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ODYSSEV

OPTIMISED DYNAMICS OF HIGH VOLTAGE POWERTRAINS
DEVELOPING SUSTAINABLE SYSTEMS FOR ELECTRIC VEHICLES

D2.1 Overall ODYSSEV methodology and KPIs

CIRCE

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Authors

First Name	Last Name	Beneficiary
Lucía	Orcos	CIRCE
Elena	Laborda	CIRCE
Víctor	Fernández	CIRCE
Pietro	Castellani	CIRCE

In case you want any additional information, or you want to consult with the authors of this document, please send your inquiries to: elaborda@fcirce.es

Quality Reviewers

First Name	Last Name	Beneficiary
Javier	Ballestín	CIRCE
Alberto	Costilla	CIRCE
Aristotelis	Folas	Q-PLAN
All partners		

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Executive Summary

This document defines the system-level framework used to coordinate the technical work across the project. It ensures that project activities follow a consistent approach and contribute to the development of common ODYSSEV powertrain architecture. It reports on the selection of the voltage level, and the establishment of a set of technical requirements and Key Performance Indicators (KPIs) for each vehicle component.

The work was structured around three main activity blocks: (i) powertrain architecture design and implementation, (ii) voltage level assessment and selection, and (iii) KPI definition and monitoring strategy development. These activities were carried out through a coordinated consortium-driven process to ensure alignment across all subsystems, providing a common technical framework for the subsequent design and integration activities.

A structured system methodology, based on Quality Function Deployment (QFD), was implemented to translate project objectives and internal KPIs into a set of technical specifications for the main vehicle components. These requirements were then grouped into five categories — electrical, mechanical, safety, sustainability and cost — to ensure that performance targets were considered together with regulatory, integration and sustainability aspects from the early design stages.

Based on this requirement baseline, dedicated component-level workshops were carried out for the battery pack, inverter and motor, onboard charger, packaging and cooling, control system and energy management system. These workshops refined the prioritised requirements into preliminary technical specifications and identified pending parameters and areas requiring further definition. In parallel, alternative voltage levels were assessed, supporting the selection of the reference powertrain architecture and voltage level that will serve as the basis for KPI monitoring throughout the project.

A key outcome of the task was the selection of the 1200 V system architecture as the reference voltage for the project. The analysis of alternative voltage levels (400 V, 800 V, 1200 V and higher) considered efficiency, charging capability, safety constraints and technology maturity, concluding that 1200 V provides the most suitable choice between performance and feasibility.

Furthermore, the basic requirements that powertrain components must meet have been established, ensuring that the technical aspects are consistent with the overall powertrain design and fostering a valuable exchange of views amongst the partners. These sessions have facilitated the definition of key design and workflow aspects with partners.

Finally, a comprehensive KPI framework was defined, linking subsystem-level indicators to project objectives. The KPIs cover performance, efficiency, cost, environmental impact and integration aspects, and are associated with specific evaluation methods, responsibilities and timeframes.

Table of Contents

List of Figures

List of Tables

List of Terms and Definitions

Table 1. Terms and Definitions

Abbreviation	Definition
AHP	Analytic Hierarchy Process
BMS	Battery Management System
CDA	Criteria Decision Analysis
CRM	Critical Raw Materials
EMS	Energy Management System
EV	Electric Vehicle
GA	Grant Agreement
HIL	Hardware-in-the-Loop
HV	High Voltage
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
KPI	Key Performance Indicator
MCI	Material Circularity Indicator
OBC	On-Board Charger
QFD	Quality Function Deployment
SSbD	Safe and Sustainable by Design
TRL	Technology Readiness Level
WP	Work Package

1. Introduction

Task T2.1, *Powertrain architecture design procedures and voltage level selection* (M1–M6), is responsible for leading the technical aspects of the ODYSSEV project at system level.

To address the different objectives included within Task T2.1, the work was structured around three main activity blocks: **(i) powertrain architecture design and implementation, (ii) voltage level assessment and selection, and (iii) KPI definition and monitoring strategy development.** D2.1 fulfils the contractual scope of T2.1.

The first activity block focused on the overall powertrain architecture design process. This included leading the technical discussions across the consortium, aligning technical specifications between partners and work packages, defining design requirements based on economic, mechanical and safety criteria, and ensuring compliance with applicable regulations and project objectives. In parallel, a common prototype design strategy based on Safe and Sustainable by Design (SSbD) principles was established to guide the development of the different innovations and facilitate future integration activities. This process also involved defining the interactions between work packages and establishing a common framework to support convergent developments throughout the project.

The second activity block addressed the selection of the most suitable voltage architecture for the ODYSSEV powertrain. Particular attention was given to the evaluation of the battery voltage level, considering the minimum requirement of 1200 V established in the Grant Agreement as well as higher-voltage alternatives. The implications of the different voltage scenarios on the battery system, inverter, motor, charging architecture, insulation requirements, packaging constraints and safety aspects were analysed in order to support a consortium-wide decision.

The third activity block focused on the definition of Key Performance Indicators (KPIs) and the establishment of a monitoring framework capable of supporting the validation of the project outcomes. This included the identification of subsystem-level and system-level KPIs, the prioritisation of technical requirements and performance targets, and the definition of responsibilities and monitoring procedures to be applied throughout the project duration.

The development of Deliverable D2.1 followed a structured and collaborative systems-engineering approach aimed at ensuring alignment between technical requirements, project KPIs and subsystem integration needs. The adopted methodology combines requirement analysis, consortium-wide technical discussions, subsystem-level specification activities and validation processes to ensure consistency across all developments. The overall process was organised into four main steps, which are described in the following sections.

Requirement Definition and KPI Mapping

The first phase consists of the implementation of a Quality Function Deployment (QFD) methodology to translate project objectives and stakeholder expectations into measurable technical requirements. This activity included:

- Identification and definition of the main system requirements derived from the Grant Agreement and project objectives.
- Definition of key performance indicators (KPIs) for the different subsystems and the overall powertrain architecture.
- Mapping of interactions and dependencies between work packages (WPs), ensuring consistency between subsystem developments.
- Identification of critical interfaces and integration constraints affecting the overall prototype design.

This step provides the foundation for a coordinated technical development process and supports traceability between project objectives and engineering decisions.

Technical Specification Meetings

A series of dedicated technical meetings were organised with the relevant partners to define the specifications and operational requirements of each subsystem. These meetings are conducted on the basis of the QFD results for each of the components. The discussions cover the following components:

- Battery pack
- On-board charger
- Inverter and electric motor
- Packaging and thermal management/cooling systems
- Control architecture and Energy Management System (EMS)

The purpose of these meetings was to align subsystem requirements, identify technical limitations, assess integration feasibility, and establish preliminary design targets. Participation of system integration partners and component manufacturers ensures that both electrical and mechanical integration aspects are considered from the early design stages.

Consolidation and Analysis of Technical Outcomes

Following the technical meetings, all meeting minutes and technical inputs were compiled and analysed in a structured manner. This phase included:

- Identification of technical aspects that need further definition in a later stage of the project or in other tasks and work packages.
- Assessment of compatibility between subsystem (component) specifications.
- Evaluation of trade-offs associated with different technological options.
- Definition of a common prototype design strategy shared among consortium partners.

This iterative analysis process supports convergence towards a coherent system architecture and facilitates informed decision-making during the prototype definition stage.

Deliverable Development and Partner Review

The final step consists of the preparation and consolidation of Deliverable 2.1 based on the outcomes obtained during the previous phases. The deliverable undergoes an internal review process involving the relevant project partners to ensure:

- Technical consistency and completeness.
- Alignment with project objectives and KPIs.
- Validation of subsystem specifications and integration assumptions.
- Incorporation of partner feedback and agreed technical decisions.

This collaborative review process ensures that the final deliverable accurately reflects the consortium's common understanding of the prototype architecture and associated technical requirements.

Overall, Task T2.1 establishes a quantitative, traceable and consensus-based framework that supports the coherent development of the ODYSSEV powertrain, enabling alignment across work packages and providing the basis for subsequent design, integration and validation activities.

2. Methodology

Task T2.1 acts as the system-level integrator of the ODYSSEV project. Its objective is not the detailed design of individual components, but the definition of a shared powertrain architecture, design logic and key priorities that enable coherent development across WP3–WP6, in line with the project objectives and the Safe and Sustainable by Design (SSbD) approach.

Given the strong interdependencies between battery voltage level, inverter topology, motor insulation constraints, charging architecture, packaging and thermal management, a structured methodology was required to ensure traceability, alignment and convergence of design choices.

To address this challenge, the use of advanced Criteria Decision Analysis (CDA) tools, in particular **Quality Function Deployment (QFD)** and **Analytic Hierarchy Process (AHP)**, was decided.

Quality Function Deployment (QFD) is a structured methodology originally developed to translate customer or stakeholder needs ("WHATs") into technical characteristics ("HOWs") using matrix-based representations. QFD emphasizes traceability, early-stage prioritization, and cross-functional alignment. (Jaiswal, 2012)

On the other hand, the Analytic Hierarchy Process (AHP) decomposes a decision problem into a hierarchical structure (goal, criteria, sub-criteria, and alternatives) and relies on pairwise comparisons to quantitatively assess relative importance and final rankings of alternatives. (Russo & Camanho, 2015)

The purpose of Task 2.1 is not to perform final optimization or to select a definitive powertrain architecture, but to:

- Align technical developments across work packages,
- Identify and priorities system-level requirements,
- Define KPIs and guide early convergence decisions.

For these reasons, QFD was considered more appropriate to ensure clarity and consensus during the initial system architecture phase. The AHP methodology was considered at the beginning of the task, but not applied in the final approach. The primary role of AHP was to support the evaluation and comparison of alternative voltage scenarios for the powertrain. However, during the task, the project voltage level (1200 V) was agreed and validated through consortium discussions, based on the collective technical assessment and alignment among partners. As a result, the application of AHP for scenario comparison became unnecessary, since no alternative design scenarios required analysis.

The methodology developed in Task 2.1 incorporates safety and sustainability considerations from the early stages of the design process, ensuring their consistent treatment alongside performance, cost, and regulatory aspects. This is reflected in the definition and prioritization of technical requirements, where dedicated categories related to sustainability and SSbD are considered together with the rest of the design drivers.

More broadly, the structured and consensus-based framework adopted ensures that these aspects are systematically addressed across all subsystems and work packages, supporting a coherent and aligned development of the powertrain architecture, and integrating SSbD concepts as part of the overall design approach.

2.1 QFD

QFD allows the systematic translation of high-level requirements (WHATs) into technical enablers and design elements (HOWs), making relationships between project objectives, system requirements and component-level design considerations. The key characteristics of QFD include:

- Collective input from multiple stakeholders
- Use of qualitative or semi-quantitative relationships
- Translation of qualitative requirements into structured technical priorities

Figure 1 provides the general step-by-step QFD methodology developed, showing the progression from objective definition and requirement identification to subsystem mapping, quantification, and final prioritization.

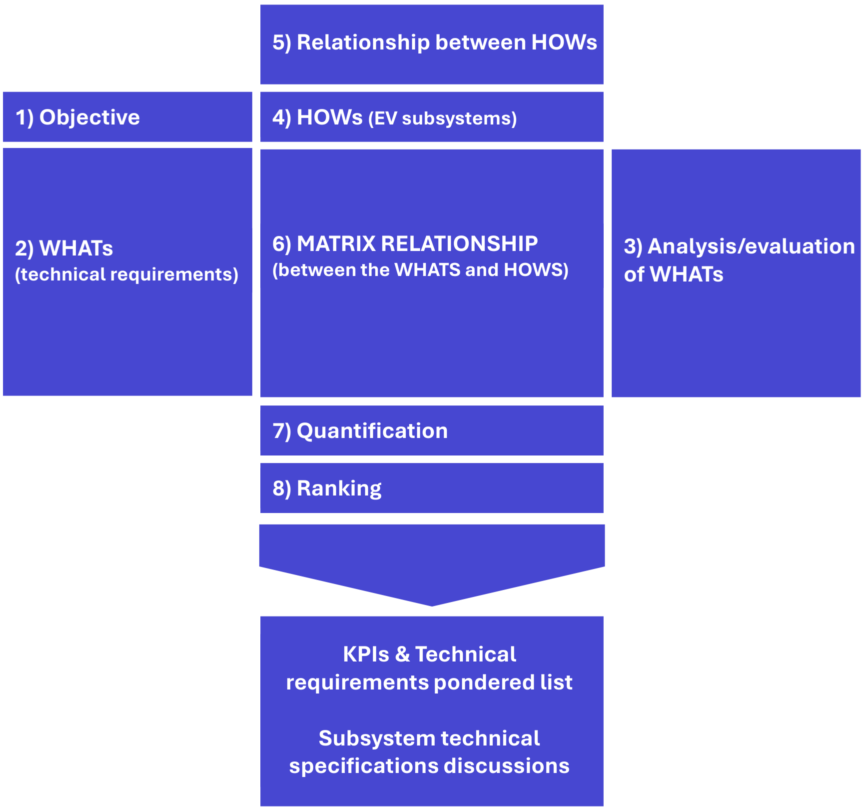


Figure 1. Visual step-by-step QFD methodology summary.

In the context of ODYSSEV, QFD was applied both at system and component level. It served two main purposes:

1. To visualize and quantify the relative influence of each powertrain subsystem (battery, inverter, motor, OBC, packaging/thermal system, control) on system-level requirements.
2. To provide a transparent and shared basis for defining KPIs and fundamental design requirements guiding subsequent WPs.

QFD step by step methodology

To structure the work in a traceable and consortium-driven way, the project applied QFD template presented below:

Table 2. QFD template.

	Subsystems HOW (technical building blocks and project structuring elements)	Battery pack	Inverter	Electric motor	On-board charger	Packaging & cooling	Control & EMS	
	WP2 weights							
	WP3 weights							
	WP4 weights							
	WP5 weights							
	WP6 weights							
ID	Key design requirements and constraints WHATs (Battery voltage choice impacts)	Ensure compatibility among all innovations						Targets (description)
		Multiple DC Levels for Variable-Voltage Charge/Discharge	Modular Power Electronics Reconfigurable AHXS converter Enhanced diode performance in AHXS	Optimized design algorithm development with multiple constraints Optimization to operate coupled with AHXS inverter	HV On-board charger	Optimization of system packaging and thermal management by cloud based lab integration	Control and operation of the automotive drivetrain	

Step 1 — Define the objective of the QFD

The objective was to translate the project's early system goals into a prioritized set of technical requirements that guide: 1) architecture alignment, 2) voltage-level discussion, 3) KPI definition and follow-up, and 4) cross-WP convergence.

Step 2 — Definition of the WHATs (system requirements)

The WHATs represent the technical requirements that the electric vehicle powertrain must fulfil in order to achieve the project objectives.

The initial WHAT list was derived from the Project Internal Key Performance Indicators, used as a baseline input to ensure consistency with expected outcomes and monitoring needs. The WHATs were grouped into five requirement families according to a SSbD approach:

1. Electrical performance & efficiency (E)
2. Mechanical & packaging performance (M)
3. Safety & regulatory compliance (S)
4. Sustainability & Safe and Sustainable by Design (ST)
5. Cost & manufacturability (CM)

Step 3 — Consolidation and validation of the WHATs

The initial WHATs list was discussed between all partners to specify, expand, or reformulate the requirements. Partners provided feedback based on their technical analyses and WP scope. This consolidation step ensured that the final WHAT list reflected consortium-wide consensus, and covered all relevant technical, safety, sustainability, and cost aspects.

Step 4 — Definition of the HOWs (EV subsystems)

The HOWs represent how the technical requirements are fulfilled. To facilitate the technical specifications, it was decided that they were going to be the EV subsystems involved in the powertrain architecture:

- Battery pack
- Inverter
- Electric motor
- On-board charger
- Packaging & cooling
- Control & Energy Management System (EMS)

Step 5 — Weighting of HOWs through WP contributions

Each work package was assigned with importance weights to the EV subsystems to reflect its technical responsibility and influence. The goal was capturing the real contribution of each WP to each subsystem and prevents over- or under-representation of specific viewpoints. The final set of WP importance weights is presented below:

Table 3. HOWs weighting values through WP contributions.

		Subsystems					
Work Package	WP2 – Overall design of the next generation HV electric powertrains	15	15	15	20	**70**	15
	WP3 - Development of the powertrain elements for charging	**60**	5	0	**65**	10	10
	WP4 - Development of the hybrid switch inverter concept for HV powertrain	5	**65**	5	5	5	10
	WP5 - Development of ODYSSEV motor system	5	0	**70**	0	5	5
	WP6 - Simulation and control strategies for ODYSSEV powertrain	15	15	10	10	10	**60**

The weighting values assigned to each subsystem were established during the ODYSSEV Kick-off Meeting held in Zaragoza in January 2026. The process involved all consortium partners and was carried out through a consensus-based discussion in which each Work Package leader and participating partners assessed their expected level of contribution, technical expertise and responsibility within each subsystem.

