

Driving circular economy in electric vehicle batteries

In pursuit of Europe's vision for a more sustainable future, the MARBEL European consortium has created an electric vehicle battery pack with a longer lifespan. By combining modular, reusable designs with lifecycle-driven eco-design principles, this EU-funded initiative aims to shrink the impact of batteries and streamline dismantling, refurbishment and second-life repurposing.

In recent years, Europe has seen a dramatic shift toward electric-based transportation, spurred by ambitious policies aimed at achieving climate neutrality by 2050. Among the initiatives propelling this transformation, MARBEL project—a European Union Horizon 2020 initiative running from January 2021 to March 2025—addressed one of the most significant challenges in the electric vehicle sector: the development of lightweight, sustainable and high-performance batteries through a circular economy approach.

MARBEL batteries are specifically designed for a more efficient recyclability and repurposing for a second life. The project brought together 16 partners from eight countries, including leading research institutions, SMEs, automotive companies and material specialists. The battery system developed is capable of enhancing electric vehicle performance, reducing charging times and minimising environmental impact, marking a major milestone in the race toward decarbonised mobility.

Sustainability at the core: batteries for Europe's green transition

The project tackled significant challenges of the electric vehicle battery sector, ranging from limited lifespans and high environmental costs to logistical inefficiencies in recycling. MARBEL's modular design and circular economy framework proved essential in addressing these issues. By extending the useful life of batteries to 300000 km, which represents an increase of 30% compared to the industry average, the project battery prototypes bring hope to the transformative impact on Europe's electric vehicles' landscape.

“Our approach to modularity, recyclability and optimisation of battery systems performance creates a path forward for electric vehicles technology that is not only sustainable but also scalable for the mass market.”

Eduard Piqueras, European Programme Manager at Eurecat Technology Centre and coordinator of MARBEL

Additionally, the project adopted modular designs and incorporated up to 60% recycled content materials in intensive materials like extruded aluminium alloys, which entails savings of 777 kg of CO₂ equivalents per battery pack, contributing to an overall environmental impact reduction in the life cycle of the battery and consequently in mobility.

The project also enabled ultra-fast charging solutions. This was accomplished through the implementation of a targeted cooling system design that maintained uniformity of heat extraction from the cells, combined with optimisation algorithms for the charging process. In addition, a switchable junction box is incorporated, allowing an easy adaptation of the battery architecture.

The MARBEL project directly addressed the European Union's target of reducing greenhouse gas emissions by 55% by 2030 compared to 1990 levels. Road transport, responsible for nearly 16% of Europe's emissions, represents the focal point of these efforts. The MARBEL team concentrated on delivering a sustainable battery solution that could significantly advance the mass adoption of electric vehicle and, thus, contribute to the European goals.

Technological innovations: a modular and circular economy approach

Advanced technologies for electric vehicle batteries

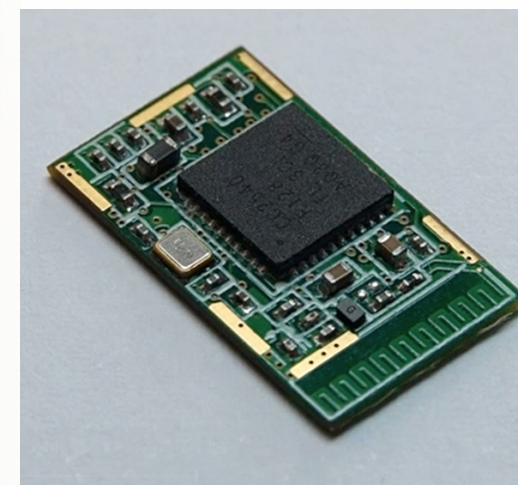
A core aspect of MARBEL has been its focus on modular battery architecture. Unlike traditional battery systems, MARBEL's modularity allows easy customisation, assembly and disassembly. This approach ensures compatibility with

a wide variety of electric vehicle models while simplifying maintenance, repair and recycling processes.

This intelligent architecture starts with the design of power connections in the form of busbars that can be easily assembled and disassembled using standard fastening components, which overcome the typical use of solder joints used in this type of application.

These busbars have also been optimised in their flexible form factors, which add simplicity during assembly operations and allow them to withstand potential vibrations to which the battery pack may be subjected on the vehicle. The battery management system (BMS) incorporates wireless communications and real-time smart energy monitoring, which significantly decreases weight, cost, and design complexity, providing greater flexibility by decoupling battery pack configuration from BMS constraints.

Designed to enhance the BMS, the intelligent Smart Cell Manager (iSCM) is integrated into each battery cell, enabling local monitoring of each individual cell's health and direct communication with the BMS via RF technology. This advanced electronic solution eliminates complex wiring, facilitates local passive cell balancing, reduces energy losses and improves overall reliability. With the usage of iSCMs, the wiring of a 16-cell battery pack is reduced from over 20 metres to just 80 centimetres, cutting on material costs, weight and assembly complexity while improving efficiency.



