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Eco-operated, Modular, highly efficient, and flexible multi-POWERtrain for long-haul heavy-duty vehicles

Acronym: **EMPOWER**

Grant Agreement No.: **101096028**

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Written by	Michele MICCIO (FPT) Imad MATRAJI (FMF) Leonidas TSIKONIS (FMF) Giacomo MANCA DI VILLAHERMOSA (FMF) Niklas GUENTERT (FMF) Michael STRIEDNIG (FMF) Leonardo CHIACCHIARARELLI (FMF)	2023-09-29 to 2024-10-31
Checked by	Manasa SRIDHAR (FMF) Dragan SIMIC (AIT) Claudio MEZZA (IVECO)	2024-10-21 to 2024-10-31
Approved by	Michele MICCIO (FPT) Neeta KHARE (FPT)	2024-11-12
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Publishable Executive Summary

The EMPOWER project aims to revolutionize the transport sector by developing two modular and flexible Zero-Emission Heavy-Duty Vehicles (ZE HDVs) with a Gross Vehicle Weight (GVW) of at least 40 tons. These vehicles include a Fuel Cell Electric Vehicle (FCEV) suitable for long-haul operations with a maximum unrefuelled range of 750 km, and a Battery Electric Vehicle (BEV) designed for regional distribution with a maximum un-recharged driving range of 400 km.

The project focuses on achieving a maximum load capacity of no less than 90 %, making these vehicles ready to enter the market by 2029 with an equal Total Cost of Operation (TCO) as 2020 engine-based solutions, assuming a production volume of more than 10,000 vehicles per year. Key areas of focus include modularity, scalability, and competitiveness in terms of performance, cost, and customer acceptance.

The deliverable of Task 2.2, which is the focus of this document, consists of a fuel cell system designed to achieve the vehicle performance targets. Chapter 1 provides an introduction to the project and the task; Chapter 2 focuses on the vehicle definition and its impact on the requirements for the fuel cell system in relation to the work performed in D1.1; Chapter 3 describes in detail the design choices and driving principles behind the definition of the system and its components as well as the SW developed for this system and the safety and functional safety implications.

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Abbreviations and Nomenclature

Table 1: Abbreviations and Nomenclatures

Symbol or Short name	Description
ADC	Amperes Direct Current
ASIL	Automotive Safety Integrity Level
BEV	Battery Electric Vehicle
BMS	Battery Management System
Cab	Cabin
CAD	Computer Aided Design
DC	Direct Current
DC/DC	Direct Current to Direct Current Converter
EMC	Electromagnetic Compatibility
EV	Electrical Vehicle
e-VECOP	Electrified Vehicle Control Platform
FCCU	Fuel Cell Control Unit
FCEV	Fuel Cell Electric Vehicle
FCS	Fuel cell system
FP	Full Pneumatic
FTA	Fault Tree Analysis
GCW	Gross Combination Weight
GVW	Gross Vehicle Weight
HDV	Heavy-Duty Vehicles
HS	High Side of the DC/DC converter
HSS	Hydrogen Storage System
HV	High Voltage
HVAC	Heating, Ventilation and Air Conditioning
HVI	Human Vehicle Interaction
HW	Hardware
IG	Iveco Group
IGBT	Insulated-gate bipolar transistor
IMD	Isolation Monitoring Device
IPMSM	Interior Permanent Magnet Synchronous Machine

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IVG	Iveco Group
LCA	Life Cycle Assessment
LCV	Light Commercial Vehicle
LS	Low Side of the DC/DC converter
LV	Low Voltage
MBD	Model Based Development
MD	Medium-Duty
P	Pneumatic
PDU	Power Distribution Unit
PTO	Power take-off
SiC	Silicon Carbide
SOC	State of charge
SW	Software
TCO	Total Cost of Operation
TMS	Thermal management system
TRL	Technology Readiness Level
UC	Use-Case
V2G	Vehicle-to-Grid
VCU	Vehicle Control Unit
VDC	Volt Direct Current
VECTO	Vehicle Energy Consumption Calculation Tool
VP	Iveco vehicle identification code
WP	Work Package
ZE-HDV	Zero-Emission Heavy-Duty Vehicles
ZEV	Zero Emission Vehicle

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1 Introduction

In 2020 the CO_2 emissions of the transport sector in the EU-27 accounted for approximately 27 % of the total emissions [1]. Thereof about 5.6 % are produced by Heavy Duty Vehicles (HDVs) and buses [2]. However, the year 2020 is, due to COVID-19 related restrictions and lockdowns and therefore altered mobility patterns, not very representative. Analyses of the last months in 2020 show that road transport activity was expected to recover to pre-COVID-19 levels in 2021, with CO_2 emissions rising to just 5 % below the 2019 level [3]. Therefore, this sector calls for a massive shift to zero tailpipe emissions to achieve full carbon neutrality by 2050. A study conducted by the European Automobile Manufacturers' Association (ACEA) found out, that in 2020 about 6.2 million medium and heavy-duty commercial vehicles were on the EU's roads [4]. Approximately 96.3 % of these trucks ran on diesel fuel, 0.7 % on petrol and only 0.24 % were zero-emission, providing potential for the transformation of the transport sector to ZE HDVs to reach carbon neutrality by 2050.

The objective of EMPOWER is to deliver two modular and flexible ZE HDVs of VECTO group 9 with a GVW of at least 40 tons, both at TRL 8 level:

- a Fuel Cell Electric Vehicle (FCEV), suitable for long-haul operation conditions with a maximum unrefuelled range of 750 km;
- a Battery Electric Vehicle (BEV) vehicle, designed for regional distribution mission profiles with a maximum un-recharged driving range of 400 km.