The weighting factors do not represent quantitative engineering calculations but rather the collective technical judgement of the consortium regarding the relative influence of each Work Package on the development of the different powertrain components. Partners assigned higher weights to the subsystems where they possess the strongest technical knowledge, development responsibilities and expected contribution throughout the project. Conversely, lower weights were assigned to areas with limited involvement or expertise.

This collaborative approach ensured that the subsequent QFD analysis accurately reflected the distribution of knowledge and responsibilities across the consortium, while avoiding the overrepresentation of partners with limited relevance to a given subsystem. The final weighting matrix was reviewed and validated by all partners during the meeting and adopted as the common reference framework for the QFD exercise.

Step 6 — Definition of relationships between WHATs and HOWs

Partners were then asked to define relationships between technical requirements (WHATs) and subsystems (HOWs), focusing at least on the subsystem(s) where their WP had the highest weighting. Subsystems not evaluated by a WP correspond to areas where the WP had no relevant role or sufficient technical basis. Relationships were expressed using a qualitative scale:

Table 4. Qualitative mapping of QFD relationships.

Legend (core)	
◎	Strong relationship
○	Medium relationship
.	Regular relationship
△	Weak relationship
-	No relationship

To establish relationships, each WP leader followed internal procedures (e.g. technical meetings or expert discussions) and produced its own QFD matrix.

Step 7 — Quantification of WP-specific QFD matrices

Different QFDs, with different relationships, were collected. That is, for each EV subsystem and each WHAT, several expert evaluations were available. To consolidate these inputs, firstly the qualitative relationship symbols were converted into numerical values (Table 5), and then, a weighted value was calculated by combining:

- The numerical value assigned to the relationship (from the qualitative scale), and
- The relative weight of each WP for the corresponding subsystem.

Example formula for E1 (Voltage level selection) battery pack:

E1 = (WP2_puntuation*WP2_weight on battery pack) + (WP3_puntuation*WP3_weight on battery pack) + (WP4_puntuation*WP4_weight on battery pack) + (WP5_puntuation*WP5_weight on battery pack) + (WP6_puntuation*WP6_weight on battery pack)

When a WP did not explicitly assess a given WHAT–HOW relationship, a medium relationship value was assigned by default. By combining the five WP-specific QFD matrices, a single consolidated QFD was obtained, containing weighted values for each requirement and EV subsystem.

Table 5. Qualitative-to-Quantitative Mapping of QFD Relationships.

Legend (core)		
◎	Strong relationship	3
○	Medium relationship	2
.	Regular relationship	1,5
△	Weak relationship	1
-	No relationship	0

Step 8 — Component-level and global ranking of KPIs and requirements

Component-level rankings were established, reflecting subsystem-specific priorities. In parallel, a global ranking was also derived by aggregating results across all subsystems (averaged value). In these rankings the technical specifications (WHAT) were separated into measurable KPIs and actual requirements.

Both subsystem-specific and global rankings were shared with the WPs leaders to provide a common system-level reference, enabling each WP to understand how its most relevant KPIs and requirements compared within the overall project priorities. This dual ranking approach ensured both local relevance and system-wide coherence.

Once the partners have assigned these scores to each requirement and KPI, an importance value is calculated for each one, based on the following scores:

Importance	Value
Very high importance	>7,5
High importance	6-7,5
Medium importance	3-6
Low importance	<3

KPI definition

The KPIs used for this task were defined by consensus amongst all partners during the project's kick-off meeting in January 2026, as indicated in meeting minutes. As some of the indicators defined in the Grant Agreement corresponded to several indicators deemed relevant during the identification process, the terminology used for some of them does not fully correspond to that specified in the Grant Agreement. Terminology does not alter committed GA KPI targets.

Therefore, the next table presents the correspondence between the KPIs defined in the Grant Agreement and their implementation within the D2.1 framework through subsystem-level KPIs and technical requirements. KPIs defined in D2.1 that are not directly linked to a specific GA KPI are not included in this mapping.

Table 6. Correspondence between GA KPIs and D2.1 KPIs

ID	GA nomenclature	KPI
E2	KPI 2. Battery lifetime increase compared to existing solutions	Battery architecture (number of modules, configurations, voltage range per module)

E3		Battery reconfiguration requirements (active battery balancing and parallelizing modules)
E5		Charger/battery interface definition (CCS2 for mode-3 + CCS2/MCS for mode-4, TBD by demo)
E6	KPI 4. Charging time (minutes) from 20 to 80 percent with currently available 350kW chargers KPI 20. Overall increase in drive range after powertrain integration and optimization KPI 21 Nominal power of the working prototype duly validated in relevant environment (TRL5)	Power rating and fast charging capability (these could be in two separate rows Power: 100kW Charging time 20%-80%: 10min)
E7	KPI 19. Overall reduction in energy losses after powertrain integration and optimization	Reduction of lifecycle energy losses for battery [kWh/year]
E8	KPI 8. Energy losses reduction in the inverter, because of the AHXS topology KPI 19. Overall reduction in energy losses after powertrain integration and optimization	Reduction of lifecycle energy losses for Inverter [kWh/year]
E9	KPI 19. Overall reduction in energy losses after powertrain integration and optimization	Reduction of lifecycle energy losses for electric motor [kWh/year]
E10	KPI 19. Overall reduction in energy losses after powertrain integration and optimization	Reduction of lifecycle energy losses for OBC [kWh/year]
E11	KPI 5. Efficiency improvement, particularly in partial load operation, vs. the SoA full Si IGBT-based VSI KPI 10. Lifetime in comparison with SiC-based inverters	Inverter efficiency improvement, especially at partial load, vs SoA full-Si IGBT VSI
E12	KPI 12. Electric machine energy efficiency in the most frequent operating point	Electric machine energy efficiency in the most frequent operating point
E15	KPI 15. Insulation duration period	Insulation duration period
M3	KPI 18. Autonomy (driving range) increase due to improved control algorithms KPI 20. Overall increase in drive range after powertrain integration and optimization	Compact integration of HV components
M5	KPI 9 Increase in travel range only because of the higher efficiency of the AHXS	Efficiency of the demonstrator Extended Drive Range (% of km/kWh)
M6	KPI 13. Converter + machine + gearbox volume and weight reduction	Converter + machine + gearbox volume and weight reduction
S4	KPI 6. Reduction in common-mode current emission versus the SoA full SiC MOSFET-based VSI	Reduction of common-mode current emission vs SoA full-SiC MOSFET VSI
ST2	KPI 5. Efficiency improvement, particularly in partial load operation, vs. the SoA full Si IGBT-based VSI 25%	System efficiency improvement
ST3	KPI 11. Equivalent CO2 emission compared to Si-based inverters	Total CO_2 equivalent emissions [kg CO_2eq/kW]
ST4	KPI 11. Equivalent CO2 emission compared to Si-based inverters	CO_2 emissions reduction vs Si-based inverter

ST13	KPI 14. Reduction of rare-earth permanent magnets of the initial design stage	Reduction of rare-earth permanent magnets of the initial design stage
CM1	KPI 1. Reduction in charging costs per (OBC) power unit (€/kW)	Specific powertrain cost [€/kW]
CM4	KPI 7. Cost reduction of the inverter power electronic modules vs. the SoA full SiC MOSFET-based VSI	Cost reduction of inverter power-electronic modules vs SoA full-SiC MOSFET VSI
CM6	KPI 21 Nominal power of the working prototype duly validated in relevant environment (TRL5)	Electric power levels (Lab test vs. Simplified demo)
CM9	KPI 16. Time reduction for integration tests and development cycles KPI 21 Nominal power of the working prototype duly validated in relevant environment (TRL5)	Lab test vs. Simplified demo
CM10	KPI 17. Reduction in development costs at prototype level	Demo responsibilities (breakers, wiring, plugs required for integration) to be provided by each partner
CM11	KPI 3. Operation and maintenance costs decrease linked to the battery compared to existing solutions	Reduced maintenance/repair cost due to multi-pack battery

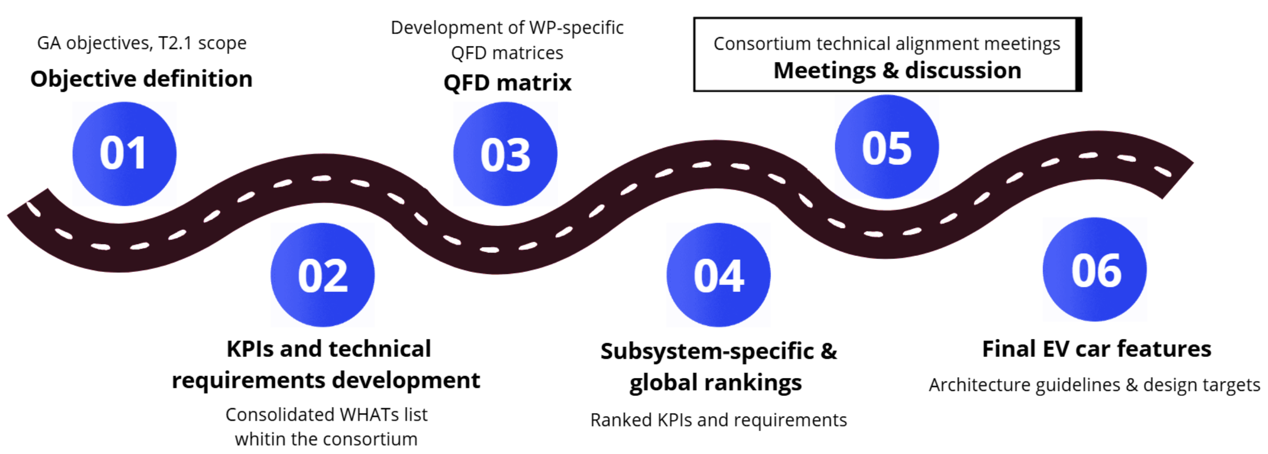
2.2Technical specifications workflow

This section describes the process followed to define and consolidate the technical specifications of the ODYSSEV powertrain, based on the previously established KPIs and technical requirements.

It focuses on process governance, explaining how technical discussions were organized, how consortium input was collected, and how final specifications were agreed. It does not address the detailed technical content of the specifications themselves.

The approach ensures that all relevant decisions were consortium-driven, transparent, and traceable, in line with the objectives of Task 2.1. The next figure presents the overall workflow.

Figure 2. Technical specifications workflow procedure.



Organization of subsystem-level discussions

To ensure a structured and efficient discussion process, meetings were organized per EV subsystem/component, where the previously defined KPIs and technical requirements were reviewed and translated into technical specifications.

The following working groups were established, with designated partners responsible for coordinating the discussions:

- Battery pack: UCL (meeting leader).
- Inverter and Electric motor: UT and KTH (meeting leaders), with participation from EFT, WP4 partners, and WP5 partners.
- On-board charger: CIRCE (meeting leader), with participation from UCL and EFT.
- Packaging and cooling: EFT and FHDO (meeting leaders), with participation from WP leaders.
- Control and Energy Management System (EMS): FHNW (meeting leader), with participation from WP leaders.

Each working group defined the organization of its meetings according to its technical needs and internal structure, including meeting frequency, participants, and internal preparation and discussion procedures. Participation was not restricted to predefined members, additional partners participated when relevant or upon request.

During these meetings:

- The most relevant KPIs and technical requirements were analyzed,
- Technical implications and constraints were discussed,
- Specifications were proposed and refined.

Consolidation and Validation of Results

The key outputs and meeting minutes generated during the subsystem discussions were collected by the responsible partners and reported to CIRCE, acting as the coordinator of Task 2.1. CIRCE subsequently consolidated all contributions in order to develop a coherent and validated set of system-level technical specifications.

This consolidation process enabled the establishment of a consortium-validated framework of technical specifications, derived from structured technical discussions and supported by the prioritization outcomes obtained through the QFD methodology. The adopted approach ensured both subsystem-level relevance and overall system-level consistency, thereby providing a robust basis for the subsequent design, integration, and development activities within the project.

For each component analyzed, CIRCE organized the collected outputs into the following categories:

1. **Agreed technical requirements and KPIs for the component**
   This section includes the technical specifications, performance targets, and KPIs agreed during the meetings, together with the corresponding QFD results and relevant conclusions extracted from the technical discussions.

2. **Technical Aspects for Further Definition**
   This section identifies information and technical parameters that are expected to be further developed in subsequent project tasks or work packages. Where possible, a preliminary proposal is provided regarding the partner or partners that could assume responsibility for these activities.

Following CIRCE's analysis and consolidation of the collected outputs, an additional consortium-wide meeting was organized involving all project partners, on **20th May 2026**. During this meeting, the consolidated technical results and preliminary conclusions were presented component by component, allowing dedicated time for technical discussion, feedback and debate among consortium members.

The conclusions, comments, and agreements resulting from this joint discussion were subsequently used as a validation step for CIRCE's analysis and have also been incorporated into the present deliverable. This final review process ensured a common understanding among partners and reinforced the technical consistency and consensus behind the reported specifications and system-level decisions.

3. Voltage level selection

The selection of the powertrain voltage level represents one of the most critical system-level decisions within the ODYSSEV project, as it directly influences the design, performance, safety, integration complexity and industrial feasibility of all major subsystems, including the battery pack, inverter, electric motor, charging system and thermal management architecture.

In line with the objectives of Task T2.1, dedicated discussions were conducted to evaluate different voltage scenarios, considering their technical benefits, implementation challenges and compatibility with the project objectives. The analysis was supported by technical discussions involving the relevant partners and focused on balancing efficiency improvements, ultra-fast charging capability, component availability, safety requirements and technology maturity. The outcomes of this process ultimately supported the selection of the most suitable voltage architecture for the ODYSSEV demonstrator and subsequent developments.

Discussion on DC Bus Voltage Selection and System Implications

Voltage Levels and Motor/Inverter Options

- For traction, 800 V and 400 V are suitable; chargers require higher voltage.
- Current semiconductors are rated 700 V, allowing traction inverter operation up to 1200 V. Achieving 1500–1600 V is challenging.
- Open winding connection could allow high motor voltage with lower-voltage power electronics.

High-Voltage Motor Design

- Experience exists in rewinding a 600 V motor to 1250 V without modifying stator or rotor.
- A high-voltage, high-speed motor with a one- or two-stage gearbox may enable a more compact system. Motor conductor's size can be reduced.
- Proposed joint study between UCL and KTH teams to evaluate motor voltage options.

Main decisions

- Traction inverter voltage: The voltage for the traction inverter was finally set by consortium at 1200 V in accordance with the GA and supporting meeting minutes.
- Battery voltage for ultra-fast Charging: Proposed 1200 V.
- It was agreed that WP2 leadership should organize a meeting as soon as possible to discuss the powertrain requirements. This discussion should aim to define both electrical and mechanical requirements and should involve the system integration partners as well as the motor manufacturer.

Based on the technical discussions, the consortium assessed the advantages and limitations of the different voltage architectures considered for the project. The main findings of this evaluation, together with the rationale supporting the final selection, are summarized in table below.

Table 7. Benefits and downsides of different voltage scenarios.

Voltage Level	Benefits	Downsides / Challenges considered by consortium	Status
400 V traction system	- Mature and widely adopted technology. - Broad availability of commercial components and infrastructure. - Simpler insulation, protection, and safety requirements. - Lower development and integration complexity.	- Higher current levels for the same power demand. - Increased cable losses and thermal stress - Larger conductor cross-sections and heavier cabling required. - Limited suitability for ultra-fast charging applications.	Discarded
800 V traction system	- Lower current levels and reduced conductive losses.- Improved overall system efficiency. - Reduced cable size and system weight. - Compatible with emerging high-performance EV architectures and fast-charging solutions. - Facilitates more compact drivetrain concepts.	- Increased insulation and safety requirements. - Higher component and integration complexity. - Increased development and certification costs compared with 400 V systems.	Discarded
1200 V traction / battery system	- Supports ultra-fast charging capability with reduced charging current. - Lower thermal stress in cables and connectors. - Potential reduction in charging times. - Improved power density and system compactness - Reduced conductor size and associated weight. - Aligns with the minimum voltage requirement established in the Grant Agreement.	- Semiconductor limitations become increasingly significant above conventional 800 V architectures. - Testing and validation infrastructure for this voltage level is limited. - More demanding insulation, isolation, and protection requirements. - Increased system integration complexity and safety considerations. - Limited availability of mature commercial components.	Selected
1500–1600 V system	- Further reduction of current levels and conductive losses. - Potential for extremely high-power charging and traction operation. - Very high theoretical system power density.	- Considered technologically challenging with current semiconductor capabilities. - Existing power electronics are not sufficiently mature for reliable implementation at this voltage level - Major insulation, safety, and certification challenges. - Very limited testing and validation infrastructure available. - Significantly increased cost and system complexity. - Uncertain industrial readiness at the current stage of development.	Discarded

The evaluation of the different voltage scenarios concluded that a **1200 V architecture represents the most suitable solution for the ODYSSEV powertrain**. This option provides a balanced compromise between performance, charging capability, system efficiency and technological feasibility, while remaining aligned with the minimum voltage requirement established in the Grant Agreement.