Intelligent Smart Cell Manager (iSCM) – OTC Engineering.

The data collected through the BMS and the iSCM feeds into a data-driven Digital Twin, which, leveraging artificial intelligence and machine learning algorithms, supports several dynamic predictive analytics processes, employing data from the heterogeneous data sources into a single web application. This system can predict, for example, the remaining useful life of the battery, its state of charge and health and when it will reach its end of life. The system features can be combined into a single software application, following the specific use case requirements and available data.

Additionally, MARBEL includes ultra-fast charging systems that enable electric vehicle batteries, addressing one of the biggest barriers to consumer adoption: range anxiety. This was made possible by combining an innovative cooling system and developing a switchable junction box. The cooling system developed can dissipate the heat generated during the charging process evenly across all the cells in the pack, helping to prevent overheating and limiting the temperature gradients between different points of the battery pack to optimum operating values.

Meanwhile, the junction box constitutes a safety system that facilitates the adaptation of the battery architecture from 400V to 800V and vice versa. This technological development engenders greater flexibility in comparison to current systems, thereby enabling charging at a greater number of stations and facilitating more efficient and safer completion of charging processes with the 800V architecture.

“By incorporating eco-design, second-life and recycling processes, MARBEL extends the useful life of batteries and material flows, reducing waste while maintaining material value, advancing both sustainability and economic viability.”

Violeta Vargas, researcher at Eurecat Technology Center Waste, Energy and Environmental Impact Unit.

Combined with a thermal management system that prevents overheating, these innovations ensured that MARBEL's batteries performed efficiently and reliably across a wide range of operating conditions.

Reducing environmental impact by closing the loop

At the heart of MARBEL's mission was the principle of circularity, achieved through a Life Cycle Assessment (LCA) guided ecodesign methodology. By systematically evaluating environmental hotspots opportunities were identified to reduce resource consumption, emissions, and waste across the battery's life cycle. Design for disassembly enabled a second life of the battery, while 60% recycled aluminium in the housing reduced carbon footprint and weight.

LCA-driven material choices, like switching from copper to aluminium, cut human toxicity by up to 88%.

MARBEL established processes for recovering valuable materials such as

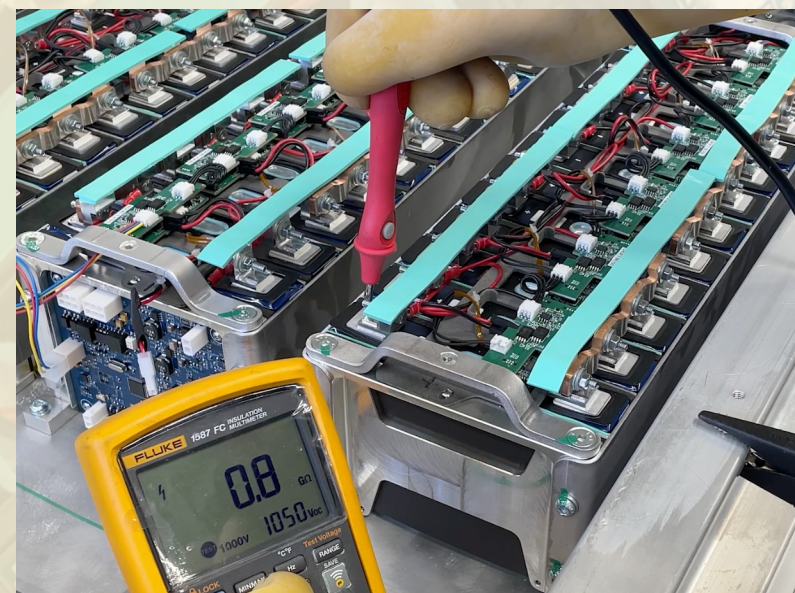
cobalt, lithium and nickel, ensuring they could be repurposed for new batteries or alternative applications like energy storage systems.

Moreover, the project addressed logistical challenges associated with end-of-life electric batteries by creating standards for testing and classifying used battery components. By combining ecodesign with LCA insights, MARBEL set a benchmark for sustainable battery development, reinforcing the EU's goals of reducing resource dependency and enhancing the circular economy.

Bridging policy goals and consumer needs

MARBEL project's outcomes are closely aligned with the European Green Deal and the Circular Economy Action Plan, which envisions a sustainable, resource-efficient and competitive EU economy. By reducing the environmental footprint of electric vehicle batteries and focusing on eco-design and circularity, the project contributed to the EU's broader climate objectives, including the target of cutting transport emissions by 55% by 2030, and the goals to reduce material waste, promoting resource efficiency and building resilient supply chains.

Importantly, the project also addressed consumer concerns with advancements in battery lifespan and charging convenience. MARBEL has contributed to increasing the accessibility and attractiveness of electric vehicles, helping to accelerate their market penetration. Additionally, the project directly supported Europe's ambitions to grow its EV fleet from one million vehicles in 2019 to over five million by 2025.