The **ambition of EMPOWER** involves the development, implementation, and demonstration of these vehicles at TRL 8, guaranteeing a maximum load capacity of not less than 90 %. They will be compared to conventional trucks of the same vehicle class, making them ready to enter the market in 2029 with equal Total Cost of Operation (TCO) as 2020 engine-based solutions, assuming a production volume of more than 10,000 vehicles/year.

A particular attention will be focused on:

- **Modularity,** between different vehicles with specific electrification technology;
- **Scalability** of content under development with possible integration into other applications (even outside project perimeter);
- **Competitiveness** of product and technology in terms of performance, cost, automotive manufacturing, customer acceptance.

The products that will be presented in the current deliverable (D2.2) contribute positively to the achievement of EU CO_2-targets, depending on customer acceptance and sales volumes. The product specifications will be detailed, and the choice of selected concepts explained, to show how these fit into the project context.

1.1 Scope and objectives

The aim of this document is to present and describe the deliverable of Task 2.2 consisting of a fuel cell system designed to achieve the vehicle performance targets.

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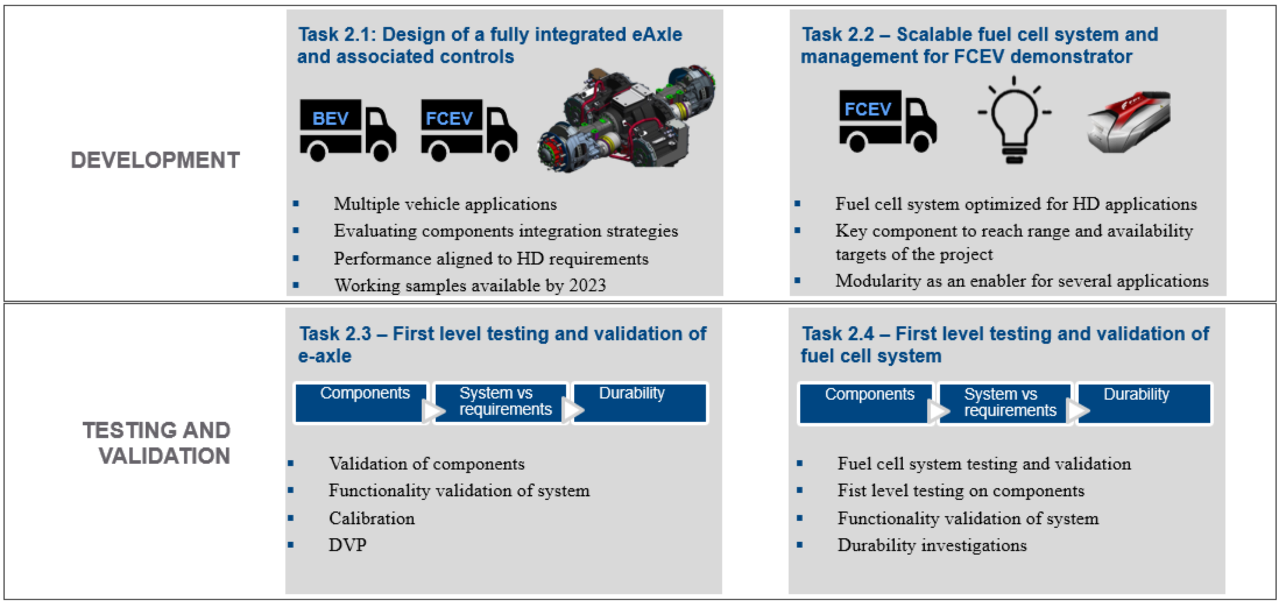

Figure 1: Overview of Tasks in WP2.