Although higher-voltage architectures could offer additional theoretical benefits in terms of power density and current reduction, their limited technological maturity, increased integration complexity and higher implementation risks were considered significant drawbacks at the current stage of development. Consequently, the consortium agreed to adopt 1200 V as the reference voltage level for the project, providing a common baseline for the definition of technical specifications, subsystem development and subsequent integration activities.

4. QFD results

The key results extracted from the QFD methodology included: (i) a final consolidated list of system-level technical requirements that the EV powertrain must fulfil, (ii) the separation of these requirements into Key Performance Indicators (KPIs) and technical requirements, and (iii) overall rankings of these KPIs and requirements. These rankings were obtained through numerical, weighted aggregation formulas, which account for the relative importance of each Work Package within each EV subsystem.

The resulting lists and rankings were developed and validated at consortium level, integrating the contributions of all relevant stakeholders involved in each subsystem, and support prioritization, alignment, and convergence at system level.

Consolidated List of System Requirements (WHATs)

The final list of system requirements (WHATs) was validated at consortium level. These requirements were grouped into five categories: Electrical performance and efficiency (E), Mechanical and packaging performance (M), Safety and regulatory compliance (S), Sustainability and Safe and Sustainable by Design (SSbD) (ST), and Cost and manufacturability (CM).

Table 8. Final consolidated list of system requirements.

ID	Key design features
E1	Voltage level selection
E2	Battery architecture (number of modules, configurations, voltage range per module)
E3	Battery reconfiguration requirements (active battery balancing and parallelizing modules)
E4	OBC architecture (CIRCE proposes to develop an isolated AC/DC converter per module, so that they can operate independently of the configuration of the modules and charge each one independently. Operation values: three (or single TBD)-phase 230 V, 50 Hz)
E5	Charger/battery interface definition (CCS2 for mode-3 + CCS2/MCS for mode-4, TBD by demo)
E6	Power rating and fast charging capability (We can put these in two separate rows Power: 100kW Charging time 20%-80%: 10min)
E7	Reduction of lifecycle energy losses for battery [kWh/year]
E8	Reduction of lifecycle energy losses for Inverter [kWh/year]
E9	Reduction of lifecycle energy losses for electric motor [kWh/year]
E10	Reduction of lifecycle energy losses for OBC [kWh/year]
E11	Inverter efficiency improvement, especially at partial load, vs SoA full-Si IGBT VSI
E12	Electric machine energy efficiency in the most frequent operating point
E13	Reduced switching & conduction losses
E14	Reduced current harmonics & EMI (Reduction in common-mode current emmision)
E15	Insulation duration period
E16	Control Software functionality
E17	Auxilliary voltage (12 V battery with a dedicated charger from the HV battery)
E18	Communication network: architecture and protocol (CAN 2.0b)

E19	Simulation framework (common software TBD)
E20	Power train architecture definition (number of motors, number of poles…)
M1	Power density increase (kW/kg, kW/L)
M2	Weight reduction at system level
M3	Compact integration of HV components
M4	Thermal management compatibility at HV
M5	Efficiency of the demonstrator Extended Drive Range (% of km/kWh)
M6	Converter + machine + gearbox volume and weight reduction
M7	Commercial Gearbox
M8	Cooling specifications (flow, pressure, temperature range, cooling plate, inlets) definition for each INN
M9	HV plugs definition
M10	Housing (size, form factor, envelope)
S1	Partial discharge avoidance at selected voltage - insulation aging risk
S2	Insulation coordination & creepage/clearance compliance
S3	Insulation monitoring device / leakage current detection
S4	Reduction of common-mode current emission vs SoA full-SiC MOSFET VSI
S5	Functional safety compatibility (ISO 26262 concept level)
S6	Charging compatibility with infrastructure and regulation (ISO 15118 & IEC 61851 considered but not inplemented in demo)
S7	Type approval certification challenges
ST1	Reduction of lifecycle energy losses [kWh/year]
ST2	System efficiency improvement
ST3	Total CO_2 equivalent emissions [kg CO_2eq/kW]
ST4	CO_2 emissions reduction vs Si-based inverter [%]
ST5	Specific material intensity [kg/kW]
ST6	Critical Raw Materials (CRM) intensity [kg CRM/kW]
ST7	Copper use reduction [%]
ST8	Material Circularity Indicator (MCI)
ST9	Water consumption [m^3 H_2O eq/kW]
ST10	Land use [m^2·year/kW]
ST11	Overall environmental impact reduction [%]
ST12	Reduced degradation and improvement of inverter cyclelife Vs Si-based inverter [number of cycles or years to end of life]
ST13	Reduction of rare-earth permanent magnets of the initial design stage
CM1	Specific powertrain cost [€/kW]
CM2	End-of-life residual value [%]
CM3	Innovation specific cost reduction [%]
CM4	Cost reduction of inverter power-electronic modules vs SoA full-SiC MOSFET VSI
CM5	Manufacturability at automotive scale
CM6	TRL progression compatible with industrial uptake
CM7	Scalability across vehicle classes
CM8	Regulatory risk
CM9	Lab test vs. Simplified demo
CM10	Demo responsabilities (breakers, wiring, plugs required for integration) to be provided by each partner
CM11	Reduced maintenance/repair cost due to multi-pack battery
CM12	Charging Cost Reduction
CM13	… Reliability cost tag … (to be completed)

Technical specifications from previous table were divided into Key Performance Indicators (KPIs) and technical requirements. This distinction ensures that measurable performance targets can be monitored throughout the project, while fundamental technical requirements act as design drivers and constraints for the development of powertrain architecture.

Finally, priority rankings (calculated as described in' QFD step by step methodology') were developed to provide a system-level reference in technical meetings. These lists reflect a shared understanding among partners of the key technical drivers for the ODYSSEV powertrain and constitute the baseline reference for prioritization.

Table 9. Overall Requirements Ranking

Ranking	Subsystem	ID	Key design requirements and constraints	Score
1	Packaging & Cooling	CM9	Lab test vs. Simplified demo	8,5
2	Packaging & Cooling	M8	Cooling specifications (flow, pressure, temperature range, cooling plate, inlets) definition for each INN	8,5
3	Motor + Inverter	E20	Power train architecture definition (number of motors, number of poles…)	8,5
4	Packaging & Cooling	M4	Thermal management compatibility at HV	8,5
5	Packaging & Cooling	M9	HV plugs definition	8,5
6	Motor + Inverter	S1	Partial discharge avoidance at selected voltage - insulation aging risk	8,5
7	Packaging & Cooling	E19	Simulation framework (common software TBD)	8,5
8	Packaging & Cooling	S2	Insulation coordination & creepage/clearance compliance	8,5
9	Battery	CM10	Demo responsabilities (breakers, wiring, plugs required for integration) to be provided by each partner	8,5
10	Packaging & Cooling	M3	Compact integration of HV components	8,5
11	Motor & Inverter	M7	Commercial Gearbox	8,5
12	Packaging & Cooling	E4	OBC architecture (CIRCE proposes to develop an isolated AC/DC converter per module, so that they can operate independently of the configuration of the modules and charge each one independently. Operation values: three (or single TBD)-phase 230 V, 50 Hz)	8,25
13	Packaging & Cooling	S6	Charging compatibility with infrastructure and regulation (ISO 15118 & IEC 61851 considered but not inplemented in demo)	8,25
14	Battery	E1	Voltage level selection	7,5
15	Battery	E2	Battery architecture (number of modules, configurations, voltage range per module)	7,5
16	Onboard charger	E3	Battery reconfiguration requirements (active battery balancing and parallelizing modules)	7,5
17	Packaging & Cooling	M10	Housing (size, form factor, envelope)	6,17
18	Packaging & Cooling	S3	Insulation monitoring device / leakage current detection	6,17

19	Onboard charger	E15	Insulation duration period	6,17
20	Onboard charger	E17	Auxilliary voltage (12 V battery with a dedicated charger from the HV battery)	6,17
21	Packaging & Cooling	E5	Charger/battery interface definition (CCS2 for mode-3 + CCS2/MCS for mode-4, TBD by demo)	6,08
22	Packaging & Cooling	CM8	Regulatory risk	3,83
23	Motor & Inverter	S5	Functional safety compatibility (ISO 26262 concept level)	3,83
24	Packaging & Cooling	E6	Power rating and fast charging capability (We can put these in two separate rows Power: 100kW Charging time 20%-80%: 10min)	1,75
25	Onboard charger	E16	Control Software functionality	1,5
26	Packaging & Cooling	E18	Communication network: architecture and protocol (CAN 2.0b)	1,5
27	Packaging & Cooling	S7	Type approval certification challenges	1,5

Table 10. Overall KPIs Ranking

Ranking	Subsytem	ID	Key design requirements and constraints	Score
1	Packaging & Cooling	ST7	Copper use reduction [%]	8,5
2	Motor + Inverter	E12	Electric machine energy efficiency in the most frequent operating point	8,5
3	Packaging & Cooling	M2	Weight reduction at system level	8,5
4	Motor + Inverter	CM13	… Reliability cost tag … (to be completed)	8,5
5	Packaging & Cooling	M5	Efficiency of the demonstrator Extended Drive Range (% of km/kWh)	8,5
6	Motor + Inverter	M6	Converter + machine + gearbox volume and weight reduction	8,5
7	Motor + Inverter	E9	Reduction of lifecycle energy losses for electric motor [kWh/year]	8,5
8	Packaging & Cooling	ST5	Specific material intensity [kg/kW]	8,5
9	Motor + Inverter	E8	Reduction of lifecycle energy losses for Inverter [kWh/year]	8,25
10	Onboard charger	CM12	Charging Cost Reduction	8,25
11	Motor + Inverter	E11	Inverter efficiency improvement, especially at partial load, vs SoA full-Si IGBT VSI	8,25
12	Motor + Inverter	ST12	Reduced degradation and improvement of inverter cyclelife Vs Si-based inverter [number of cycles or years to end of life]	8,25
13	Motor + Inverter	S4	Reduction of common-mode current emission vs SoA full-SiC MOSFET VSI	8,25
14	Motor + Inverter	CM4	Cost reduction of inverter power-electronic modules vs SoA full-SiC MOSFET VSI	8,25

15	Battery	E7	Reduction of lifecycle energy losses for battery [kWh/year]	7,5
16	Battery	CM11	Reduced maintenance/repair cost due to multi-pack battery	7,5
17	Packaging & Cooling	E14	Reduced current harmonics & EMI (Reduction in common-mode current emmision)	6,17
18	Packaging & Cooling	M1	Power density increase (kW/kg, kW/L)	6,17
19	Packaging & Cooling	CM7	Scalability across vehicle classes	6,17
20	Control & EMS	ST1	Reduction of lifecycle energy losses [kWh/year]	6,17
21	Packaging & Cooling	ST2	System efficiency improvement	6,17
22	Packaging & Cooling	CM1	Specific powertrain cost [€/kW]	6,17
23	Packaging & Cooling	CM3	Innovation specific cost reduction [%]	6,17
24	Packaging & Cooling	ST11	Overall environmental impact reduction [%]	6,17
25	Onboard charger	E10	Reduction of lifecycle energy losses for OBC [kWh/year]	6,08
26	Packaging & Cooling	CM5	Manufacturability at automotive scale	3,83
27	Packaging & Cooling	ST3	Total CO_2 equivalent emissions [kg CO_2eq/kW]	3,83
28	Packaging & Cooling	ST8	Material Circularity Indicator (MCI)	3,83
29	Packaging & Cooling	ST6	Critical Raw Materials (CRM) intensity [kg CRM/kW]	3,83
30	Packaging & Cooling	ST9	Water consumption [m^3 H_2O eq/kW]	3,83
31	Packaging & Cooling	E13	Reduced switching & conduction losses	1,5
32	Packaging & Cooling	CM6	TRL progression compatible with industrial uptake	1,5
33	Packaging & Cooling	CM2	End-of-life residual value [%]	1,5
34	Packaging & Cooling	ST13	Reduction of rare-earth permanent magnets of the initial design stage	1,5
35	Packaging & Cooling	ST4	CO_2 emissions reduction vs Si-based inverter [%]	1,5
36	Packaging & Cooling	ST10	Land use [m^2·year/kW]	1,5

5. Technical specifications

This section presents the information collected and agreed for each of the main components of the electric vehicle powertrain. The objective is to provide a consolidated overview of the technical specifications defined throughout the project, ensuring alignment among partners and facilitating the monitoring of component development against the project objectives and the targets established in the Grant Agreement.

For each component, the section identifies the partner leading the technical specification activities, the participants involved in the related technical discussions, and the specifications agreed upon by the consortium. In addition, it summarizes the performance targets to be achieved, highlights any pending specifications that still require validation or agreement, and outlines technical aspects that need further definition in subsequent stages of the project.

5.1 Battery pack

5.1.1 Agreed technical requirements

Requirements defined in QFD methodology

Priority Ranking	ID	Key design requirements and constraints	Previous comments from partners	Technical specifications for the requirement
Very high importance	E1	**Voltage level (this seems to be at least 1200 V, according to the proposal)**	400V/800V/1200V	-
	E2	**Battery architecture (number of modules, configurations, voltage range per module)**	6*400V	It was agreed that each 400 V battery pack will comprise 96 cell groups. However, the detailed cell architecture within the battery pack remains subject to further definition and optimisation during subsequent design activities.

Results from technical discussions

Voltage Levels

- The operating voltage levels were agreed to be set at 400 V, 800 V, and 1200 V.
- The 400 V level is intended to support charging through single-phase and three-phase residential chargers, as well as low-voltage charging stations via the onboard charger (OBC).
- Where required by the OBC architecture, individual 400 V battery packs may be charged independently through the implementation of suitable isolation mechanisms.
- The 800 V level was identified as compatible with current DC fast-charging infrastructure.
- The 1200 V level was considered primarily for traction system operation and compatibility with future high-power charging infrastructures.

Battery System Architectures

- It was concluded that the implementation of the three targeted voltage levels would require a minimum of six 400 V battery packs.
- Several architectural concepts for the implementation of the multi-voltage DC system were analysed and compared.

- A modular and scalable configuration was identified as the preferred approach due to its potential to reduce system complexity, cabling requirements, and interconnections.
  Preliminary considerations regarding the internal cell architecture of the battery packs were discussed. However, final decisions remain dependent on the definition of system-level requirements, including energy capacity, power demand, packaging constraints, and cell format selection.

Estimation of Volumetric and Gravimetric Requirements

- Preliminary volumetric and gravimetric estimations were performed based on the analysis of representative battery systems currently available in the electric vehicle market.
- The initial target considered for the battery system was the delivery of 100 kW of power with a total energy capacity of approximately 40 kWh.
- Reference battery pack dimensions for capacities within the 20–40 kWh range were reviewed to support the preliminary packaging assessment.
- Different cell formats, including cylindrical, pouch, and prismatic technologies, were considered during the estimation process.
- Based on the preliminary assessment, the estimated pack volumes for a 40 kWh battery system are:
  - Cylindrical (18650): approximately 317 L
  - Cylindrical (21700): approximately 310 L
  - Pouch: approximately 446 L
  - Prismatic: approximately 680 L

  The corresponding preliminary estimations indicate a total cell mass of approximately 210 kg and an overall battery system mass of approximately 315 kg.

Cooling System and Thermal Management

- It was concluded that active thermal management solutions are likely to be required for the battery system, particularly under fast-charging conditions and operation at elevated ambient temperatures (e.g., above 40°C), in order to ensure adequate performance, safety, and durability.
- The integration of active cooling technologies was identified as a potential requirement for ensuring battery performance, safety, and durability.
- It was recognised that the final cooling system configuration should be defined considering both battery requirements and the thermal demands of the overall powertrain.