Checking the performance of the battery before commissioning.

Rethinking battery design for a circular future

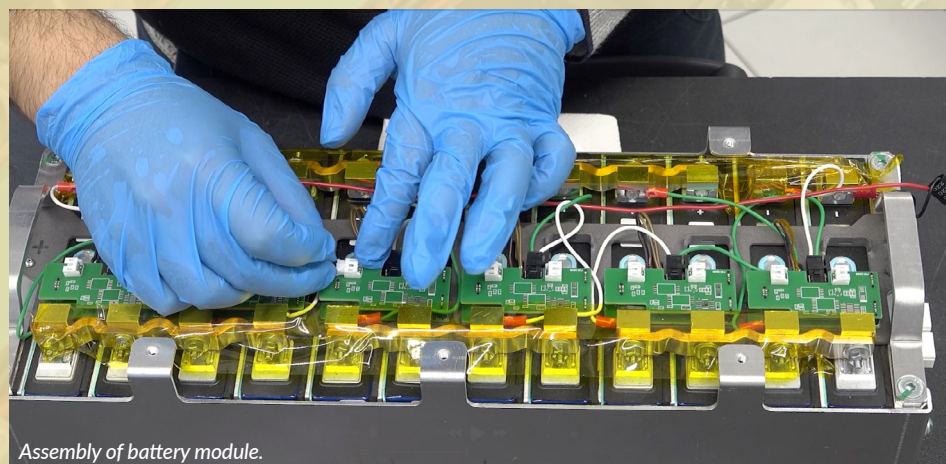
To ensure the reliability and safety of its solutions, MARBEL employed state-of-the-art testing protocols that combined physical experiments with advanced simulation tools. By leveraging artificial intelligence, the project team significantly reduced the time required for laboratory testing, enabling faster innovation cycles.

To validate the final concept, a rigorous mechanical, electrical and thermal testing programme was conducted to ensure the robustness, performance and safety of the MARBEL battery. The system was subjected to a range of tests, including thermal abuse, overload, overtemperature, vibration and impact tests. These tests were completed in accordance with the relevant standards in the sector, such as UN38.3 and R100.

In addition, a series of realistic tests were developed based on the eVIL concept (electric-vehicle-in-the-loop). This test methodology involves the functional validation of all battery components in

conjunction with a motor/inverter system that allows validation under real operating conditions. The creation of a flexible and versatile test environment is an additional benefit of eVIL, as it decouples the testing process from mechanical constraints such as car dimensions. The flexibility of the testing framework allowed MARBEL to evaluate different battery configurations, simulate real-world electric vehicle conditions and adapt its technologies to diverse requirements. These capabilities were critical for ensuring the final battery packs met industry standards and consumer expectations.

While the MARBEL project concluded its execution phase, its legacy endures through its contributions to sustainable mobility and its alignment with EU policy goals. This collaborative effort resulted in a comprehensive battery solution that addressed not only performance and sustainability but also cost-efficiency and manufacturability. For the millions of Europeans poised to embrace electric vehicles in the coming years, the outcomes of MARBEL represent not just technological progress but a tangible step toward a greener, more sustainable future.



Assembly of battery module.

PROJECT NAME

MARBEL - Manufacturing and Assembly of Modular and Reusable EV Battery for Environment-Friendly and Lightweight Mobility

PROJECT SUMMARY

MARBEL project has designed, developed and demonstrated new modular, compact, lightweight and high-performance battery packs together with flexible and robust battery management systems for battery electric vehicles and plug-in hybrids, while maintaining safety levels, allowing fast, high quality and cost-effective large-scale production and following ecodesign principles.

PROJECT PARTNERS

The consortium is formed by six research centres (Eurecat, the project's coordinator, Catalonia Institute for Energy Research (IREC) SINTEF, ICCS at the National Technical University of Athens, Technische Hochschule Ingolstadt and Fraunhofer (IWU), one automotive engineering company (IDIADA Automotive Technology), two SMEs (Powertech Systems and OTC Engineering); one OEM (Centro Ricerche Fiat - CRF) and five component manufacturers (FICOSA and AVL Thermal, HVAC and AVL Italia, ASAS Aluminyum Sanayi Ve Ticaret Anonim Sirketi, Agrati and Tes-Recupyl).

PROJECT LEAD PROFILE

Violeta Vargas, PhD, is an advanced researcher at Eurecat, specializing in Life Cycle Assessment and Design for Circularity topics.

Carlos Andrés Pérez, leads the Mobility and Energy Storage Systems research group, specialising in battery-oriented testing and developing modelling techniques for Li-ion batteries.

Eduard Piqueras-Jover, MscEng, is a programme manager in Eurecat, coordinating collaborative R&I projects in the areas of circular industries and energy transition.

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