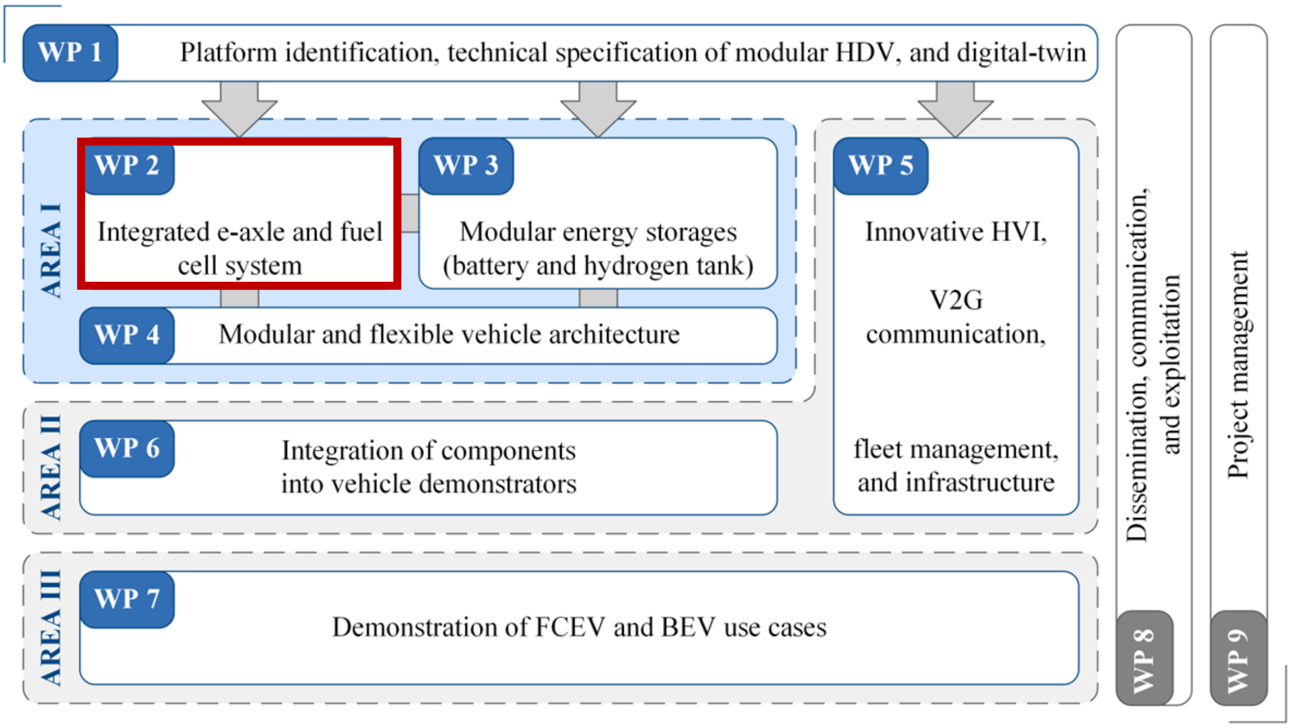

Figure 2: EMPOWER work packages diagram.

The presented solutions are based on the fulfilment of the nine main objectives of EMPOWER (see Figure 3), moreover, the defined vehicle platform allows the installation of modular (Battery Electric or FC-Electric) powertrain solutions, exploiting the scalability and modularity of the installed power units. This aspect allows cost efficient solutions for any kind of dedicated mission.

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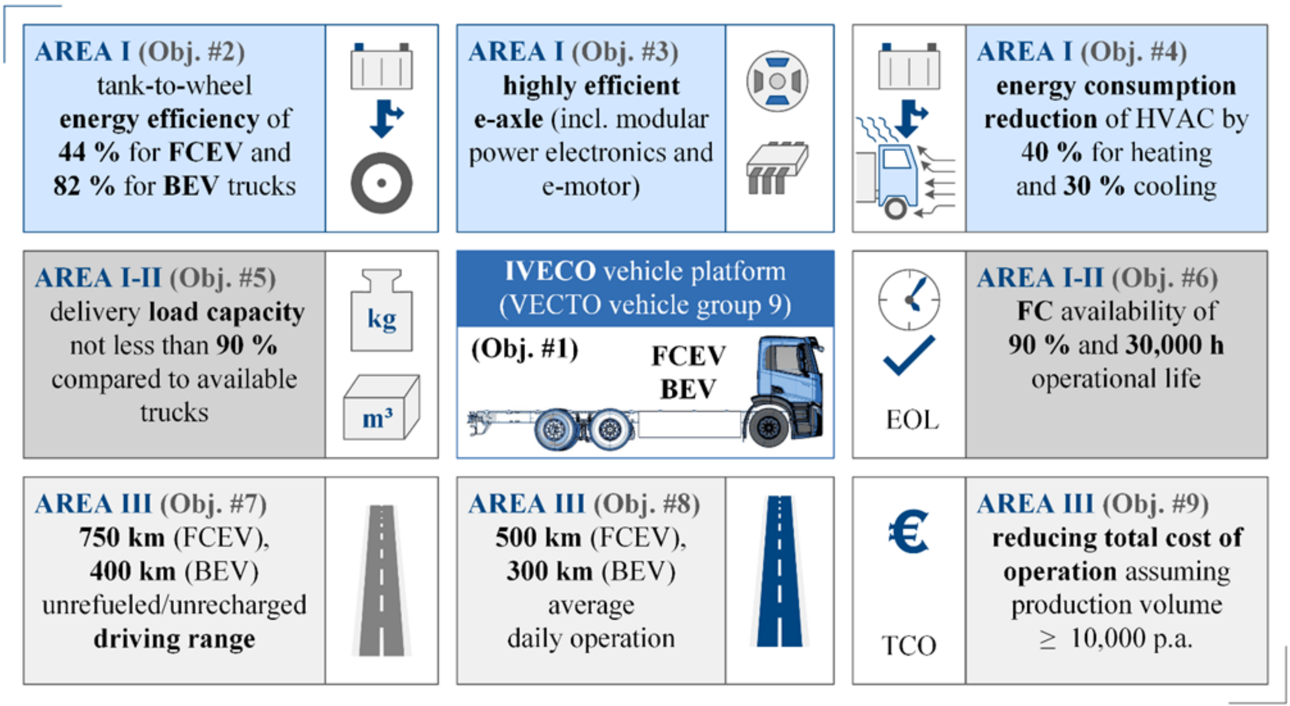

Figure 3: Nine EMPOWER objectives.

EMPOWER has three AREAs in which its activities take place. AREAs I and II develop the modular and scalable vehicle concept, a highly efficient e-axle, an electric braking energy recovery system, an efficient HVAC system based on the refrigerant CO_2 combined with infrared panels for efficient cabin heating, and an innovative HVI that provides functionalities like eco-routing and predictive maintenance.

AREA III deals with the six-month demonstration of the FCEV and BEV demonstrators at TRL 8, making the EMPOWER technology ready to approach the market by 2029.

Nine main objectives have been identified and separated into several distinctive key features developed in EMPOWER.

Table 2: EMPOWER objectives and KPIs.