Battery Capacity and Demonstrator Strategy

- Different battery capacities were evaluated in relation to the demonstrator objectives, available installation space, budgetary constraints, and integration requirements.
- It was recognised that a balance must be achieved between demonstrating the targeted system performance and ensuring practical implementation within the demonstrator platform.
- The possibility of validating the full-power concept under laboratory conditions while implementing a reduced-capacity battery system in the vehicle demonstrator was discussed as a potential development pathway.
- The relationship between battery capacity, discharge rates, and thermal management requirements was highlighted as a critical design consideration.
- It was agreed that battery sizing decisions should be supported by detailed thermal and performance analyses in subsequent project activities.
- It was recognised that the use of a relatively low-capacity battery system (e.g., around 20 kWh) in combination with a 100 kW traction motor could result in high discharge C-rates. Such operating conditions may introduce significant thermal management challenges and could require enhanced cooling solutions beyond those typically employed in conventional commercial battery systems.

Integration into the Vehicle Platform

- It was agreed that the weight and weight distribution of the electrified powertrain should remain as close as reasonably possible to those of the original vehicle configuration in order to preserve vehicle dynamics and handling characteristics.

- Packaging constraints associated with battery placement, cooling systems, and powertrain components were identified as important challenges requiring further optimisation during the design phase.
- The availability of vehicle integration data and design information was recognised as an important enabler for the development activities.

Fast-Charging Specification Alignment

- It was clarified that the high-power charging figures considered during the initial project definition should be interpreted primarily as infrastructure compatibility targets rather than mandatory charging power levels for the demonstrator battery system.
- It was recognised that charging power must be aligned with the final battery capacity and thermal management capabilities.
- Consequently, charging performance is expected to be assessed primarily through charging-time indicators (e.g., charging from 20% to 80% state of charge within a specified time window) rather than through a fixed charging power value.

5.1.2 Technical Aspects for Further Definition

The space allocated for the battery

- Based on preliminary estimations, a 40 kWh battery system is expected to require a volume in the range of approximately 320 L to 450 L, depending on the selected cell format. Therefore, information regarding the available installation space and packaging envelope is required to support the continuation of the battery system design activities.
- The definition of the available space is necessary to assess the feasibility of the targeted power and energy specifications, support the selection of the most appropriate cell technology, and evaluate potential integration solutions.
- Vehicle packaging information and component allocation data are required to enable detailed design and integration assessments.

Battery pack design

- Information regarding the available installation space, dimensions, and layout constraints for the battery system and associated components is required to support detailed design and integration activities.
- Vehicle packaging constraints and component allocation information remain important inputs for the final definition of the battery system architecture and integration strategy.

Battery Capacity

- Battery capacity remains under evaluation within the approximate range of 10–20 kWh, considering preliminary design.
- The final battery capacity will need to be aligned with system-level requirements, including power performance targets, thermal management constraints, vehicle integration considerations, and demonstrator objectives.

Constraints on the mass of the battery system

- Further definition of the allowable battery system mass is required to ensure compatibility with vehicle integration requirements and to minimise any impact on vehicle balance, handling characteristics, and overall performance.
- Additional vehicle integration constraints related to chassis and suspension characteristics are required to support the definition of the final battery system design.

Preferences or requirements of the cooling system

- The high power demand of approximately 100 kW during battery discharge is expected to occur primarily under transient operating conditions. However, the associated thermal loads will need to be further assessed once the intended driving cycle has been fully defined.
- It was recognised that the thermal management requirements of the complete powertrain should be considered in addition to those of the battery system. During vehicle operation, components such as the inverter and electric motor will also contribute to the overall cooling demand, whereas charging conditions may impose different thermal management requirements.
- Consequently, the overall cooling capacity and thermal management strategy are expected to depend on the final operating conditions and driving cycle definition.
- In addition to cooling capacity, the selection of the cooling architecture was identified as an important design consideration. Different approaches may be evaluated, including liquid-cooling solutions and integration with the vehicle's broader thermal management system.
- The definition of the cooling requirements and architecture is considered a key input for the design and optimisation of the battery modules and battery packs.

Test driving cycle

- The driving cycle to be used for vehicle testing remains to be defined and constitutes an important input for the subsequent design activities.
- Although the target peak power has been provisionally defined at approximately 100 kW, a detailed understanding of the expected operating conditions is required to appropriately size the battery system and assess its performance under representative driving scenarios.
- The definition of the driving cycle is necessary to support the selection of suitable battery cells capable of meeting the expected power and energy demands.
- The driving cycle definition is also required to estimate the thermal loads generated during operation and to establish the corresponding cooling capacity requirements for the battery system and associated powertrain components.

5.2 Inverter & Motor

5.2.1 Agreed technical requirements

Requirements defined in QFD methodology

Priority Ranking	ID	Key design requirements and constraints	Previous comments from partners	Technical specifications for the requirement
Very High Importance	E20	**Power train architecture definition (number of motors, number of poles…)**	-	A single traction motor is foreseen for integration into the Morgan Plus Four vehicle. Preliminary targets indicate a power rating in the range of 100 kW and a maximum rotational speed of approximately 12,000 rpm. Final values remain subject to confirmation based on vehicle speed requirements, wheel rotational speed, and gearbox ratio considerations. For the traction inverter, the development of three-phase inverter solutions has been considered, including a modular prototype with a power rating of approximately 25 kW and a final system targeting 100 kW. Different converter topologies have been identified for evaluation, including Hybrid Si/SiC and Multi-level Hybrid Si/SiC architectures.

	M7	**Commercial Gearbox**	A combined converter + motor + gearbox frame that fits the available volume/space in the selected vehicle.	A highly integrated powertrain solution combining the converter, motor, and gearbox within a common assembly has been identified as a desirable objective in order to facilitate integration within the available vehicle packaging constraints. Preliminary assessments indicate that a gearbox ratio in the order of 10:1 may be suitable for the intended vehicle application, although the final selection remains subject to detailed system design and integration studies.
	S1	**Partial discharge avoidance at selected voltage - insulation aging risk**	-	It was recognised that phase-to-ground and phase-to-phase voltage levels should, where feasible, remain below approximately 1200 V in order to minimise insulation requirements and support practical system integration. Relevant standards and insulation design constraints will be considered during subsequent development activities.

Results from technical discussions

Gearbox

- A commercial gearbox solution is being considered for the demonstrator vehicle.
- Preliminary assessments indicate that a gearbox ratio in the order of 10:1 and torque capability compatible with the project requirements may be suitable for the intended application.
- Initial packaging evaluations suggest that integration within the selected vehicle platform is feasible.
- Final gearbox selection remains dependent on the overall powertrain architecture and system-level integration studies.

Insulation and partial discharge

- The transition from 400 V to 1200 V operating conditions was identified as a key design challenge for the electric powertrain.
- It was agreed that phase-to-phase and phase-to-ground insulation requirements must be carefully addressed to ensure safe and reliable operation.
- Excessive insulation thickness should be avoided where possible in order to minimise impacts on machine performance and current density within the windings.
- Several design approaches may be considered to address insulation requirements while maintaining overall system performance.
- Relevant standards and acceptance criteria will be considered during the detailed design phase.

Inverter architecture

- The target final inverter architecture consists of a three-phase traction inverter for a single electric machine with a target power rating of approximately 100 kW.
- A dual development approach was agreed, combining the development of a modular research prototype at lower power level with a final vehicle-oriented inverter targeting full system performance.
- Modularity was identified as an important design principle, enabling flexibility and scalability of the power electronics architecture.
- Different inverter topologies remain under consideration, including conventional and advanced converter architecture.

- Final implementation choices will be defined during subsequent development activities based on system-level requirements, component availability, and performance targets.

Experimental validation strategy for inverter + motor

- It was agreed that the primary validation of inverter efficiency and key performance indicators should be carried out using representative electrical load configurations rather than a complete motor-driven setup.
- Inductive and resistive load arrangements were identified as a suitable approach for reproducing representative voltage and current operating conditions while maintaining testing flexibility and safety.
- Motor-based testing may be performed during later validation stages to support the assessment of the complete powertrain system.
- Available laboratory infrastructure was considered adequate to support the planned validation activities for both the inverter and the electric machine.

Semiconductor strategy

- Semiconductor technologies suitable for operation in the targeted voltage range are being evaluated for the final inverter implementation.
- It was agreed that the selected devices should provide an appropriate balance between performance, reliability, efficiency, and integration requirements.
- Different semiconductor technologies, including Si and SiC-based solutions, remain under consideration.
- Final device selection will be supported by detailed technical assessments performed during subsequent project activities.

Motor and Transmission Definition

- A synchronous machine was identified as the preferred direction for the traction motor.
- Different machine configurations remain under evaluation and will be assessed against performance, efficiency, sustainability, and integration criteria.
- The interaction between motor design, transmission ratio, and overall vehicle performance was recognised as a key aspect of the powertrain optimisation process.
- Preliminary assessments indicate that the selected transmission concept can be integrated within the vehicle packaging constraints.

Control and Safety Considerations

- Protection strategies for fault conditions were identified as an important requirement for the final inverter and motor system design.
- The implementation of appropriate protection and control functions will be considered according to the selected machine topology and operating requirements.
- The parallel operation of modular power electronic units was identified as an area requiring further assessment in order to ensure stable operation and avoid undesired circulating currents.

5.2.2 Technical Aspects for Further Definition

Parallelisation of the 25-kW modules

- The implementation and validation strategy for the parallel operation of the four 25 kW power modules requires further definition.

- Particular attention will need to be given to the management of circulating currents and the associated control and protection strategies to ensure stable and reliable operation of the parallelised system.
- It was recognised that the parallelisation of four 25 kW modules may also create opportunities for the implementation of multiphase machine configurations (e.g., 6-phase or 12-phase architectures), which may be considered during subsequent system design and optimisation activities.

5.3 Onboard charger

5.3.1 Agreed technical requirements

Requirements defined in QFD methodology

Priority Ranking	ID	Key design requirements and constraints	Previous comments from partners	Technical specifications for the requirement
Very High Importance	E4	**OBC architecture (CIRCE proposes to develop an isolated AC/DC converter per module, so that they can operate independently of the configuration of the modules and charge each one independently. Operation values: three (or single TBD)-phase 230 V, 50 Hz)**		- Modular OBC architecture with one OBC per 400 V battery module. - Support for European single-phase and three-phase AC grids (230/400 V, 50 Hz). - Isolated AC/DC topology with galvanic isolation. - Auxiliary HV-to-LV conversion considered as a separate function.
	S6	**Charging compatibility with infrastructure and regulation (ISO 15118 & IEC 61851 considered but not inplemented in demo)**		- Charging interoperability requirements remain subject to further definition. - Relevant charging standards will be considered during system integration activities.
High Importance	E5	**Charger/battery interface definition (CCS2 for mode-3 + CCS2/MCS for mode-4, TBD by demo)**		- The charger–battery interface remains under evaluation. - Compatibility with the selected charging scenarios will be ensured.
Low Imp.	E6	**Power rating and fast charging capability (We can put these in two separate rows Power: 100kW Charging time 20%-80%: 10min)**	100kW Only for off-board charger	- Target charging power of approximately 100 kW. - Fast-charging performance to be assessed through charging-time KPIs. - Final performance dependent on battery capabilities and thermal management constraints.

Results from technical discussions

On-board Charger (OBC)

- A modular OBC architecture was agreed, comprising six OBC modules, each associated with a 400 V battery module.
- A modular multi-converter OBC architecture was selected as the preferred implementation approach.
- The OBC architecture is intended to support both single-phase and three-phase AC operation.
- An isolated AC/DC converter architecture was identified as the preferred approach for the OBC implementation.
- The 1200 V level was confirmed as the primary system voltage level.
- To reduce demonstrator complexity and facilitate vehicle integration, it was agreed that the 800 V operating configuration will not be implemented in the physical demonstrator. Compatibility with intermediate voltage levels may instead be assessed through laboratory validation activities.
- The OBC power rating is expected to be within the range typically associated with residential and commercial AC charging applications.
- A simplified demonstrator approach was adopted, prioritizing technical feasibility and system integration over the implementation of all possible operating configurations.
- The physical demonstrator will adopt simplified architecture focused on technical feasibility and system integration.

Battery Pack Design Considerations

- Battery capacity options within the approximate range of 10–20 kWh were discussed for the demonstrator implementation.
- It was recognised that battery capacity, power capability, thermal management requirements, cost, and vehicle integration constraints must be evaluated together at system level.
- The relationship between battery capacity and achievable power performance was identified as a key design consideration, particularly due to the impact of discharge C-rates on thermal management requirements.
- It was agreed that battery sizing decisions should be aligned across the relevant technical activities to ensure consistency at system level.
- Information regarding the available installation space and packaging constraints remains an important input for the final battery system definition.

Battery Management System (BMS) and Active Balancing

- Active balancing was identified as a key functionality at the 400 V battery pack level due to the increased risk of imbalance in high-energy battery systems.
- Active balancing at battery pack level was confirmed as the primary innovation focus within the battery management system development activities.
- Passive balancing was considered sufficient at cell level, where imbalances are expected to be primarily related to manufacturing tolerances.
- It was agreed that the active balancing system should be developed as a dedicated function rather than being integrated directly within the OBC architecture.
- The development approach will focus on the most impactful innovative functions while allowing the use of established solutions for supporting monitoring and protection functionalities where appropriate.

Simulation and Hardware-in-the-Loop (HIL)

- Hardware-in-the-loop validation was identified as an important activity for system integration and control verification.
- Simulation models of the battery system, OBC, and BMS will be required to support integration within the HIL environment.
- It was agreed that the models should focus on system dynamics and controller behaviour while maintaining an appropriate level of complexity for real-time simulation.
- Detailed electrochemical modelling was not identified as a requirement for the planned HIL activities.

- Further definition of model interfaces and integration requirements will be performed during subsequent development stages.

Demonstrator and Vehicle Strategy

- The selected vehicle platform was recognised as presenting significant integration challenges due to packaging and system integration constraints.
- A clear distinction was established between laboratory validation activities and demonstrator implementation.
- Laboratory validation and demonstrator implementation were defined as complementary activities addressing different validation objectives.
- Full-power operation, efficiency assessments, and performance-related KPIs are expected to be validated primarily through laboratory testing.
- The vehicle demonstrator will focus on functional system integration and validation of the complete powertrain concept rather than operation at the absolute performance limits of the technology.
- Full-power and efficiency performance indicators will be validated primarily through laboratory testing, while the demonstrator will focus on system integration and functional validation.
- It was agreed that demonstrator objectives should prioritise system-level integration while maintaining alignment with the overall project targets.

KPIs and Requirements

- The charging-time target corresponding to charging from 20% to 80% state of charge within 10 minutes was recognised as a performance indicator rather than a mandatory operational requirement for the OBC.
- It was agreed that this KPI should be assessed through analytical studies and laboratory validation activities, considering battery and thermal management limitations.
- Cost-related KPIs should be assessed from a system-level perspective, considering both component-level and integration-related benefits.
- Lifecycle energy-loss indicators are expected to be evaluated through the exchange of data between the relevant technical activities.
- It was concluded that the defined KPIs remain measurable and suitable for assessing the project objectives.

5.3.2 Technical Aspects for Further Definition

Space and Layout Definition

- Further definition of the available installation space and component layout is required to support packaging, integration, and thermal management activities.
- The allocation of space and positioning of major system components will be consolidated during subsequent design and vehicle integration studies.
- Detailed vehicle packaging information is required to support the finalisation of component layouts and system integration assessments.

5.4 Packaging & Cooling

5.4.1 Agreed technical requirements

Requirements defined in QFD methodology

Priority Ranking	ID	Key design requirements and constraints	Previous comments from partners	Technical specifications for the requirement
Very High Importance	M3	**Compact integration of HV components**	-	HV components with 20% increased driving range integrated in same space
	M4	**Thermal management compatibility at HV**	-	HV compatibility ensured for increased voltage
	M8	**Cooling specifications (flow, pressure, temperature range, cooling plate, inlets) definition for each INN**	-	Specification optimized to meet efficiency targets
	M9	**HV plugs definition**	-	Plugs suited for DC fastcharging and AC charging
	S2	**Insulation coordination & creepage/clearance compliance**	-	Fulfilment of Insulation requirement for increased voltage levels
	CM9	**Lab test vs. Simplified demo**	-	30% time reduction of integration test and development cycles
	CM10	**Demo responsabilities (breakers, wiring, plugs required for integration) to be provided by each partner**	-	25% reduction of costs at prototype level
High Importance	E15	**Insulation duration period**	-	150.000 h
	E17	**Auxilliary voltage (12 V battery with a dedicated charger from the HV battery)**	-	-
	M10	**Housing (size, form factor, envelope)**	-	-
	S3	**Insulation monitoring device / leakage current detection**	-	-

Results from technical discussions

Vehicle Demonstrator

- The Morgan Plus Four was confirmed as the vehicle demonstrator for the project.
- The availability of vehicle technical information, including CAD data, CAN communication information, and supporting technical documentation, was recognised as a key enabler for system integration and validation activities.
- Preliminary integration concepts for the powertrain components were reviewed to assess their compatibility with the vehicle platform.
- CAD data and packaging information were identified as essential inputs for evaluating the available installation space and supporting detailed integration studies.
- It was agreed that the vehicle demonstrator should primarily focus on system integration and functional validation, while full-performance assessments will be carried out through laboratory testing activities.

