prioritizes: 1- battery life extension, by

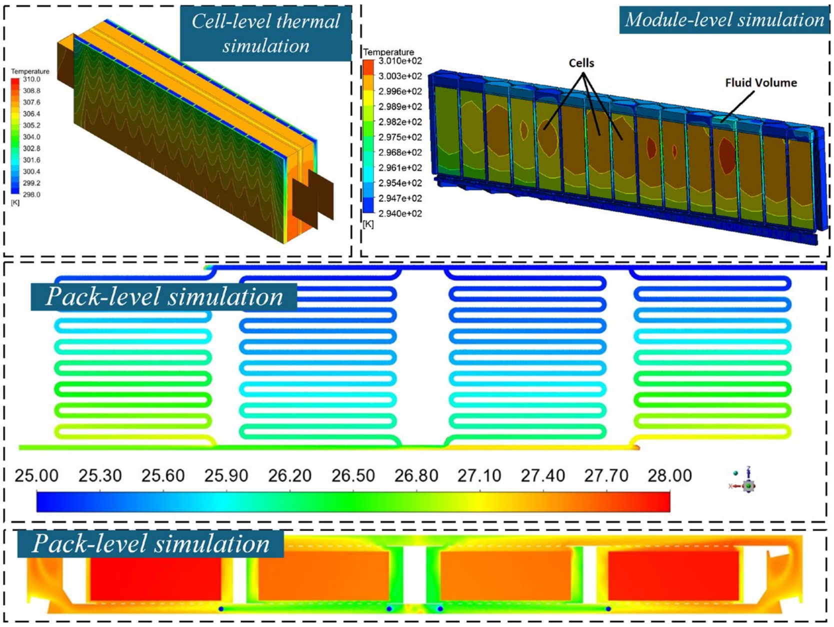


Figure 8: Temperature distribution within the serpentine simulated in the subpack

maintaining cells within optimal operating temperatures, and 2- energy efficiency, by minimizing the power consumption of fans and pumps without compromising safety. The control logic is based on air velocity, coolant flow, C-rate, battery temperatures, and ambient temperature inputs. The TMS has been validated through CFD and FEA simulations, 1D thermal modeling, and experimental discharge tests at 1C–5C rates. A key innovation in the HELIOS thermal design is the elimination of traditional cold plates. By re-engineering the cooling interface through direct cell-to-coolant contact and advanced structural integration, the system achieves a 70% reduction in coolant volume compared to conventional designs. This contributes directly to increased gravimetric and volumetric energy density, supporting the lightweight and compact design goals of the HELIOS architecture. The HELIOS TMS is designed through a thorough analysis of thermal behavior across all system levels—from individual cells to modules and the full battery pack. Figure 8 shows thermal responses at different levels, which were investigated to optimize the TMS design, e.g. cooling channels, etc. The TMS is optimized according to the specific requirements of each subpack—HE and HP—taking into account their distinct thermal characteristics, heat dissipation profiles, and expected operational limits, such as charge and discharge rates. The overall system assures temperature uniformity within ±2°C across modules during high-rate discharges.

5 DC-DC power converter

The DC-DC converter in the HELIOS battery is a central enabler of the hybrid dual-chemistry battery architecture, facilitating controlled energy exchange between the HE and HP subpacks. The converter is designed cutting-edge wide bandgap (WBG) semiconductor technologies, the converter achieves high switching frequencies and reduced losses. The topology is based on a non-isolated bidirectional interleaved structure as depicted in Fig. 9.

This contributes to improvements in both volumetric and gravimetric energy density at the pack level. Specifically, the new converter design enables a ~5% improvement in volumetric energy density and a ~2.5% improvement in gravimetric energy density, supporting the HELIOS objective of reducing system size and weight without compromising installed capacity. Beyond hardware efficiency, the HELIOS DC-DC converter also plays a crucial role in enhancing overall vehicle performance and range [14]. By minimizing conversion losses and optimizing energy flow between the HE and HP packs, the converter together with the EMS contributes to increased system-level energy efficiency. This results in improved driving autonomy by dividing appropriate shares of load power between HE and HP subpacks to maintain a balanced performance and homogenous degradation as well as to de-rate the battery pack when the available power from either sub-pack is limited.