Topics	SotA 2022	KPIs	EMPOWER target	AREA	EMPOWER key features (contributing to the specific objective)	Target TRL	Demonstrator platform
FCEV and BEV demonstrators **(Obj. #1)**	diesel long-haul and regional distribution vehicles	↑	zero-emission long-haul and regional distribution vehicles	I	re-designed and innovative components, modularity, and digital twin models	TRL 8	FCEV & BEV
				II	new improved HVI, eco-routing and assistance, V2G communication	TRL 7	
				III	demonstrators (FCEV and BEV) and corresponding LCA of the vehicles	TRL 8	

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tank-to-wheel energy efficiency **(Obj. #2)**	40 % for FCEV[1] 70 % for BEV[2]	+4 % +12 %	44 % for FCEV 82 % for BEV	I	FC continuous power 250 – 300 kW	TRL 7	FCEV
				I	next-generation power electronics		FCEV & BEV
				I	e-motor continuous power 350 – 540 kW[3]		FCEV & BEV
				I	integrated and efficient multi-speed transmission		FCEV & BEV
efficiency and modularity of e-axle **(Obj. #3)**	95 % peak efficiency[1]	+1.5 %	96.5 % peak efficiency	I	functionally integrated e-motor combined with modular electrified braking system	TRL 8	FCEV & BEV
				I	improved power electronic solution		
HVAC system power **(Obj. #4)**	5 kW heating 8 kW cooling	-40 % -30 %	3 kW heating 5.6 kW cooling	I	infrared radiative panels	TRL 7	FCEV & BEV
				I	CO_2-based HVAC system		
				I	thermal insulation and optimised energy management of the truck cabin		
delivery load capacity **(Obj. #5)**	100 %	≤ -10 %	≥ 90 %	I-II	verify targeted delivery load capacity of ≥ 90 % compared to SotA vehicles	TRL 8	FCEV & BEV
operation lifetime of FC **(Obj. #6)**	20,000 hrs[4]	+50 %	30,000 hrs	I-II	testing and verification of FC operational life for a safe and efficient operation under real-life driving conditions	TRL 7	FCEV
maximum driving range **(Obj. #7)**	400 km[5]	+87 %	750 km FCEV	III	unrefuelled maximum driving ranges	TRL 8	FCEV
	300 km[6]	+33 %	400 km BEV	III	unrecharged maximum driving ranges		BEV
daily average driving range **(Obj. #8)**	n.a.		500 km FCEV	III	500 km average daily driving range in real-world long-haul mission	TRL 8	FCEV
			300 km BEV	III	300 km average daily driving range in real-world regional distribution mission		BEV
total cost of operation **(Obj. #9)**	Diesel 2020 long-haul 2.4 ct/tkm Diesel 2020 reg. Distr. 2.5 ct/tkm	FCEV -15.6 % BEV -26.4 %	FCEV 2.0 ct/tkm BEV 1.8 ct/tkm	III	TCO reduction analysis of demonstrators assuming a mass production volume of ≥ 10.000 vehicles/year	n.a.	FCEV & BEV

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1.2 Timeline

The following timeline (Table 3) focuses on WP2 and its Tasks, showing how they are located with respect to the entire program. Task 2.1 and Task 2.2 have been closed and they are instrumental for the execution of Tasks 2.3 and 2.4; Task 2.1 is described in the deliverable document 2.1 while Task 2.2 is the focus of this document, and the details are described in the following chapters. Based on inputs and targets identified during the execution of WP1, Task 2.2 has been started in 2023 to design a fuel cell system, source all the needed components and work on the development of the needed SW functionalities to have a completely built system to perform the validation activity.

Task 2.3 consists in the first level testing and validation of e-axle and Task 2.4 consists of first level testing and validation of fuel cell system; both activities have been started and will be object of D2.3 in 2025.

Table 3: Project timing status.

WP / Task leader	EMPOWER gantt chart		Year:	2023				2024				2025				2026			
			Project quarter:	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
FPT	WP2	Integrated e-axle and fuel cell system																	
FPT	Task 2.1	Design of fully integrated e-axle and associated controls																	
FMF	Task 2.2	Scalable fuel cell system and - management for FCEV demonstrator																	
FMF	Task 2.3	First level testing and validation of e-axle																	
FMF	Task 2.4	First level testing and validation of fuel cell system																	

1.3 Methodology

The development and design of a fuel cell system requires a structured, multi-phase approach that balances performance, cost, and integration challenges. This process typically follows several key stages, from defining system requirements to optimizing the integration of the fuel cell stack and balance of plant components (Figure 4). The following description outlines the critical steps taken for the development of the fuel cell system described in this document.

The first step has been to identify the specific needs and constraints of the application described in D1.1 and tightly connected with the overall performance targets of the EMPOWER project. This includes defining the required power output, operational lifespan, and environmental conditions under which the system will operate as well as weight and volume allowable for integration. Key performance indicators (KPIs) such as efficiency, power density, and H2 consumption have also been established, along with regulatory and safety requirements that govern homologation, durability, and safety.

The next step involves defining the overall architecture of the fuel cell system, considering that major choices such as the type of fuel cell (PEM Fuel Cell) and supply of Hydrogen (Gaseous Hydrogen) have been taken as starting point and already described in the proposal for the project. The major focus in this step is planning for the balance of plant (BoP) components, such as air supply systems, cooling circuit and hydrogen recirculation concept. To achieve this goal, the focus shifts to sourcing commercially available components, or components