Packaging Constraints and System Integration

- Different battery technologies and packaging concepts were reviewed in order to assess their impact on system volume, mass, and integration feasibility.
- The influence of packaging constraints on component dimensions and overall vehicle integration was identified as a key design consideration.
- It was agreed that the mass and weight distribution of the electrified powertrain should remain as close as reasonably possible to those of the original vehicle configuration in order to preserve vehicle dynamics and handling characteristics.
- Further definition of installation space, component layout, and packaging constraints is required to support detailed system integration activities.

System Architecture and Component Requirements

- Representative electric vehicle architectures were reviewed to support the definition of the high-voltage system architecture.
- Open requirements affecting component design, integration, and validation activities were discussed and consolidated.
- The interactions between battery, inverter, motor, charger, cooling system, and auxiliary components were recognised as important factors in the optimisation of the overall system architecture.

Cooling System Architecture

- Thermal management was identified as a critical aspect of the demonstrator design due to the different operating requirements of the battery system and the remaining high-voltage components.
- A cooling architecture based on dedicated thermal management functions for the battery system and the powertrain components was identified as a suitable approach for further evaluation.
- Active thermal management solutions were considered particularly relevant for supporting operation under demanding ambient conditions and charging scenarios.
- The possible integration of refrigerant-assisted cooling technologies was identified as a potential option for enhancing battery thermal management performance, although simpler liquid-cooling architectures remain under consideration.
- It was recognised that the final cooling architecture will depend on the thermal requirements of the individual components, demonstrator operating conditions, packaging constraints, and overall system integration considerations.
- The final configuration of the cooling system, including the number of cooling loops and the level of thermal integration between components, will be determined during subsequent design activities based on detailed thermal analyses.

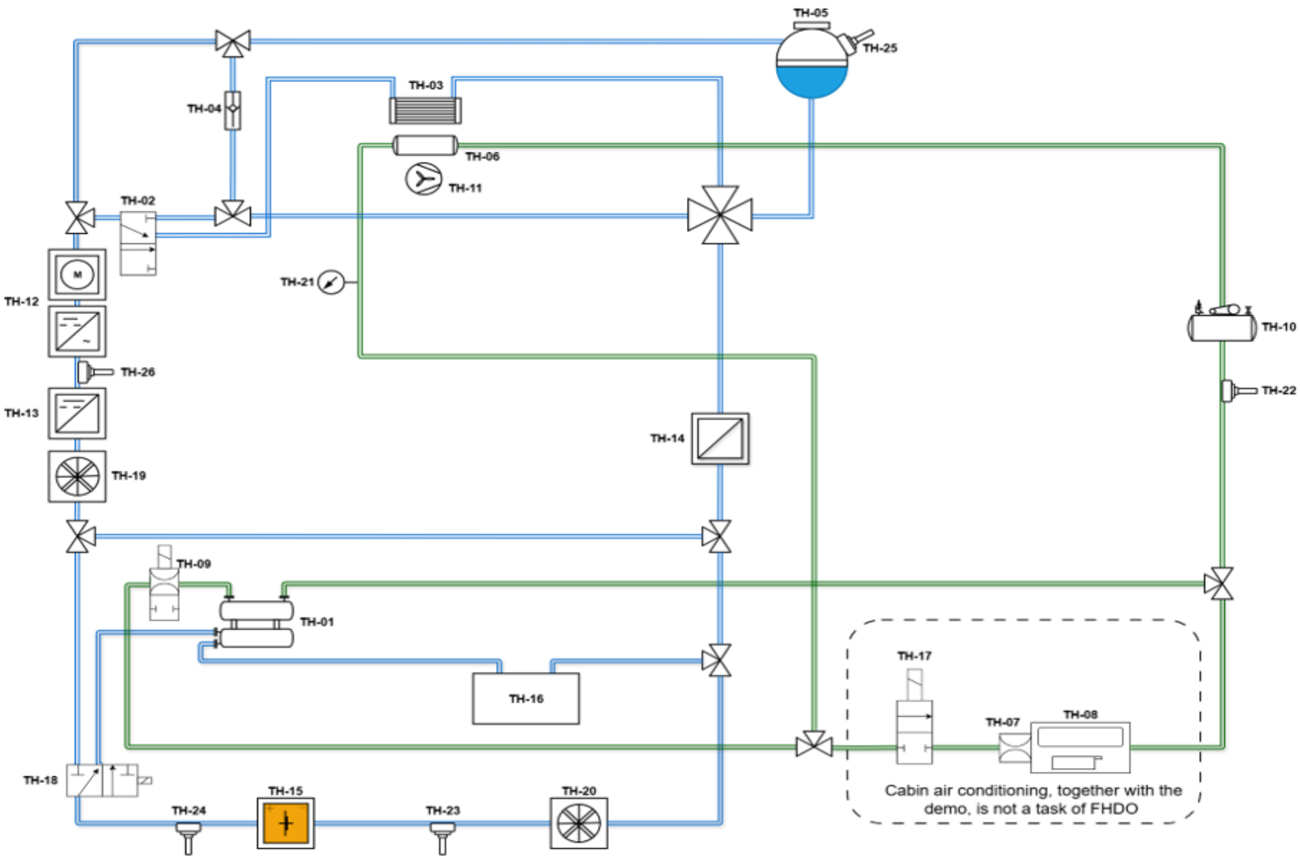


Figure 3. Cooling system general diagram

Outstanding Technical Dependencies

- The definition of the final cooling architecture remains dependent on the availability of detailed thermal and operational data for the major high-voltage components.
- Hydraulic operating parameters, including flow rates, pressure levels, temperature ranges, and cooling distribution strategies, require further definition through detailed thermal analyses.
- Packaging and routing studies remain dependent on the availability and assessment of detailed vehicle integration information.
- The selection of specific thermal management technologies and supporting components will be aligned with the final system architecture and demonstrator requirements.
- Further integration studies are required to consolidate the interfaces between the cooling system, vehicle packaging constraints, and the remaining powertrain subsystems.

5.4.2 Technical Aspects for Further Definition

Cooling specifications

- Cooling specifications, including flow rates, pressure levels, and operating temperature ranges, require further definition based on quantified thermal loads for the main high-voltage subsystems, including the battery, traction inverter, electric motor, OBC, and HV-LV converter.
- The definition of cooling requirements will require information regarding component power losses, efficiency under representative operating conditions, peak power levels, peak current levels, operating durations, and allowable temperature limits.

- The distribution of cooling resources within the system, including flow allocation and prioritisation strategies between components, remains to be defined.
- The overall cooling architecture, including the number of cooling loops, the level of integration between subsystems, and the configuration of the cooling circuits, requires further assessment and optimisation.

Housing and packaging specifications

- Further definition of housing requirements is required, including component dimensions, packaging envelopes, form factors, and cooling integration constraints.

CAN bus network information

- The communication architecture and associated vehicle network interfaces require further consolidation to support the integration of the different subsystems within the demonstrator platform

Global cooling architecture

- The final cooling architecture, including the number of cooling loops and the degree of coupling between the battery system, traction inverter, and electric motor, remains dependent on system-level design decisions and integration trade-offs.
- Further definition will be supported by detailed thermal analyses and the consolidation of the overall system architecture.

Thermal load assessment

- The quantification of thermal loads for the main high-voltage subsystems, including the battery, traction inverter, electric motor, OBC, and HV-LV converter, remains an important input for the final cooling system design.
- This assessment requires representative operating conditions, including drive cycles, voltage levels, power requirements, efficiency characteristics, peak operating conditions, and charging scenarios.
- Additional modelling and simulation activities are required to support the final definition of thermal management requirements.

Hydraulic System Design

- The design of the hydraulic system, including piping layout, routing, and flow distribution, remains dependent on the final packaging definition and component allocation within the vehicle.
- Detailed hydraulic design activities will be performed once the spatial layout and integration constraints have been consolidated.

Pump sizing and configuration

- The sizing and configuration of pumps, including the number of units, flow rates, and pressure levels, will depend on the selected cooling architecture and the results of hydraulic and thermal analyses.
- Further definition is required following the consolidation of the thermal management concept.

Coolant selection

- The selection of the coolant and the definition of its operating characteristics remain dependent on thermal requirements, high-voltage system constraints, and component compatibility considerations.
- This activity will be addressed as part of the detailed thermal management design process.

Cooling interfaces

- The definition of cooling interfaces for the major high-voltage components requires alignment between subsystem designs and the overall integration strategy.
- Further consolidation of interface requirements will be carried out during subsequent design activities.

Heat exchanger integration

- The sizing and integration of heat exchangers will depend on the final thermal loads, cooling architecture, and vehicle packaging constraints.
- Further thermal and integration studies are required before these specifications can be finalised.

Thermal control strategy

- The thermal control strategy, including the interaction between pumps, valves, and higher-level energy management functions, remains subject to further definition.
- The final control approach will depend on the selected cooling architecture and overall system design.

Vehicle integration inputs

- Detailed vehicle integration information, including packaging constraints, installation space, and component layout, remains a key input for the finalisation of the cooling and integration studies.
- The alignment between vehicle packaging requirements and thermal management needs will be further refined as the system design matures.

Inverter and HV-LV converter integration

- The integration requirements associated with the traction inverter and HV-LV converter remain subject to further definition within the overall system architecture.
- Relevant interfaces, packaging requirements, and integration constraints will be consolidated during subsequent design and integration activities.

5.5 Control & EMS

5.5.1 Agreed technical requirements

Requirements defined in QFD methodology

Priority Ranking	ID	Key design requirements and constraints	Previous comments from partners	Technical specifications for the requirement
Very High Importance	S5	**Functional safety compatibility (ISO 26262 concept level)**		
	CM9	**Lab test vs. Simplified demo**		Test requirement specifications will be defined to evaluate performance under different scenarios in different platforms: 1. integrated simulation for complex scenarios und advanced control methods. 2. Laboratory testbench of individual components for basic operantion and data

				extraction for advanced features, 3. full vehicle operation
	E18	**Communication network: architecture and protocol (CAN 2.0b)**		Based on existing network in the vehicle a possible extension, redesign will be considered. Latency and reliability criteria.
High Importance	**E19**	**Simulation framework (common software TBD)**		Simulink will be used by all partners. Plecs blocks integrated in Simulink will be used for the power converter.
Medium Importance	**E16**	**Control Software functionality**		Basic functionalities for the vehicle demonstrator. Advanced functionalities implemented and tested in simulation environments
	CM8	**Regulatory risk**		

Results from technical discussions

Control Architecture

- A decentralised control architecture was agreed, whereby each major subsystem implements its own dedicated control functions, including control algorithms, sensing requirements, and local control hardware.
- A central Vehicle Control Unit (VCU) will coordinate the operation of the different subsystems and manage system-level supervision, communication, and control functions.
- The overall control architecture is intended to support modularity, scalability, and efficient integration of the battery system, powertrain, charging system, and thermal management functions.

On-Board Charger (OBC) Control

- The OBC control strategy is being developed for a modular onboard charging system within the power range typically associated with residential and commercial AC charging applications.
- Compatibility with standard charging interfaces and charging infrastructure was identified as an important requirement for the demonstrator.
- Different approaches for charging communication and protocol implementation remain under evaluation, including the use of established commercial solutions where appropriate.
- The HV-LV conversion functionality is considered a separate subsystem and is not currently foreseen as part of the OBC architecture.

Cooling Control

- The thermal management strategy is based on the recognition that different high-voltage components operate within distinct temperature ranges and therefore may require differentiated cooling approaches.
- A cooling architecture comprising dedicated thermal management functions for the battery system and the remaining powertrain components has been identified as a suitable solution for further development.
- Active thermal management solutions may be required to support operation under demanding ambient conditions, charging scenarios, and vehicle operating modes.
- The possible integration of refrigerant-assisted cooling technologies remains under evaluation and will be assessed against system requirements, thermal performance targets, integration complexity, and demonstrator constraints.
- Simplified cooling architectures remain under consideration where appropriate to support demonstrator feasibility and system integration objectives.

- The final thermal management control strategy, including subsystem coordination and interaction with vehicle-level controls, will be defined during subsequent development activities.
- The communication requirements necessary for thermal monitoring and control have been identified as an important aspect of the system integration process.

Communication and CAN network

- The communication architecture between the different subsystems remains subject to further definition.
- Data exchange requirements for monitoring, diagnostics, thermal management, and system control functions will be consolidated during subsequent integration activities.
- Communication interfaces, message structures, and data exchange protocols will be defined to ensure reliable coordination between all project subsystems.

Inverter and Motor Control

- The powertrain control architecture will follow established electric drive control principles, including cascaded control loops for speed, torque, and current regulation.
- Advanced converter control strategies aimed at improving efficiency, reliability, and operating flexibility are being considered as part of the power electronics development activities.
- The final motor control strategy will be adapted to the selected machine topology and system requirements.
- Protection functions and fault-management strategies will be incorporated to ensure safe operation under abnormal and fault conditions.
- The inverter, motor, cooling system, and communication infrastructure will be developed to support efficient subsystem integration and coordinated operation.
- Advanced control concepts will be evaluated through simulation and laboratory testing activities prior to demonstrator integration.

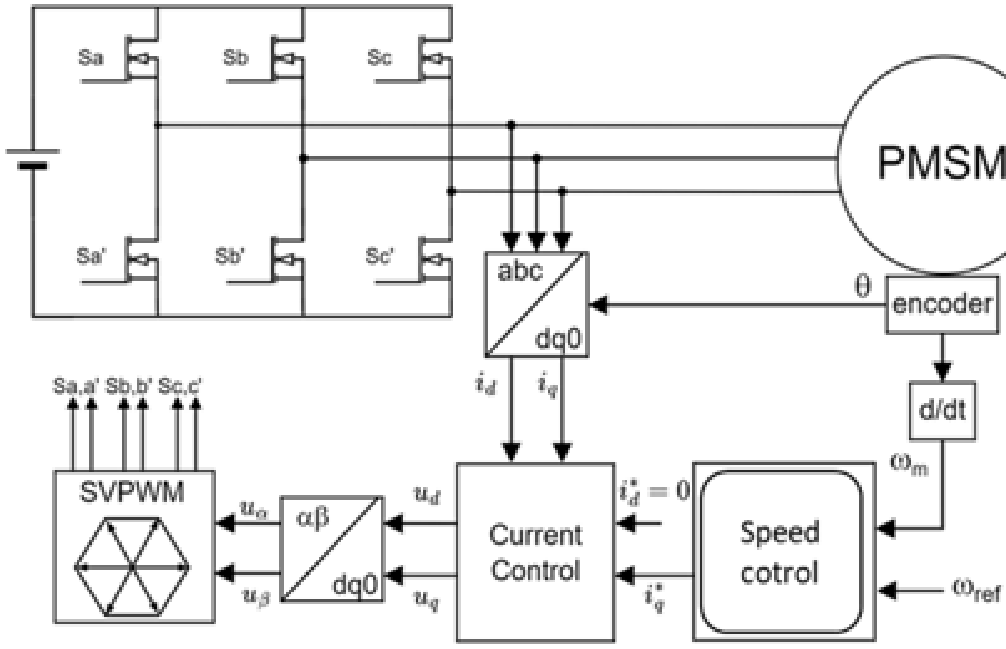


Figure 4. Motor and converter control diagram based on PMSM motor.

System Control

- The Vehicle Control Unit (VCU) will coordinate the exchange of information between the battery system, thermal management system, and powertrain subsystems.
- System-level commands and operating limits will be distributed to the relevant subsystems through a central communication architecture.
- Local control functions will remain implemented within the respective subsystems, while the VCU will provide supervisory coordination and vehicle-level management.
- Vehicle operation will rely on the continuous monitoring of key operating parameters, including electrical, thermal, and hydraulic variables, to ensure safe and efficient operation.