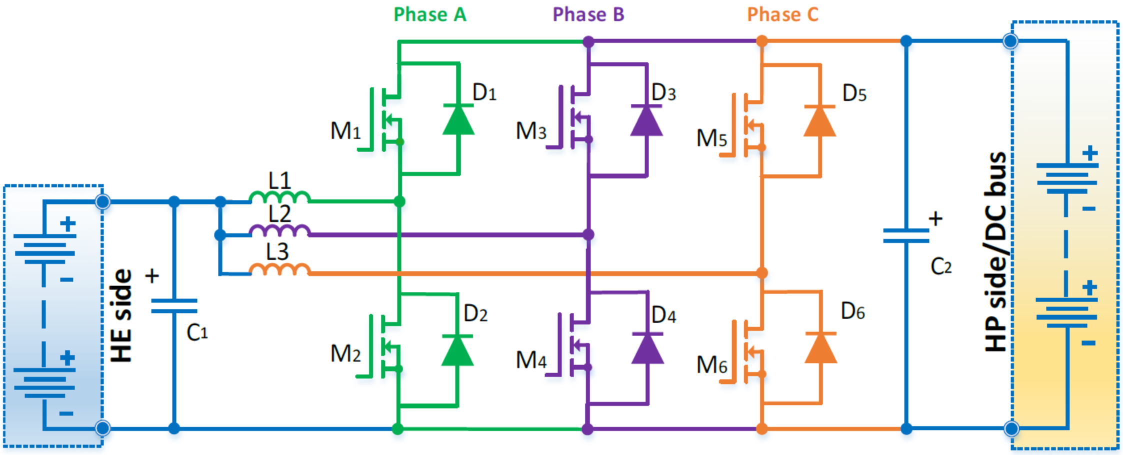


Figure 9: Topology of the interleaved bidirectional DC-DC converter

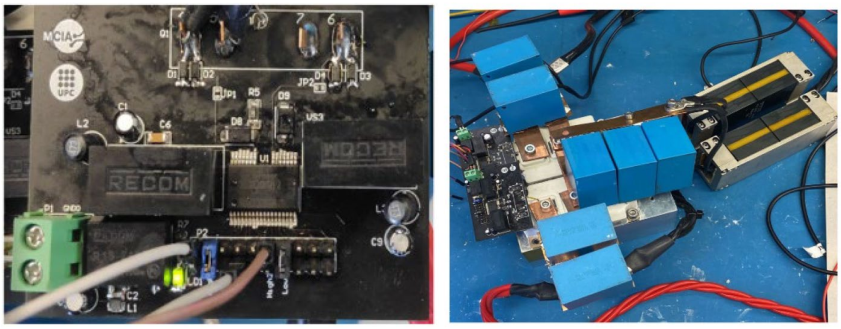


Figure 10: Picture of the prototyped 3kW bidirectional DC-DC converter to interface HE and HP subpacks

One of the key performance targets for the HELIOS architecture is achieving 90% SoC in under 30 minutes with minimal battery degradation. The DC-DC converter contributes to this goal by enabling high-rate charging while regulating power delivery between subpacks to reduce stress on the more sensitive HE cells. The converter supports up to 2C discharge rates on the HE sub-pack and its control loop interconnects with the TMS, which is optimized to maintain safe temperatures during rapid charge/discharge events. This coordinated control ensures both charging speed and battery longevity. A first prototyped version of the HELIOS DC-DC converter is shown in Fig. 10. In addition, a novel DC-DC converter enables lossless cell balancing as demonstrated by one HELIOS partner in [14] .

6 Digital twin for advanced pack monitoring and control

In the HELIOS project, the digital twin plays a central role in meeting the stricter requirements imposed by fast-charging demands—such as achieving 65% charge in just six minutes. To support such aggressive performance targets without compromising battery safety or longevity, advanced modeling and monitoring tools are essential. The HELIOS digital twin enables real-time optimization of battery performance by continuously collecting and analyzing both real-time and historical data from the battery pack [15]. A dedicated CAN-FD bus is employed to transmit battery measurements to a gateway and onward to the digital twin via an IoT-based service. This infrastructure ensures continuous data flow and serves as the basis for advanced battery analytics. The digital twin supports multiple functions, including enhanced control, diagnosis, and prognosis. By leveraging substantial computational resources and memory capacity, it can store and analyze vast volumes of historical battery data, which in turn enables predictive management strategies [16]. These capabilities are key for AI-driven prognostic tasks, such as estimating the Remaining Useful Life (RUL) of battery cells and packs.