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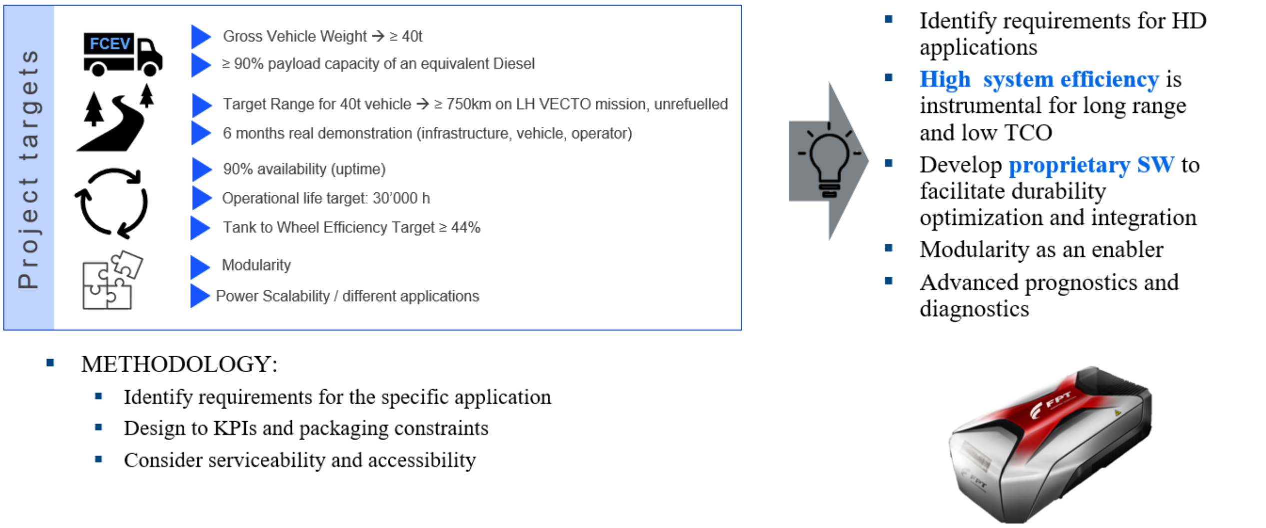

Figure 4: Overview Targets and Methodology.

under development, that meet the system's performance requirements; the starting point involves market research and suppliers' discussions to identify stacks and stacks assemblies (power modules) that can potentially satisfy the targets at system level. Key considerations include component compatibility, cost, availability, and technical performance. Close collaboration with suppliers is essential to gather detailed specifications and ensure compatibility with the intended system design. Based on specific operating conditions required on potentially viable stacks, several BoP components are evaluated; with the key components identified, system modelling and simulation are carried out to evaluate the performance of different fuel cell system configurations under various operating conditions. Thermodynamic models are developed to predict electrochemical performance, including efficiency, fuel consumption, and heat generation. Iterative simulations are performed to assess potential configurations and optimize the system for performance targets (Figure 5). Based on the results, the configuration is selected to achieve the KPIs as well as the timing of the activity.

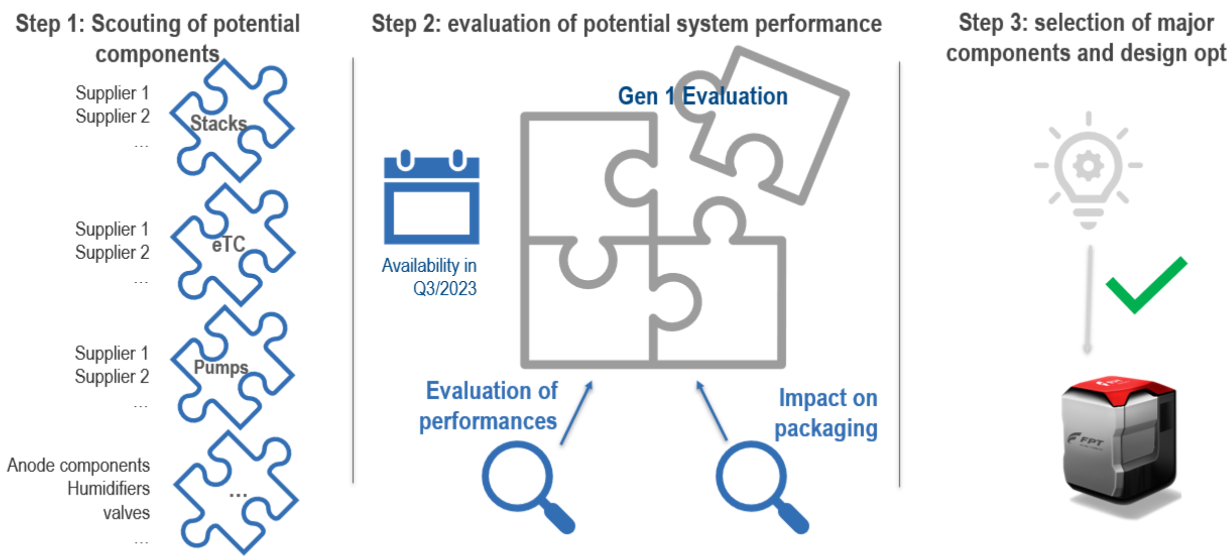

Figure 5: Overview of step-by-step methodology process

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The results of the modelling phase and components selection inform the optimization of the system to meet the design KPIs. This involves adjusting various parameters, such as overall space claim, water management, structural integration, reduction of pressure losses in air, H_2 and cooling lines. Mechanical integration of the fuel cell stack and balance of plant components is a critical phase of the design process. The goal is to create a compact, modular system layout that facilitates ease of assembly, maintenance, and operational reliability. Thermal management is a major concern, particularly for higher-power applications, and requires close collaboration between the fuel cell design team and the vehicle integration team to manage heat generated during operation. Mechanical robustness is also essential, requiring the design of enclosures that protect the system from environmental factors such as vibration, shock, and corrosion.