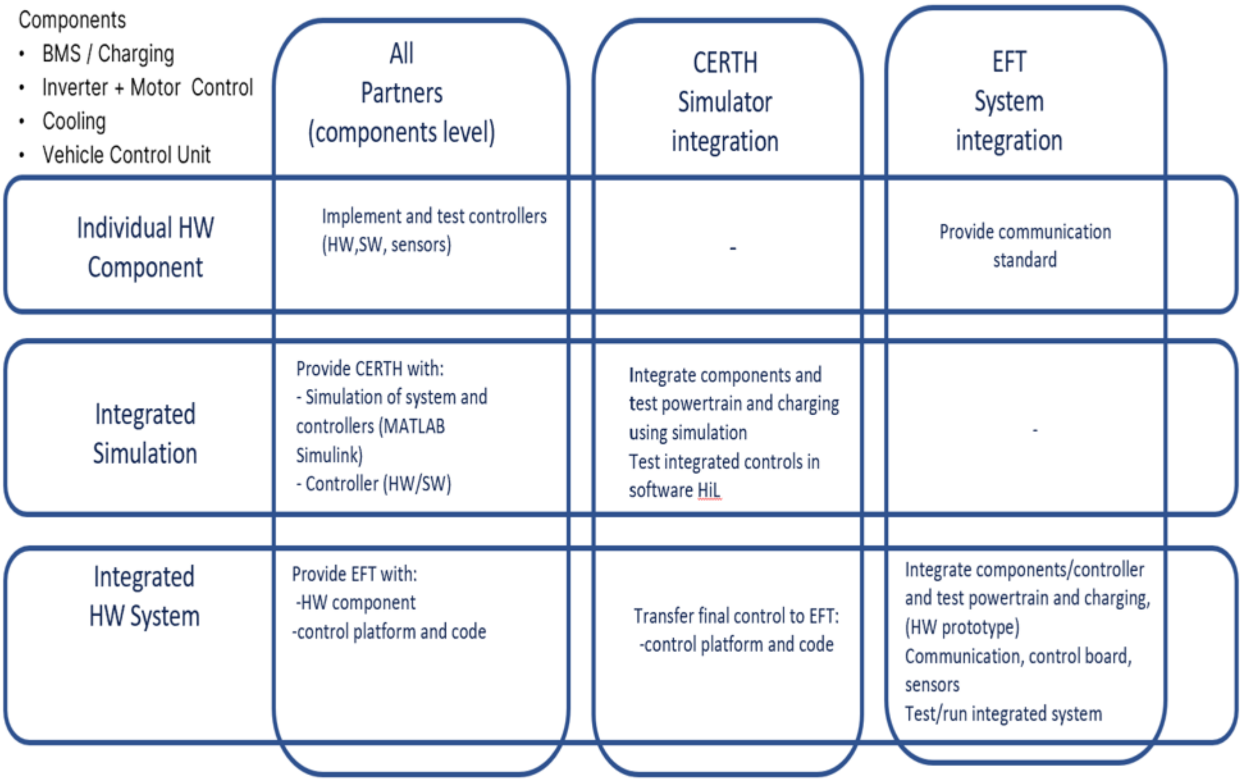


Figure 5. Control implementation plan

Validation strategy

- The validation strategy is structured around both demonstrator-oriented activities and research-oriented developments, ensuring that project objectives can be achieved while managing technical risks.
- A pragmatic and robust approach has been adopted for the vehicle demonstrator, prioritising reliability, integration feasibility, and safe operation.
- Research-oriented developments may be evaluated independently within laboratory environments before selection and implementation within the demonstrator platform.
- Control concepts and system performance will be assessed through a combination of simulation, hardware-in-the-loop activities, subsystem testing, integrated powertrain testing, and vehicle-level validation.
- Hardware-in-the-loop environments will be used to support the validation of control strategies, integration functions, and safety-related behaviours prior to deployment within the demonstrator.
- Individual subsystem testing will be performed to verify component functionality and operating performance under representative conditions.
- Integrated validation of the electric powertrain will be carried out using dedicated laboratory facilities capable of reproducing the targeted operating conditions.
- Following successful subsystem and integration validation activities, the complete demonstrator will be assembled and subjected to vehicle-level testing.

Validation tests – OBC

- Validation activities for the OBC will focus on charging functionality, charging strategies, interoperability requirements, and compatibility with the selected charging infrastructure.
- Fast-charging performance is expected to be evaluated primarily through laboratory validation activities rather than through the onboard charging system itself.

Validation tests – Powertrain

- A staged validation approach will be adopted, progressing from individual subsystem testing to integrated powertrain testing.
- Appropriate test infrastructures and representative energy sources or emulators may be employed to support the validation activities.
- Protection functions and safety strategies will be verified as part of the powertrain validation programme.
- Outputs from the powertrain validation activities will support the development and verification of the thermal management system.

Validation tests – Demonstrator

- The integrated control software will be validated through simulation and hardware-in-the-loop environments prior to vehicle deployment.
- Vehicle-level validation will be performed following the successful verification of subsystem functionality, system integration, and safety requirements.
- The demonstrator vehicle will be used to validate the functional integration of the developed technologies under representative operating conditions.

5.5.2 Technical Aspects for Further Definition

Communication protocol definition

- The final communication standard and vehicle communication architecture remain subject to further definition.
- Data exchange requirements between the Vehicle Control Unit (VCU), battery system, inverter, motor, thermal management system, and charging system require further consolidation.
- A dedicated interface specification is expected to be developed to define exchanged signals, communication requirements, update rates, and integration interfaces.

Sensor architecture definition

- The sensing architecture remains under development and requires further consolidation.
- Measurement requirements for key operating variables, including current, voltage, temperature, and coolant flow, must be defined according to subsystem and system-level requirements.
- Sensor update rates, monitoring requirements, and diagnostic functions will need to be established to support system supervision, safety, and control activities.

Cooling control integration strategy

- The final thermal management control strategy remains dependent on the demonstrator architecture and the selected cooling system configuration.
- The interaction between the Vehicle Control Unit, thermal management functions, battery management functions, and powertrain controllers requires further definition.
- The allocation of thermal management functions across the different control layers will be established following the consolidation of the overall system architecture.

- The final strategy will be supported by vehicle integration studies, thermal analyses, and subsystem-level design activities.

Advanced control functions

- Advanced control concepts beyond the baseline demonstrator functionality are planned to be developed and validated through simulation, hardware-in-the-loop, and laboratory testing activities.
- The scope and level of implementation of these advanced functions will be refined during subsequent development phases.

Active short-circuit protection

- The specification of active short-circuit protection functions for the motor–inverter system remains subject to further definition.
- Appropriate fault-management and protection strategies will be evaluated to ensure safe and reliable operation of the electric powertrain under fault conditions.

Vehicle model and data

- Detailed vehicle integration information remains an important input for the finalisation of system design activities.
- Vehicle packaging information, communication interfaces, available installation space, and existing subsystem configurations will support the assessment of integration opportunities and constraints.

Vehicle-level communication architecture

- Although a centralised communication approach has been identified, the complete vehicle-level communication architecture requires further consolidation.
- Coordination of communication requirements across the different subsystems will be necessary to ensure seamless integration and data exchange.

Thermal management control architecture

- The overall thermal management control architecture remains subject to further definition.
- The interaction between cooling circuits, supervisory vehicle control functions, and local subsystem controllers will be established during subsequent design and integration activities.

Demonstrator-level control integration

- The final integration strategy for the different subsystem controllers within the demonstrator platform requires further definition.
- Integration activities will focus on ensuring coordinated operation, system-level functionality, and compliance with safety and performance requirements.

Motor design and safety

- Certain aspects of the final motor configuration remain under evaluation and will be aligned with the overall powertrain architecture.
- Safety, reliability, and fault-tolerance requirements have been identified as key design considerations for the motor–inverter system.
- Protection concepts, redundancy measures, and fault-management strategies will be assessed to ensure robust operation under representative vehicle operating conditions.

6. KPIs: definition and monitoring plan

This section presents the set of key performance indicators (KPIs) defined within Task 2.1 to support the monitoring and validation of the powertrain architecture design, including voltage level selection and the application of a Safe and Sustainable by Design (SSbD) approach.

In alignment with the project objectives defined in the Grant Agreement, the KPIs included in this section operationalise the Project Internal Key Performance Indicators by translating them into measurable technical requirements at subsystem level. This ensures full traceability between the project targets and the design and validation activities carried out across the different WPs. The nomenclature used for the KPIs defined in this task is as set out in Table 6.

In order to reflect their relative relevance for the project objectives, all KPIs have been prioritised using a four-level scale ranging from Very High Importance to Low Importance. This prioritisation enables a clearer focus on the most critical design aspects, guiding both the allocation of efforts and the monitoring strategy.

For each subsystem (component) under analysis, the KPIs assess the technical feasibility and expected performance of the proposed solutions, while also defining their measurability, responsible partners and evaluation framework in line with their assigned importance.

6.1 Battery pack

Within the battery pack domain, two key performance indicators have been identified, both considered of very high importance, although with different levels of maturity in terms of quantification and measurability.

The first KPI relates to the reduction of lifecycle energy losses in the battery system (E7), focusing on the impact of the balancing strategy on overall efficiency, and representing the battery-level contribution to the system-level objective defined in the DoA as KPI 19: overall reduction in energy losses after powertrain integration and optimization. Based on the current system design assumptions, each battery pack operates at 400 V and contains 96 cells, with a total system capacity of 40 kWh distributed across six (6) packs. Due to manufacturing tolerances and ageing effects, a typical capacity variation of around 3% is expected at cell level. This variability is illustrated in Figure 6, which shows the distribution of cell capacities within a pack, highlighting the dispersion that drives balancing needs and associated energy losses.

As observed, even small deviations in cell capacity lead to a dispersion that requires balancing and ultimately drives energy losses at system level.

In a conventional dissipative balancing approach, surplus energy from higher-capacity cells is lost as heat, leading to approximately 170 Wh of losses per pack, or around 1 kWh per cycle at system level. By contrast, the implementation of hierarchical active balancing allows this energy to be redistributed, reducing losses to approximately 50 Wh per cycle, assuming an efficiency of around 95%. Over an estimated 100 cycles per year, this results in annual energy savings of about 95 kWh.

This KPI is considered measurable, as it can be directly assessed through data provided by the battery management system (BMS), including balancing activity, energy flows, and number of cycles, complemented by cell- and pack-level performance data. Responsibility for its definition and monitoring lies within WP3, particularly in tasks related to battery system architecture and BMS development. Monitoring is expected to be continuous at technical level, supported by BMS data acquisition during operation and testing, and consolidated through project reporting. From an economic perspective, this indicator contributes directly to the reduction of system losses and improvements in energy efficiency, translating into lower operational energy consumption and associated costs.

The second KPI addresses the reduction of maintenance and repair costs enabled by the modular multi-pack battery architecture (CM11). This KPI is derived from the system-level KPI 3 defined in the DoA ("operation and maintenance costs decrease linked to the battery compared to existing solutions"), which is here interpreted at component level. In this case, the benefit stems from the possibility of replacing individual battery packs in the event of failure, instead of substituting the entire system, as well as from the increased operational resilience, since the system can continue functioning, albeit with reduced performance, even if one pack is not available.

While this indicator reflects an important expected impact of the system design, it is not currently defined in quantitative terms and is not considered directly measurable within the project timeframe. Its assessment would require long-term data on failure rates, maintenance interventions and cost structures, which fall outside the scope of the project.

Despite these limitations, the KPI remains relevant as an indicator of expected economic impact. Its responsibility is also linked to WP3, particularly to activities related to modular design and system integration, with potential contributions from cross-cutting activities on cost and impact assessment. Monitoring is therefore qualitative, based on design choices and validation activities, and integrated into project reporting. In terms of economic relevance, it contributes to higher-level objectives related to the reduction of operation and maintenance costs and the improvement of system reliability.

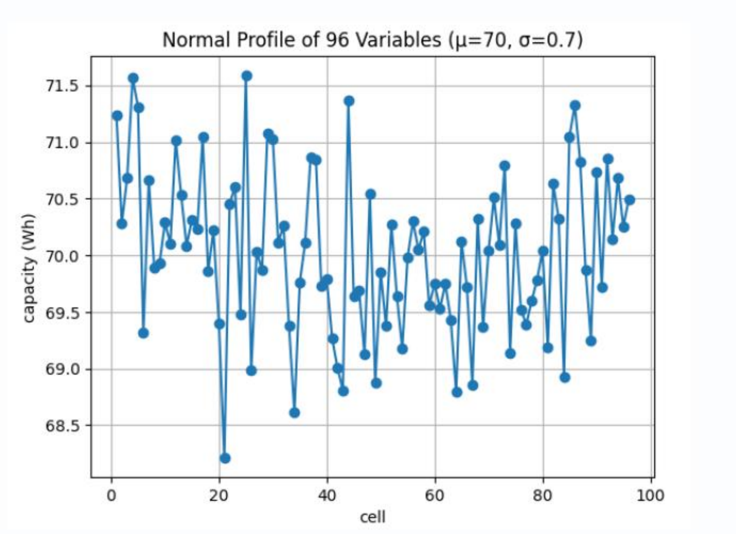


Figure 6. Cell capacity distribution within a battery pack

Table 7. Battery pack - Technical KPIs

<table>
<tr><th>Priority Ranking</th><th>KPI ID</th><th>KPI description</th><th>Unit of measurement</th><th>Target</th><th>Responsible partner</th><th>Relevant tasks</th><th>Timeframe (months)</th></tr>
<tr><td rowspan="2">Very high importance</td><td>E7</td><td>Reduction of lifecycle energy losses for battery</td><td>kWh/year</td><td>~ 95kWh/ year</td><td>CIRCE, UCL, EFT</td><td>T3.2, T3.3, T3.4, T3.5</td><td>Continuous monitoring through simulation, battery characterisation and prototype validation activities (M4–M30)</td></tr>
<tr><td>CM11</td><td>Reduction of maintenance/repair cost due to multi-pack battery</td><td>€/year</td><td>to be defined</td><td>CIRCE, UCL, EFT</td><td>T3.1, T3.2, T3.4</td><td>Qualitative assessment during prototype integration and validation phase (M30)</td></tr>
</table>

6.2 Inverter & Motor

Within the inverter and motor subsystem, the defined KPIs reflect the main performance dimensions required to optimise the electric drivetrain, particularly in terms of efficiency, integration and reliability. Their prioritisation is consistent with the overall assessment approach agreed within the project, where simulation-based evaluation is complemented, when feasible, with experimental validation at prototype level.

Among the Very High Importance KPIs, particular emphasis is placed on the reduction of lifecycle energy losses for both the inverter (E8) and the electric motor (E9), both contributing to the system-level objective defined in the DoA as KPI 19 (overall reduction in energy losses after powertrain integration and optimization), while the inverter-related KPI (E8) is also linked to KPI 8, addressing energy losses reduction in the inverter due to the selected topology. These indicators are primarily evaluated through simulation activities, supported by component characterisation and the use of inverter and motor loss models. Full lifecycle testing is not considered within the experimental scope, and therefore the assessment relies on combining modelling results with representative operating assumptions.

Responsibility for these KPIs lies within the technical work packages dedicated to power electronics and electric drive development, where continuous model refinement and parameter validation are carried out. Monitoring is therefore performed iteratively through simulation campaigns and performance analysis, with results consolidated through project reporting and formally assessed at periodic stages. From an economic perspective, improvements in these indicators are directly linked to reduced energy consumption at vehicle level, contributing to lower operational costs.

Closely related to these aspects, the KPI on inverter efficiency improvement under partial load conditions (E11) captures performance under realistic operating scenarios, where systems rarely operate at nominal conditions, and is linked to the DoA KPIs 5 and 10, addressing efficiency improvement under partial load operation and lifetime performance compared to state-of-the-art inverter technologies. In line with the agreed assessment methodology, this KPI is considered measurable through a combination of experimental validation at prototype level and simulation, with partial-load operation explicitly addressed. Its monitoring is therefore based on combined validation campaigns, ensuring that efficiency improvements are demonstrated under representative conditions. This KPI contributes significantly to overall system performance by reducing energy conversion losses during typical operation.

In addition, the KPI related to electric machine efficiency at the most frequent operating point (E12), with a target value of 0.95, introduces a more specific performance objective. This KPI is directly aligned with DoA KPI 12, focusing on electric machine efficiency under the most representative operating conditions. This indicator focuses on optimising efficiency at typical working conditions rather than peak performance and is assessed through experimental validation during motor testing and characterisation. Its contribution is directly reflected in improved drivetrain efficiency and reduced energy demand.

System-level design improvements are further addressed through the KPI on converter, machine and gearbox volume and weight reduction (M6), targeting a reduction in the range of 1–3%, and directly linked to the DoA KPI 13, which focuses on volume and weight reduction of the integrated converter, machine and gearbox system. This KPI is evaluated by comparing the measured characteristics of the developed prototype with a representative conventional reference. Responsibility for this indicator is shared across component design and system integration activities, and its monitoring is embedded within design iterations and prototype validation. Its economic relevance lies in improved vehicle efficiency and potential savings in materials and integration.