The HELIOS digital twin is built on the ThingSpeak platform from MathWorks, offering a cloud-based environment for data visualization and algorithm deployment. For instance, in one application, an AI model based on a Long Short-Term Memory (LSTM) neural network is used to predict the RUL of individual

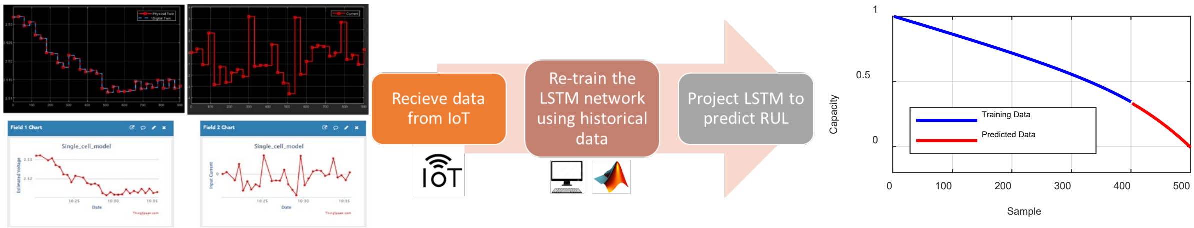


Figure 11: Workflow of RUL estimation on HELIOS digital twin

cells. These insights are critical for operational planning, preventive maintenance, and extending the functional life of battery systems. Moreover, accurate RUL estimation supports informed decision-making for battery repurposing, allowing HELIOS batteries to be safely and efficiently reused in second-life applications. Figure 11 shows the workflow of RUL estimation on the digital twin related to a typical cell.

7 Results and performances at pack level

The components and key performance indicators at the component level of the HELIOS battery pack have been presented, previously. The HELIOS pack is currently under development, with integration and testing activities ongoing. Two battery pack prototypes are being manufactured for testing in an electric bus and a Mitsubishi i-MiEV. Final performance results will be published upon completion of these tests by mid-2025. However, simulation results are already promising. Our study showed that the HELIOS pack provides an effective driving life exceeding 300,000 km—representing a 30–40% improvement over current battery warranties—and achieves a 25% shorter charging time with a 150 kW charger compared to the Tesla Model 3 mid-range battery pack. Additionally, the HELIOS pack offers a 30% reduction in weight and 20% reduction in volume compared to the Tesla Model 3 battery pack, based on equal installed battery capacity.

8 Conclusions and future work

The HELIOS project presents a groundbreaking approach to EV battery pack design through its innovative hybrid architecture that integrates HE and HP cells within a modular and scalable structure. By combining advanced BMS, TMS, and power electronics technologies, HELIOS demonstrates a holistic and forward-looking strategy to meet the increasing performance, safety, and sustainability demands of next-generation electric mobility. The key innovations developed within HELIOS include:

- A hybrid battery pack architecture with dual-chemistry modules (NMC and LTO) enabling flexible power-to-energy ratio customization.
- A wireless, dual-chemistry BMS capable of high-current passive balancing (up to 1.75 A) and universal SoX estimation algorithms.
- An advanced MSU providing early warning for thermal runaway through gas, pressure, and strain monitoring.
- A hybrid TMS that reduces coolant volume by 70% while maintaining ±2 °C temperature uniformity under high C-rate operations.
- A high-efficiency bidirectional DC-DC converter based on wide bandgap semiconductors, improving both volumetric (+5%) and gravimetric (+2.5%) energy density at the pack level.

Quantified performance highlights of the HELIOS battery pack so far are promising. The small-size pack (Mitsubishi i-MiEV) offers an effective driving life exceeding 300,000 kilometers, representing a 30–40% improvement over current battery warranties. It achieves a 25% shorter charging time when using a 150 kW charger, compared to the Tesla Model 3 mid-range battery. Additionally, the design enables a 30% reduction in weight and a 20% decrease in volume while maintaining the same installed energy capacity as the Tesla Model 3 battery pack. Fast charging is also a key feature, which is able to fill up 65% capacity in just six minutes achieved by integration of the HP subpack and coordinated energy management. The battery delivers a gravimetric energy density of approximately 166 Wh/kg, a volumetric energy density of about 208 Wh/L, and a gravimetric power density of around 1.4 kW/kg.

Based on the developed technologies, two HELIOS battery pack prototypes are planned to be manufacturered and tested for Mitsubishi i-MiEV and an electric bus as vehicle demonstrators. These tests are planned to be done toward summer of 2025.

Acknowledgments

The research work is conducted as part of the project Horizon Europe HELIOS – "High-Performance Modular Battery Packs for Sustainable Urban Electromobility Services". The HELIOS project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 963646.

References

[1] J. T. Warner, *The handbook of lithium-ion battery pack design: Chemistry, components, types, and terminology*. Elsevier, 2024.