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2 Requirements Definition

2.1 Vehicle Architecture and Performance Targets

The architecture that has been chosen for the Fuel Cell Electric Vehicle (FCEV) is a 6x2 rigid truck with flexible wheelbase depending on the application. This is the same solution adopted for the BEV concept. For this kind of application, a sleeper cab has been foreseen (driver staying with the truck over longer periods, including overnight stay, hence cabin space is larger and allows for additional comfort, with dedicated features like storage boxes, bed, etc.), but thanks to modularity it can be easily adapted to a day cab solution.
Several components can be taken as carryover from the diesel configuration (e.g. front axles, suspensions, tag-axles, trailer connections) while other systems and applications can be taken or adapted for fuel cells integration from the BEV concept, for example:

- Batteries;
- e-axles;
- power control architecture;
- electronic vehicle control systems.

2.2 Packaging Requirements Fuel Cell System

This chapter delves into a critical aspect of this funded project on advancing fuel cell technology, modularity, and performance targets. As one of the major goals of the EMPOWER project, navigating the ever-evolving landscape of sustainable transportation, the ability to adapt and customize fuel cell systems to various vehicle platforms while maintaining stringent performance standards is paramount. In this chapter, the methodologies employed to identify the dimensions suitable for different vehicle platforms are identified and the performance criteria in terms of power and efficiency to meet the project's overarching objectives are defined.

Modularity gives the possibility to fit the same fuel cell to diverse vehicle platforms. The first step to achieve modularity, is to carry on a comprehensive study to identify the critical dimensions for the applications to be considered in addition to the target vehicle of the project; the priority is to equip the EMPOWER vehicle with the necessary number of systems to deliver the target power. The possibility to install the system in other applications is crucial for competitiveness and will be explored as part of the design phase. Modularity strategies on component levels will also be evaluated.

Leveraging advanced CAD modelling and simulation tools, the key factors are explored influencing system size and shape, in particular the activities started from stack configurations analysing both horizontal and vertical orientations, to determine the most space-efficient layout while ensuring performance targets.

2.3 Performance Requirements Fuel Cell System

As reported in the D1.1, power and efficiency meeting the performance targets for the FCEV of the EMPOWER project necessitate a thorough understanding of the power demands across different vehicle classes. To this end, a parallel workstream was pursued, focused on identifying the required power output for each application; the numbers anticipated in the preparation of the WP2, were confirmed by the simulation activities, confirming the need to develop a high power and highly efficient system to minimize the H_2 consumption. The H_2 consumption has a double impact: it heavily affects operational costs, and it defines H_2 storage capacity needs for a given mission.

The identified targets for fuel cells, are pointing to have a 150 kW to 200 kW system, with unprecedented efficiencies, above 50 % also in the least efficient points. This will allow high flexibility and configuration potential:

- 1X system configuration, will allow very good efficiency levels and enough power to cover mountain mission demands, while having a moderate impact on vehicle weight and overall system cost;

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- 2X system will allow for outstanding efficiency level, unseen power availability at the expense of increased weight and cost.

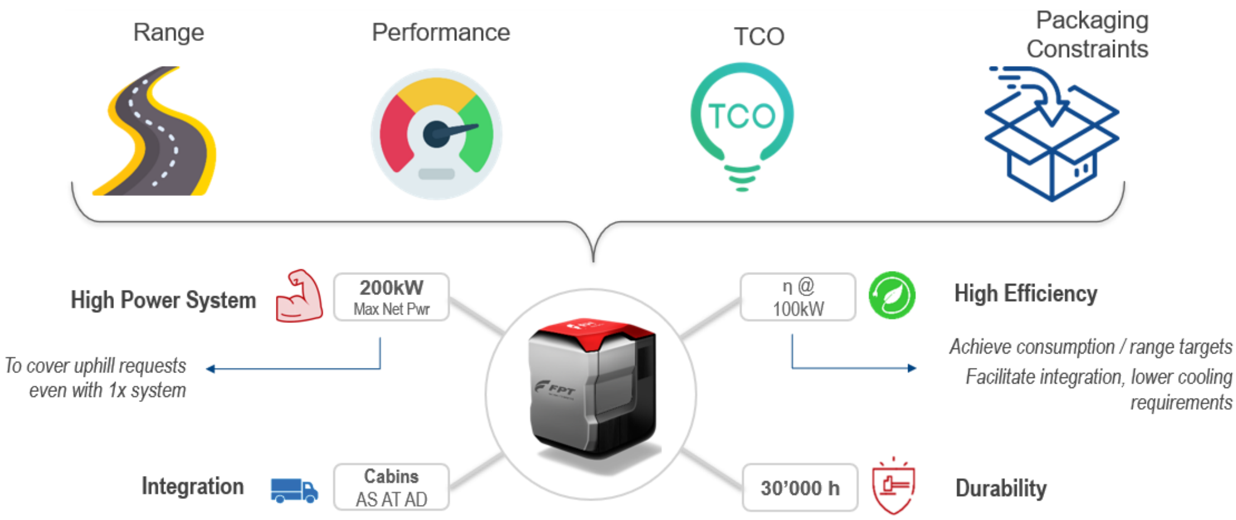

Figure 6: Fuel Cell System main drivers and KPIs summary

The durability requirement of 30'000 h will be considered during the design phase and the selection of the components, but it cannot be demonstrated in this phase of the activity. The durability will be addressed with extrapolation from measured data, simulations, and qualitative considerations.

2.4 Other integration requirements

2.4.1 Coolant Interface

The fuel cell system will have one inlet port and an outlet port for the coolant circuit. The outlet coolant from the fuel cell system will always be below 95 °C.

2.4.2 Fuel (H_2) Interface

A stainless-steel Swagelok® connection ensures a H_2 leak tight interface between the fuel cell system and the H_2 supply. The supplied H_2 will be in the range of 16 to 20 bar to ensure the defined system operation.