Reliability aspects are captured through KPI CM13, which is still under development and currently has no defined target value. According to project discussions, its definition is expected to be linked to aspects such as common-mode voltage effects in the motor and semiconductor reliability in the inverter. The agreed evaluation approach involves simulation-based reliability modelling, potentially complemented by experimental validation where feasible. Despite the lack of a quantified target, this KPI remains important for addressing durability, maintenance costs and lifecycle optimisation.

At a High Importance level, additional KPIs address system-level behaviour, including the reduction of common-mode current emissions and overall system efficiency improvement (ST2)), with the latter being directly linked to the DoA KPI 5 (efficiency improvement, particularly in partial load operation, vs. the state-of-the-art Si IGBT-based VSI). The reduction of common-mode currents is assessed through experimental measurements using laboratory setups with defined grounding configurations, while system efficiency is derived from a combination of experimental loss data and simulation results. These indicators contribute to improved electromagnetic compatibility and system performance, reducing indirect costs associated with inefficiencies or compliance requirements.

Finally, Low Importance KPIs focus on aspects such as manufacturability, cost reduction and environmental performance, including indicators linked to DoA KPIs such as KPI 7 (cost reduction of inverter power-electronic modules compared to state-of-the-art SiC-based solutions) and KPI 11 (CO_2 emissions reduction compared to Si-based inverters). Their evaluation is based on a combination of design assessment, prototype validation, cost estimations and simulation, including the calculation of CO_2 reduction from estimated energy savings and assumed operating conditions. Although their impact is secondary compared to higher-priority KPIs, they support broader objectives related to industrial feasibility, cost optimisation and sustainability.

Table 8. Inverter and motor - Technical KPIs

Priority Ranking	KPI ID	KPI description	Unit of measurement	Target	Responsible partner	Relevant tasks	Timeframe (months)
Very High Importance	E8	Reduction of lifecycle energy losses for Inverter	kWh/year	30 %	UT, UCL, FHNW, MTAL, UBremen	T4.2, T4.3, T4.4, T4.5, T4.6	Iterative monitoring during simulation and validation activities (M4-M30)
	E9	Reduction of lifecycle energy losses for electric motor	kWh/year	to be defined	KTH, UCL, iNetic	T5.1, T5.2, T5.3, T5.4, T5.5	Iterative monitoring during simulation and validation activities (M4-M30)
	E11	Inverter efficiency improvement, especially at partial load, vs SoA full-Si IGBT VSI	%	25 %	UT, FHNW, UBremen, MTAL, ZF	T4.2, T4.3, T4.4, T4.6	Combined simulation and prototype validation campaigns (M4-M30)
	E12	Electric machine energy efficiency in the most frequent operating point	-	0,95	KTH, UCL, iNetic	T5.2, T5.3, T5.4, T5.5	Experimental motor testing and characterisation activities (M7-M30)
	M6	Converter + machine + gearbox volume and weight reduction	%	1-3%	UT, FHNW, KTH, UCL, iNetic	T4.4, T4.6, T5.1, T5.3, T5.5	Design iterations and prototype validation stages (M4-M30)
	CM13	Reliability cost tag … (to be completed)	-	Reduction of common-mode voltage in the motor	UBremen, MTAL, UT, FHNW, MEU, ZF	T4.3, T4.5, T4.6	Reliability modelling and experimental reliability testing (M7-M30)

High Importance	S4	Reduction of common-mode current emission vs SoA full-SiC MOSFET VSI	-	30 %	UT, FHNW, UBremen, MTAL, ZF	T4.3, T4.4, T4.6	Laboratory measurements during inverter validation (M7-M30)
	ST2	System efficiency improvement	-	0,25	UT, FHNW, KTH, UCL, iNetic	T4.4, T4.6, T5.3, T5.4, T5.5	System-level simulation and experimental validation campaigns (M10-M30)
Low Importance		Manufacturability of the proposed electrical machine	-	The design respects modern machinery/tooling/manufacturing capabilities and tolerances.	iNetic, UCL, KTH	T5.1, T5.3, T5.5	Design review and prototype manufacturing phase (M4-M30)
	CM4	Cost reduction of inverter power-electronic modules vs SoA full-SiC MOSFET VSI	-	20 %	FHNW, UT, MTAL, ZF	T4.2, T4.4.1, T4.4.2, T4.6	Prototype cost estimation and validation activities (M4-M30)
		Cost reduction of the proposed electrical machine vs. conventional IPM solutions for traction	%	5-10%	KTH, UCL, iNetic	T5.1, T5.3, T5.5	Design optimisation and prototype assessment phases (M4-M30)
	ST4	CO_2 emissions reduction vs Si-based inverter	%	to be defined	UT, FHNW, UBremen, UCL	T4.2, T4.4, T4.5, T4.6	Simulation-based environmental assessment using estimated energy savings (M4-M30)

6.3 Onboard Charger

Within the Onboard Charger (OBC) subsystem, the defined KPIs reflect the key trade-offs between cost optimisation, energy efficiency and system integration, in line with the architectural decisions and validation approach agreed within WP3. The prioritisation of these indicators is closely linked to discussions on converter topology, modularity and the role of the OBC within the overall powertrain architecture, including its interaction with the battery system.

The KPI classified as Very High Importance focuses on charging cost reduction (CM12), with a target value of 20%. This indicator is strongly influenced by architectural decisions, particularly the choice between modular multi-converter approaches and more integrated single-stage solutions. As discussed during the OBC design activities, modular configurations can enhance flexibility and enable functionalities such as battery module balancing but may also lead to increased cost due to component duplication and system complexity.

In this context, the interpretation of the KPI has been refined to emphasise reductions in charger-related costs, rather than purely energy-related costs. This includes potential savings derived from system integration strategies, such as shared functionalities between charging and balancing, as well as optimised design choices that minimise hardware requirements. The KPI is considered measurable based on partners' inputs, with evaluation relying on design trade-offs, cost modelling and architectural comparison. Responsibility is associated with OBC design and integration activities within WP3, particularly Task 3.1, with continuous monitoring through simulation and system-level design decisions, and formal assessment during project reporting cycles.

At High Importance level, the KPI on lifecycle energy loss reduction for the OBC (E10), with a target value of 0.3, captures the efficiency performance of the charging subsystem, representing the OBC-level contribution to the system-level objective defined in the DoA as KPI 19: overall reduction in energy losses after powertrain integration and optimization. This indicator is evaluated through a combination of simulation, laboratory validation and subsystem testing, in line with the project-wide approach of validating performance KPIs primarily at laboratory level rather than through full vehicle demonstrations.

The assessment of this KPI is closely linked to the defined architecture of the OBC, which is currently based on an isolated single-stage AC/DC converter concept, with possible implementations including matrix or cycloconverter topologies. These design choices directly affect conversion efficiency, system complexity and integration with the battery pack.

Monitoring is therefore performed continuously through modelling and experimental validation activities, with results feeding into project reporting and periodic evaluation cycles. In addition, lifecycle energy losses are expected to be assessed in coordination with other work packages (e.g. WP6), using data generated within WP3, reinforcing the system-level nature of this KPI.

From an economic and operational perspective, this KPI contributes to improved charging efficiency and reduced energy losses, which translate into lower operational costs and enhanced overall system performance.

Table 9. On-board charger - Technical KPIs

Priority Ranking	KPI ID	KPI description	Unit of measurement	Target	Responsible partner	Relevant tasks	Timeframe (months)
Very High Importance	CM12	Charging Cost Reduction	€/kW	20%	CIRCE, UCL	T3.1	Iterative monitoring during simulation activities (M4-M15)
High Importance	E10	Reduction of lifecycle energy losses for OBC [kWh/year]	kWh/year	0,3	CIRCE, UCL	T3.1	Iterative monitoring during simulation activities (M4-M15)

6.4 Packaging & Cooling

Within the Packaging & Cooling subsystem, the defined KPIs reflect the cross-cutting nature of this domain, as performance is strongly dependent on the contribution of multiple subsystems, including the battery, inverter, motor and onboard charger. As highlighted during the QFD discussions, several KPIs can only be meaningfully assessed if they are decomposed into sub-KPIs corresponding to the contributing components, reinforcing the system-level role of WP2 in coordinating and integrating results across work packages.

Among the Very High Importance KPIs, the weight reduction at system level (M2) combines targets related to both material reduction, particularly a 50% reduction in copper usage for high-voltage wiring, and overall component-level improvements, such as a 1–3% reduction in the weight of the converter, motor and gearbox. The assessment of this KPI is inherently dependent on contributions from multiple subsystems and therefore requires decomposition into component-level indicators to ensure traceability and feasibility. Responsibility is accordingly distributed across subsystem development activities, with coordination within WP2 and strong reliance on inputs from component-level work packages. Monitoring is performed through system-level design iterations, integration studies and engineering calculations, with consolidation through project reporting. From an economic perspective, this KPI contributes directly to material cost savings, improved vehicle efficiency and reduced operational energy consumption.

Similarly, the KPI related to the efficiency of the demonstrator, expressed as extended drive range (M5), reflects overall system performance and is defined with a target value of 0.2. As discussed within WP2, this indicator cannot be assessed in isolation and must be broken down into sub-KPIs associated with the main energy-relevant components. Its evaluation therefore relies on system-level simulations and integration analyses, combining inputs from battery, inverter and motor performance. This KPI is directly linked to vehicle-level energy efficiency, with clear implications for operational costs and overall system optimisation.

The KPI on specific material intensity (ST5), which also targets a significant reduction in copper usage for the same output power, follows a similar logic. Its assessment depends on detailed tracking of material use across components and requires coordinated contributions from multiple work packages. Continuous monitoring is carried out through design optimisation, material selection and engineering calculations, with results consolidated through reporting activities. This KPI contributes not only to economic objectives through reduced material costs, but also to broader resource efficiency and sustainability goals.

In contrast, the KPI on copper use reduction in high-voltage wiring (ST7) is more directly attributable to the Packaging & Cooling subsystem and is therefore considered measurable at component level. Responsibility lies primarily within WP2 activities related to cabling, routing and integration design. Monitoring is performed through the design and validation of wiring configurations, and its economic relevance is linked to both material savings and associated weight reductions.

At the High Importance level, several KPIs further reflect the systemic nature of the subsystem. The KPI on reduction of current harmonics and electromagnetic emissions (E14) has been identified as not directly relevant for Packaging & Cooling, as it is primarily driven by inverter design. Within WP2, this KPI is therefore not actively monitored, but it may be considered indirectly through system integration constraints and compatibility requirements.

Other High Importance KPIs, such as power density increase (M1) and system efficiency improvement (ST2), also require decomposition into sub-KPIs, as their achievement depends on coordinated improvements across multiple components, with ST2 being directly linked to the DoA KPI 5 (efficiency improvement, particularly in partial load operation, vs. the state-of-the-art full Si IGBT-based VSI). While ST2 is supported by defined targets and system-level assessment approaches, M1 remains subject to further definition of quantitative targets across subsystems. Their monitoring is carried out through design, simulation and integration activities at system level, with consolidation in project reporting. These indicators contribute to improved compactness, enhanced performance and reduced operational energy consumption, reinforcing their economic relevance.

The KPI on overall environmental impact reduction (ST11) is mainly addressed outside WP2, within WP6 activities dedicated to sustainability assessment. Within the Packaging & Cooling subsystem, this KPI relies on input data related to material selection, system design and component integration, highlighting again the interdependency between work packages. Despite being primarily evaluated in WP6, its classification as High Importance reflects its role as an integrating KPI capturing system-level sustainability performance.

In addition, innovation-driven cost reduction (CM3) is also considered at High Importance level, reflecting the relevance of cost optimisation from an industrial perspective, although its quantitative assessment remains dependent on design maturity and cost modelling assumptions.

Finally, additional KPIs related to manufacturability and lifecycle aspects are considered of medium or low importance. These include manufacturability at automotive scale (CM5), TRL progression (CM6), end-of-life considerations (CM2), and maintenance and repair cost reduction enabled by modular architectures (CM11), the latter being linked to the DoA KPI 3 (operation and maintenance costs decrease linked to the battery compared to existing solutions). Their responsibility is distributed across subsystem and cross-WP activities, with monitoring performed where applicable through design development, prototyping and cost assessment. In some cases, measurability remains limited within the project scope, particularly where long-term or industrial-scale data would be required.

Table 10. Packaging and cooling - Technical KPIs

Priority Ranking	KPI ID	KPI description	Unit of measurement	Target	Responsible partner	Relevant tasks	Timeframe (months)
Very High Importance	M2	Weight reduction at system level	%	50% copper use reduction for HV wiring + 1-3% Converter, motor, gear box	CIRCE, FHDO, EFT, UCL, UT, KTH	T2.1, T2.2, T2.3, T2.5	System design iterations and final integration assessment (M1-M30)
	M5	Efficiency of the demonstrator Extended Drive Range	%	20 %	CIRCE, FHDO, EFT, UCL, UT, KTH	T2.1, T2.2, T2.3, T2.5	Continuous simulation and demonstrator validation activities (M1-M30)
	ST5	Specific material intensity	kg/kW	50% reduction of copper usage for same output power	CIRCE, FHDO, EFT	T2.1, T2.2, T2.5	Design definition and final blueprint assessment (M1-M30)
	ST7	Copper use reduction	%	50% copper use reduction for HV wiring	CIRCE, FHDO, EFT, UCL	T2.1, T2.2, T2.5	Packaging optimisation and system integration phases (M1-M30)
High Importance	E14	Reduced current harmonics & EMI (Reduction in common-mode current emissions)	-	0,2	FHDO, CIRCE, UT, UCL	T2.2, T2.3, T2.4	Experimental validation and simulation campaigns (M4-M30)
	M1	Power density increase	kW/kg, kW/L	to be defined	CIRCE, FHDO, EFT, UT, KTH	T2.1, T2.2, T2.5	Prototype packaging definition and final integration assessment (M1-M30)
	ST2	System efficiency improvement	-	to be defined	CIRCE, FHDO, UCL, UT, KTH	T2.2, T2.3, T2.4, T2.5	Simulation-based assessment and system-level

							validation (M4-M30)
	ST11	Overall environmental impact reduction	%	to be defined	CIRCE, FHDO, EFT	T2.1, T2.3, T2.5	Lifecycle and sustainability assessment during project execution (M1-M30)
	CM3	Innovation specific cost reduction at prototype level	%	0,25	CIRCE, EFT, FHDO	T2.1, T2.2, T2.5	Cost assessment during design and final blueprint definition (M1-M30)
Medium Importance	CM5	Manufacturability at automotive scale	-	to be defined	FHDO, EFT, CIRCE	T2.2, T2.4, T2.5	Prototype integration and industrial feasibility assessment (M4-M30)
Low Importance	CM2	End-of-life residual value	%	to be defined	CIRCE, EFT	T2.1, T2.5	Final sustainability and lifecycle evaluation (M1-M30)
	CM6	TRL progression compatible with industrial uptake	-	to be defined	CIRCE, EFT, FHDO	T2.1, T2.4, T2.5	Periodic project reviews and final demonstrator integration (M1-M30)
	CM11	Reduced maintenance/ repair cost due to multi-pack battery	-	0,1	CIRCE, FHDO, EFT, UCL	T2.1, T2.2, T2.5	System architecture validation and integration assessment (M1-M30)

6.5 Control & EMS

Within the Control & EMS subsystem, the KPIs have been prioritised according to their assigned importance levels based on the QFD results and the contributions from WP5.

The Very High Importance KPIs are mainly related to energy efficiency and loss reduction in the powertrain, including the reduction of lifecycle energy losses for the inverter (E8) and for the electric motor (E9). Both KPIs are considered measurable through simulation-based approaches, both contributing to the system-level objective defined in the DoA as KPI 19 (overall reduction in energy losses after powertrain integration and optimization), while the inverter-related KPI (E8) is also linked to KPI 8, addressing energy losses reduction in the inverter due to the adopted AHXS topology.

In addition, the KPI on inverter efficiency improvement, especially at partial load (E11) is included in this category and is considered measurable through experimental validation. The KPI on electric machine efficiency at the most frequent operating point (E12), with a target value of 0.95, is also considered measurable through experimental approaches and is directly aligned with the DoA KPI 12, which targets electric machine energy efficiency under the most representative operating conditions. Finally, the KPI on reduced switching and conduction losses (E13) is included, although no additional information regarding measurability or target definition is currently provided.

The High Importance KPIs include the system efficiency improvement (ST2), with a target value of 0.25, which is considered measurable through experimental validation. This KPI is directly aligned with the DoA KPI 5, targeting efficiency improvement under representative operating conditions, and reflects the overall performance of the powertrain as a system, being aligned with cross-component efficiency improvements.

The Medium Importance KPI focuses on durability aspects, specifically the reduction of degradation and improvement of inverter cycle life compared to state-of-the-art Si-based solutions (ST12). No specific target value or assessment approach has been defined at this stage.