[2] F. Naseri, E. Farjah, and T. Ghanbari, "An efficient regenerative braking system based on battery/supercapacitor for electric, hybrid, and plug-in hybrid electric vehicles with BLDC motor," *IEEE Transactions on Vehicular Technology,* vol. 66, no. 5, pp. 3724-3738, 2016.

[3] F. Naseri, C. Barbu, and T. Sarikurt, "Optimal sizing of hybrid high-energy/high-power battery energy storage systems to improve battery cycle life and charging power in electric vehicle applications," *Journal of Energy Storage,* vol. 55, p. 105768, 2022.

[4] S. Chen *et al.*, "Multi-objective optimization design for a double-direction liquid heating system-based Cell-to-Chassis battery module," *International journal of heat and mass transfer,* vol. 183, p. 122184, 2022.

[5] "Solid State Battery Smart & Structural Modular Integration into Vehicle through Flexible Module to Chassis Design." EU Funding & Tenders Portal https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/projects-details/43108390/101193026 (accessed 04/23/2025, 2025).

[6] https://www.helios-h2020project.eu/ (accessed 04/28/2025, 2025).

[7] F. Naseri, E. Schaltz, D.-I. Stroe, A. Gismero, and E. Farjah, "An enhanced equivalent circuit model with real-time parameter identification for battery state-of-charge estimation," *IEEE Transactions on Industrial Electronics,* vol. 69, no. 4, pp. 3743-3751, 2021.

[8] G. L. Plett, "Recursive approximate weighted total least squares estimation of battery cell total capacity," *Journal of Power Sources,* vol. 196, no. 4, pp. 2319-2331, 2011.

[9] G. L. Plett, "High-performance battery-pack power estimation using a dynamic cell model," *IEEE Transactions on vehicular technology,* vol. 53, no. 5, pp. 1586-1593, 2004.

[10] F. Naseri, P. Setoodeh, and E. Schaltz, "Online Tuning of Extended Kalman Filter Using Reinforcement Learning for Improved Battery State-of-Charge Estimation," in *2024 IEEE International Conference on Industrial Technology (ICIT)*, 2024: IEEE, pp. 1-6.

[11] M. B. Marinov, D. Dimitrov, B. Ganev, G. Todorov, and I. V. Ivanov, "Experimental Set-up for Sensors Selection for Early Fault Detection in Innovative Modular Li-Ion Battery Systems Related to HELIOS H2020 Project," in *2022 XXXI International Scientific Conference Electronics (ET)*, 2022: IEEE, pp. 1-6.

[12] M. Murugan *et al.*, "A Comprehensive Review of Thermal Management Methods and Ideal System Design for Improved Electric Vehicle Battery Pack Performance and Safety," *Energy Science & Engineering,* 2025.

[13] S. Mishra, S. Mishra, and J. K. Devanuri, "Optimization of lithium-ion battery pack thermal performance: A study based on electrical, design and discharge parameters," *Applied Thermal Engineering,* vol. 260, p. 125071, 2025.

[14] G. Garcia-Rojas, S. Busquets-Monge, À. Filbà-Martínez, T. Sarikurt, S. Alepuz, and J. Bordonau, "EV Hybrid Battery With Integrated Multilevel Neutral-Point-Clamped Interfacing and Lossless Intermodule State-of-Charge Balancing," *IEEE Open Journal of the Industrial Electronics Society,* 2025.

[15] F. Naseri, Z. Kazemi, P. G. Larsen, M. M. Arefi, and E. Schaltz, "Cyber-physical cloud battery management systems: Review of security aspects," *Batteries,* vol. 9, no. 7, p. 382, 2023.
[16] F. Naseri *et al.*, "Digital twin of electric vehicle battery systems: Comprehensive review of the use cases, requirements, and platforms," *Renewable and Sustainable Energy Reviews,* vol. 179, p. 113280, 2023.

Presenter Biography

Farshid Naseri is a Ph.D. expert in vehicular and storage technologies, currently serving as a Marie-Curie postdoctoral fellow at Aalborg University (AAU Energy), Denmark. He received his Ph.D. and M.Sc. in Electrical Power Engineering in 2019 and 2015 and his B.Sc. degree in Control Engineering in 2013. He has contributed to different EU projects related to the development of battery systems with TRL levels from 2 to 8 including HELIOS, DeepBMS, HEROES, and iBattMan. His research interests encompass electric vehicles, battery systems, control systems, and power electronic systems design. Dr. Naseri is an active member of the IEEE Young Professionals and a board member of the *Vehicle Engineering Section* in Machines.