2.4.3 Air Interface

The fuel cell system is supplied with filtered air in a temperature range between -30 to 40 °C and a relative humidity of 0 to 100 %. A silicon hose with clamp fixation is used as connection to the vehicle air inlet and the vehicle exhaust line. The air filter is installed on the vehicle, not part of the FCS.

2.4.4 HV Interface

The fuel cell system shall relate to standardized HV connectors as an interface to the HV bus. The considered voltage range can vary between 500 to 800 V depending on the battery charging status, which is also to be considered as requirement related to current conversion of the DCDC converter.

2.4.5 LV and Communication Interface

The fuel cell system control unit shall be connected to the vehicle LV battery with a standard connector and it operates in a range of 18 to 30 V (nominal 24 V). Other LV BoP components of the system will be power supplied via the fuel cell system control unit based on its specifications.

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Communication Interface – Transmitted signals (FCCU to VCU)

The fuel cell system transmits signals to the vehicle to provide information related to detected faults, operation status as well as the actual fuel cell system net output power.

Communication Interface – Received signals (VCU to FCCU)

The fuel cell system receives signals from the vehicle to operate the system in the desired way. The desired operation status and required power are needed during normal run. In case of a crash, the vehicle provides a crash detection signal to trigger the safe system reaction on fuel cell system side.

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3 Fuel Cell System

3.1 Fuel Cell System Architecture

The fuel cell system consists out of 5 main subsystems (Figure 7):

- Power module (incl. stacks)
- Anode Subsystem (H_2 path)
- Thermal Subsystem (Cooling path)
- Cathode Subsystem (Air path)
- HV Subsystem (incl. DCDC, PDU)

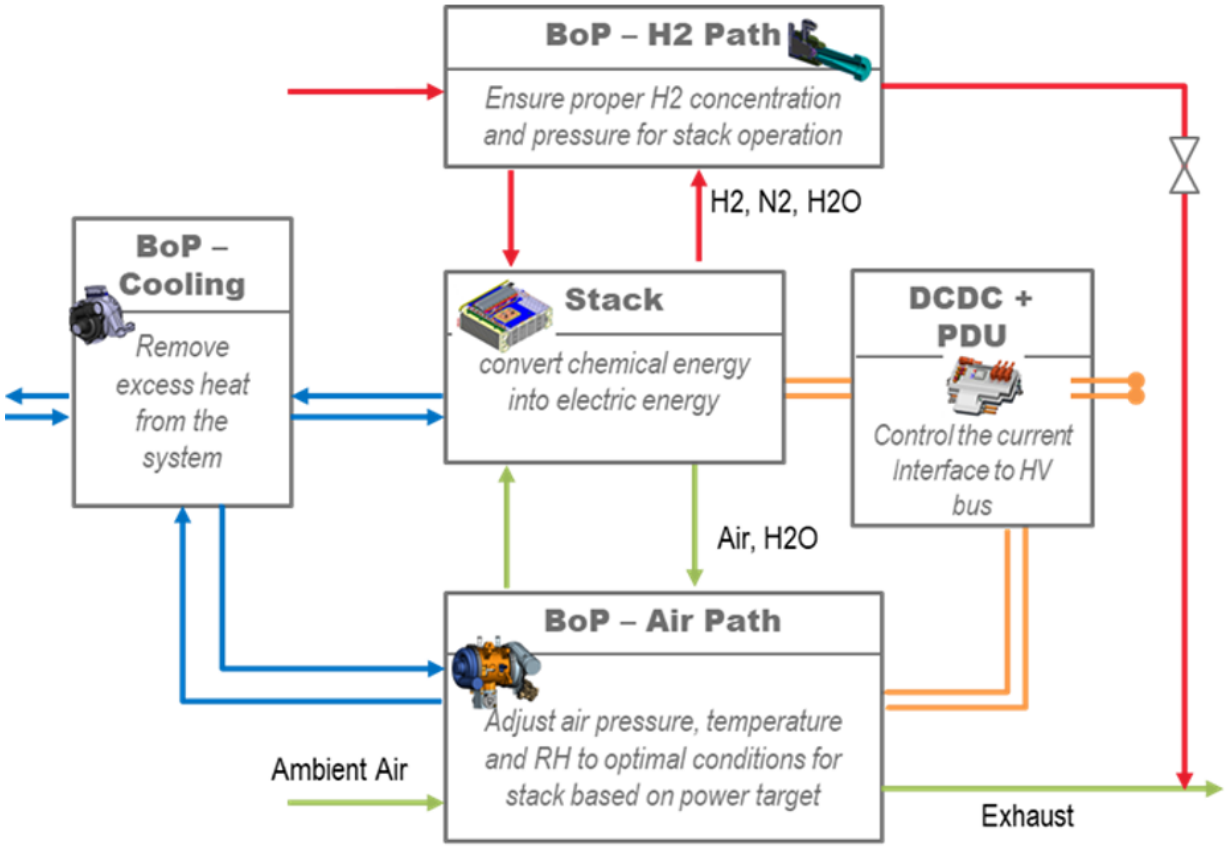

Figure 7: Overview Fuel Cell System Architecture.

The power module subsystem includes the fuel cell stacks, the enclosure and enclosure ventilation system. The stacks convert chemical energy into electric energy through the reaction of hydrogen and oxygen present in the air; to optimize performance H_2 and air need to be conditioned properly and continuously, and heat must be removed from the stacks.

The cathode subsystem adjusts the received filtered air (air filter not included in the system perimeter) with respect to air pressure, temperature, and RH according to the desired operating condition. The exhaust air flow at stack outlet is provided to the vehicle exhaust line.