The Low Importance KPIs include indicators related to environmental performance and system-level impacts, such as total CO_2 equivalent emissions (ST3), lifecycle energy losses (ST1), system efficiency improvement (ST2) and the reduction of common-mode current emissions (S4). These KPIs complement the higher-priority indicators by capturing broader system behaviour and impacts, although their role within the subsystem is less critical.

Among these, ST2 is directly linked to the DoA KPI 5 (efficiency improvement under representative operating conditions), while ST3 is aligned with KPI 11 (equivalent CO_2 emissions compared to Si-based inverters), and S4 is associated with KPI 6 (reduction of common-mode current emission versus state-of-the-art converter solutions), capturing efficiency, environmental and electromagnetic performance aspects at system level.

Responsibility for these KPIs is associated with the Control & EMS domain and linked to the activities of WP6, which focuses on simulation and control strategies at system level. However, this responsibility is mainly related to the evaluation and integration of results, as many of these KPIs rely on input data generated in other subsystems (e.g. inverter, motor or system integration).

Accordingly, their monitoring is based on a combination of simulation and experimental activities, depending on the KPI, with continuous assessment during model development and validation phases, and formal consolidation within the project's reporting framework.

From a system perspective, these KPIs support the evaluation of powertrain performance, efficiency and operational behaviour, complementing the subsystem-specific KPIs and contributing to the overall assessment of the ODYSSEV powertrain.

Table 11. Control & EMS - Technical KPIs

Priority Ranking	KPI ID	KPI description	Unit of measurement	Target	Responsible partner	Relevant tasks	Timeframe (months)
Very High Importance	E8	Reduction of lifecycle energy losses for Inverter	kWh/year	to be defined	CERTH, FHNW, CIRCE, UCL, UT	T6.1, T6.2, T6.3 T6.4	Continuous simulation-based assessment during model development and validation (M16-M42)
	E9	Reduction of lifecycle energy losses for electric motor	kWh/year	to be defined	CERTH, FHNW, CIRCE, UCL	T6.1, T6.2, T6.3 T6.4	Continuous simulation-based assessment during model development and validation (M16-M42)
	E11	Inverter efficiency improvement, especially at partial load,	.	to be defined	FHNW, CERTH, UT, UCL	T6.3, T6.4, T6.5	Experimental validation and control strategy testing (M21-M42)

		vs SoA full-Si IGBT VSI					
	E12	Electric machine energy efficiency in the most frequent operating point	.	0,95	CERTH, UCL, FHNW	T6.1, T6.3 T6.4, T6.5	Experimental validation and demonstrator assessment (M19-M42)
	E13	Reduced switching & conduction losses	.	to be defined	FHNW, CERTH, UT	T6.1, T6.3, T6.4	Control optimisation and simulation-based assessment (M16-M42)
High Importance	ST2	System efficiency improvement	.	0,25	FHNW, CERTH, CIRCE, UCL, UT	T6.1, T6.2, T6.3, T6.4, T6.5	Continuous assessment through simulation and experimental validation (M16-M42)
Medium importance	ST12	Reduced degradation and improvement of inverter cyclelife Vs Si-based inverter	number of cycles or years to end of life	to be defined	FHNW, CIRCE, CERTH, UT	T6.2, T6.3, T6.4	Reliability modelling and lifecycle assessment (M16-M42)
	ST3	Total CO_2 equivalent emissions	kg CO_2eq/kW]	to be defined	CIRCE, Q-PLAN, FHNW	T6.2, T6.6	Sustainability modelling and final impact assessment (M16-M42)
	ST1	Reduction of lifecycle energy losses	kWh/year	to be defined	CIRCE, CERTH, FHNW	T6.1, T6.2, T6.3, T6.4	Energy modelling and KPI assessment during simulation and validation phases (M16-M42)
	ST2	System efficiency improvement	.	to be defined	FHNW, CERTH, UT	T6.3, T6.4, T6.5	Simulation and experimental validation of control strategies (M21-M42)
Low importance	S4	Reduction of common-mode current emission vs SoA full-SiC MOSFET VSI	.	30 %	CERTH, FHNW, CIRCE, UCL, UT	T6.1, T6.2, T6.4	Continuous simulation-based assessment during model development and validation (M16-M42)

7. Deviations and risks

This section summarizes the main technical aspects that remain subject to further definition and the associated risks identified at the current stage of the project. While the overall system concept and responsibilities have been established, several key parameters related to component sizing, thermal management, vehicle integration, control architectures, and communication interfaces require additional clarification before detailed design activities can be finalized. As agreed during the Steering Committee meeting held on 23 June 2026 and indicated in meeting minutes, all outstanding issues are expected to be resolved through the planned activities and decisions leading up to the next General Assembly in October 2026.

7.1 Summary of Technical Aspects for Further Definition

The following subsection provides an overview of the open technical aspects and identifies the corresponding Work Packages responsible for addressing them. Table below organizes them per component and states the partners in charge for their definition.

Table 12. Technical aspects for further definition.

Battery pack	**Further definition**
The space allocated for the battery ○ Available installation volume and packaging envelope to be defined.	EFT in WP3
Constraints on the mass of the battery system ○ Acceptable battery mass to be specified. ○ Additional chassis and suspension constraints required for final design definition.	EFT in WP3
Preferences or requirements of the cooling system ○ Cooling capacity and thermal management strategy depend on the final operating conditions. ○ Cooling architecture (e.g. liquid cooling, vehicle thermal integration) to be defined.	FHDO in WP2
Driving cycle definition ○ Representative test driving cycle still to be defined. ○ Required for battery sizing, cell selection, performance assessment, and thermal load estimation.	INETIC & FHDO in WP3
Battery pack design ○ Installation space, dimensions, and packaging constraints to be defined. ○ Vehicle packaging information required to support battery integration.	UCL in WP3
Battery capacity ○ Capacity under evaluation within the 10–20 kWh range. ○ Final value to be aligned with performance, thermal, integration, and demonstrator requirements.	UCL in WP3
Space and Layout Definition ○ Available space and component layout require further definition. ○ Integration studies needed to finalise component positioning and system architecture.	EFT in WP2
Motor and Inverter	**Further definition**
Parallelisation of the 25-kW modules	UT in WP4

○ Further definition of the implementation and validation strategy for the parallel operation of the four 25 kW power modules is required. ○ Control and protection strategies must address circulating currents to ensure stable and reliable operation. ○ The parallelisation approach may enable the use of multiphase machine architectures (e.g. 6-phase or 12-phase) as part of future system optimisation activities.	
Motor Design and Safety ○ Final motor configuration remains under evaluation. ○ Safety, reliability, fault-tolerance, and protection concepts to be assessed.	KTH and UCL in WP5
Packaging and Cooling systems	**Further definition**
Cooling specifications ○ Cooling requirements (flow rates, pressures, temperatures) to be defined based on subsystem thermal loads. ○ Cooling resource allocation and overall cooling architecture to be optimised.	FHDO in WP2
Global Cooling Architecture ○ Number of cooling loops and subsystem integration strategy to be defined. ○ Final architecture dependent on system-level trade-offs and thermal analyses.	FHDO in WP2
Thermal Load Assessment ○ Thermal loads for battery, inverter, motor, OBC, and HV-LV converter to be quantified. ○ Additional modelling and representative operating scenarios required.	All partners in WP2
Thermal Control Strategy ○ Control strategy for pumps, valves, and energy management functions to be defined. ○ Final approach dependent on the selected cooling architecture	FHDO and EFT in WP2
Coolant Selection ○ Coolant type and operating characteristics to be selected based on thermal and HV requirements.	FHDO, EFT and UCL in WP2
Housing and Packaging Specifications ○ Housing dimensions, packaging constraints, and cooling integration requirements to be defined.	FHDO and EFT in WP2
CAN Bus Network Information ○ Vehicle communication architecture and network interfaces to be consolidated.	EFT and Morgan
Hydraulic System Design ○ Hydraulic layout and flow distribution dependent on final packaging definition.	FHDO and EFT in WP2
Pump Sizing and Configuration ○ Pump sizing and configuration to be defined following thermal and hydraulic analyses.	FHDO in WP2
Cooling Interfaces ○ Cooling interface requirements to be aligned across subsystems.	FHDO and EFT in WP2
Heat Exchanger Integration ○ Heat exchanger sizing and integration dependent on thermal loads and packaging constraints.	FHDO and EFT in WP2

Vehicle Integration Inputs ○ Vehicle packaging, installation space, and component layout information required.	EFT in WP2
Inverter and HV-LV Converter Integration ○ Interfaces, packaging requirements, and integration constraints to be consolidated.	All partners in WP2
Control and EMS	**Further definition**
Communication Protocol Definition ○ Communication architecture and data exchange requirements between vehicle subsystems to be defined. ○ Interface specification required to establish signals, update rates, and integration requirements.	CERTH and EFT in WP6
Sensor Architecture Definition ○ Sensor architecture and measurement requirements to be consolidated. ○ Monitoring, diagnostics, and update rates to be defined for system control and safety.	CERTH and EFT in WP6
Cooling Control Integration Strategy ○ Thermal management control strategy to be defined based on the final demonstrator architecture. ○ Integration of VCU, BMS, thermal management, and powertrain controllers to be consolidated.	FHDO and EFT in WP6
Advanced Control Functions ○ Advanced control functions to be developed and validated through simulation and testing. ○ Scope and implementation level to be refined during future development phases	CERTH, FHNW, KTH and UCL in WP6
Active Short-Circuit Protection ○ Protection and fault-management strategies for the motor–inverter system to be defined. ○ Safe and reliable operation under fault conditions to be ensured.	FHNW, KTH and UCL in WP6
Vehicle Model and Data ○ Vehicle integration, packaging, communication, and installation data required to support system design. ○ Integration opportunities and constraints to be assessed.	EFT in WP6
Vehicle-Level Communication Architecture ○ Vehicle communication architecture to be consolidated. ○ Communication requirements across subsystems to be coordinated.	EFT and CERTH in WP6
Thermal Management Control Architecture ○ Thermal management control architecture to be defined. ○ Interaction between cooling systems and control functions to be established.	FHDO in WP6
Demonstrator-Level Control Integration ○ Subsystem controller integration strategy to be defined. ○ Coordinated operation and compliance with safety and performance requirements to be ensured.	EFT and CERTH in WP6

7.2 KPI risks

Table below highlights potential risks to project KPIs arising from the current level of uncertainty. It presents the KPIs whose assessment is currently not defined because: either their target values have not yet been established; or some of the information required for their measurement is not yet available since they require tracking across multiple components and/or coordinated inputs from different work packages. Continuous monitoring and follow-up actions are therefore required to ensure that the missing information is provided, and the corresponding target values are established in due time. Associated parters, and WP where the KPI will be developed, are assigned.

Table 13. KPIs whose assessment is at risk.

KPI	Definition	Missing info	Responsible	WP assigned deployment
CM11 (Battery pack)	Reduction of maintenance/repair cost due to multi-pack battery	Not currently defined in quantitative terms and is not considered directly measurable within the project timeframe. Its assessment would require long-term data on failure rates, maintenance interventions and cost structures, which fall outside the scope of the project.	CIRCE, UCL, EFT	WP3
CM13 (Inverter & Motor)	Reliability cost tag	Lack of a quantified target. Its evaluation will involve simulations potentially complemented by experimental validation. Its definition is expected to be linked to aspects such as common-mode voltage effects in the motor and semiconductor reliability in the inverter.	-	-
E9 (Inverter & Motor)	Reduction of lifecycle energy losses for electric motor	Target value to be defined. It will depend on simulation activities, supported by component characterization and the use of inverter and motor loss models. Full lifecycle testing is not considered.	KTH, UCL, iNetic	WP5
ST4 (Inverter & Motor)	CO_2 emissions reduction vs Si-based inverter	Target value to be defined. Calculation of CO_2 reduction value from estimated energy savings and assumed operating conditions will be required.	UT, FHNW, UBremen, UCL	WP4
M1 (Packaging & Cooling)	Power density increase	Subject to further definition of quantitative targets.	CIRCE, FHDO, EFT, UT, KTH	WP2
ST2 (Packaging & Cooling)	System efficiency improvement	Subject to further definition of quantitative targets.	CIRCE, FHDO, UCL, UT, KTH	WP2
ST11 (Packaging & Cooling)	Overall environmental impact reduction	Subject to further definition of quantitative targets.	CIRCE, FHDO, EFT	WP2

CM3 (Packaging & Cooling)	Innovation specific cost reduction at prototype level	Quantitative assessment remains dependent on design maturity and cost modelling assumptions.	CIRCE, EFT, FHDO	WP2
CM5 (Packaging & Cooling)	Manufacturability at automotive scale	Measurability remains limited within the project scope. Prototype integration and industrial feasibility assessment would be required.	FHDO, EFT, CIRCE	WP2
CM2 (Packaging & Cooling)	End-of-life residual value	Final sustainability and lifecycle evaluation are needed to achieve measurability.	CIRCE, EFT	WP2
CM6 (Packaging & Cooling)	TRL progression compatible with industrial uptake	Measurability remains limited within the project scope. Final demonstrator integration would be required.	CIRCE, EFT, FHDO	WP2
E8 (Control & EMS)	Reduction of lifecycle energy losses for Inverter	Definition of quantitative targets is required.	CERTH, FHNW, CIRCE, UCL, UT	WP6
E9 (Control & EMS)	Reduction of lifecycle energy losses for electric motor	Definition of quantitative targets is required.	CERTH, FHNW, CIRCE, UCL	WP6
E11 (Control & EMS)	Inverter efficiency improvement, especially at partial load, vs SoA full-Si IGBT VSI	Definition of quantitative targets is required.	FHNW, CERTH, UT, UCL	WP6
E13 (Control & EMS)	Reduced switching & conduction losses	No additional information regarding measurability or target definition is currently provided.	FHNW, CERTH, UT	WP6
ST12 (Control & EMS)	Reduced degradation and improvement of inverter cycle life Vs Si-based inverter	Rely on input data generated in other subsystems (inverter)	FHNW, CIRCE, CERTH, UT	WP6
ST3 (Control & EMS)	Total CO_2 equivalent emissions	No specific target value has been assigned.	CIRCE, Q-PLAN, FHNW	WP6
ST1 (Control & EMS)	Reduction of lifecycle energy losses	Rely on input data generated in other subsystems (e.g. inverter, motor or system integration).	CIRCE, CERTH, FHNW	WP6

8. Conclusions and next steps

Although Task T2.1 has successfully established a common powertrain architecture, selected the 1200 V reference voltage level, and defined a project-wide KPI framework, a significant part of the work ahead, through following technical activities, will focus on resolving the technical aspects that remain open and will ultimately determine the final system design.

The main uncertainties are currently related to the integration of the powertrain into the demonstrator vehicle. Key information is still required regarding the available installation space, mass constraints, component layout, and the final battery architecture. The battery capacity is still under evaluation and must be balanced against power requirements, thermal limitations, vehicle integration constraints, and demonstrator objectives. In addition, the definition of the representative driving cycle remains a critical pending activity, as it will directly influence battery sizing, thermal load estimation, component selection, and performance validation.

Another major area requiring further development is overall thermal management and cooling architecture. Important elements such as thermal load calculations, coolant flow rates, operating temperatures, hydraulic system design, coolant selection, heat exchanger integration, and thermal control strategies are still to be defined. The resolution of these issues will be essential to ensure safe and efficient operation of the powertrain under both high-power driving conditions and ultra-fast charging scenarios.

Within the motor and inverter subsystem, further work is required to define the parallelization strategy of the power modules, validate protection and safety concepts, and finalize key aspects of the motor design. These activities will be crucial to demonstrate the technical feasibility, reliability and robustness of the proposed high-voltage architecture.

From a control and system integration perspective, additional effort is needed to consolidate the communication architecture, CAN protocols, advanced control functions, controller integration strategies, and the coordination between the Energy Management System and the thermal management system. These developments will be essential to achieve a fully integrated and reliable vehicle control architecture capable of ensuring seamless interaction between all subsystems.

Finally, although a comprehensive KPI framework has been established, several indicators still lack fully defined target values, assessment methodologies, or the data required for their evaluation. Continued collaboration between work packages will therefore be necessary to complete these definitions, reduce monitoring risks, and ensure a consistent and measurable assessment of project progress that will be reflected in following deliverables resulting from WPs and technical reports.

Consequently, the next phase of the project should focus on closing these technical gaps, consolidating partner responsibilities, and generating the missing design and validation inputs required to move from preliminary specifications to detailed subsystem designs, lab validation levels, physical demonstrator configuration and final reference architecture. Completing these activities will provide the foundation for the subsequent stages of integration, testing, and demonstrator validation within the ODYSSEV project.

9. References

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