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The anode subsystem adjusts the received H_2 flow from the H_2 tank system (not included in system perimeter) and ensures proper H_2 concentration and pressure according to the desired operating condition. Accumulated N_2 (due to H_2 recirculation) will be purged into the exhaust line of the vehicle.

The thermal subsystem removes the excess heat from the system by ensuring the required coolant flow and coolant temperature according to the operating condition; additionally, it cools down the compressed air in the air pass through a heat exchanger.

The HV subsystem converts the stack current to the corresponding current at HV bus voltage level to provide the electric power to the vehicle.

The control subsystem (fuel cell control unit) is considered as transversal subsystem which controls the BoPs of each subsystem to ensure the required medium condition based on operating point.

Furthermore, the control subsystem monitors the system behaviour and reacts in case of malfunction to ensure safe operating conditions.

3.2 Fuel Cell System Design and Packaging

Developing a high-power fuel cell system for heavy-duty, on-road applications presents a significant challenge: designing each sub-system's layout to ensure the overall dimensions and interface placements meet the stringent requirements of the vehicle's chassis and cab as well as NVH requirements. To address this, considerable effort was dedicated to defining and optimizing the system's packaging and dimensions, with the goal of minimizing its overall size.

In addition to size optimization, the design prioritized ease of assembly and serviceability of all components, while also aiming to keep the system's weight low. To achieve these objectives, a custom-made aluminium frame was engineered to secure all components in place and connect them to the vehicle chassis using vibration dampers. This frame features two main spars that support the five core subsystems:

- Power Module (including stacks)
- Anode Subsystem (H_2 path)
- Thermal Subsystem (cooling path)
- Cathode Subsystem (air path)
- HV Subsystem (including DCDC and PDU)

To protect sensitive components, such as the turbocharger, the design also incorporated damping systems that mitigate vibrations, ensuring all components operate reliably within their vibrational limits and reducing the risk of damage.

3.2.1 Stacks and Power Module

The power module consists of stacks, stack enclosure, cell voltage monitor (CVM) and enclosure ventilation. The power module has been designed for the project according to FPT specifications, (i.e., power level, efficiency level, dimensions, etc.) to allow the use of 2 stacks for a single set of Balance-of-Plant (BoP). The enclosure plays a crucial role to secure the 2 stacks mechanically while ensuring IP protection levels. An additional functionality is to support and integrate the ventilation system to avoid hazardous hydrogen concentrations in the enclosed space. Functionally, the role of this subsystem is to convert the chemical energy of hydrogen into electrical energy; to achieve this result at the best possible system efficiency, all other subsystems have been optimised to ensure a proper supply of the reactants and the necessary temperature, pressure, and humidity levels.

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The overall power module can deliver more than 250 kW gross power; given the optimization of the BoP, the maximum net power target of 200 kW is easily achievable.

3.2.2 H_2 subsystem module

The main functionality of the anode subsystem module is to provide H_2 to the stacks at the desired pressure, concentration, and flow. The stacks are always operated with a H_2 rate higher than the stochiometric value to ensure that the partial pressure of H_2 is always sufficient for the reaction through each bipolar plate and through the entire stack. This condition of having a lambda > 1 leads to a significant H_2 concentration at the stack outlet. To minimize efficiency losses, the flow at stack anode outlet needs to be recirculated to the stack anode inlet. The FPT approach is to use a supersonic ejector to passively recirculate the secondary flow using the energy of the compressed H_2 coming from the tanks and available at the H_2 injector.

An inherent problem of the recirculation (both active and passive) is the accumulation of N_2 in the anode loop that permeates from the air side and decreases the H_2 partial pressure. Therefore, regular purging of the fluid via the purge valve into the exhaust is required; the development of the purge valve control strategy is critical to achieve high efficiency while maintaining good performance and avoiding critical conditions regarding stacks durability. In addition, water at the stack outlet needs to be separated with the water separator. The separated water accumulated in the water tank needs to be drained once a certain water level is reached.

Injector and isolation valve have been sourced to work with the necessary H_2 flow and pressure.

The ejector and water separator are internal designs to optimize the recirculation while having full control on the packaging.

Purge and drain valves have been sourced externally to provide the controllability and the flows needed based on stack supplier data and short stack testing evidence.

3.2.3 Air Subsystem module

The air subsystem is responsible for delivering air to the fuel cell stack at the specified pressure, temperature, and relative humidity to ensure efficient operation. Several core components are required to achieve these targets, which are described in detail below.

The air filter in a fuel cell system not only removes physical particles that could clog or damage components, but also adsorbs pollutants that could contaminate the catalyst layer in the stack and reduce performance. To achieve this, the air filter is equipped with an activated carbon layer, capable of absorbing harmful compounds such as hydrocarbons, carbon monoxide, NOx, SOx, and ammonia. The filter used in FPT's system was selected for its high effectiveness, low pressure drops, and long service life.

While most systems use only an electric compressor, the FPT system includes a turbine to recover energy from the exhaust, improving overall efficiency. The turbocharger is a key driver of system efficiency, and extensive benchmarking and turbo-matching activities led to a custom aerodynamic design for the turbine and compressor impellers, achieving high efficiency across the entire operating range.

Due to the low enthalpy content of the exhaust flow, the turbine alone cannot drive the compressor, as it would in an internal combustion engine turbocharger. Therefore, the system includes an optimized electric motor to ensure consistent performance under varying conditions, such as high altitudes. This configuration meets airflow and pressure requirements without performance degradation, being able to supply the necessary air flow and pressure ratio.

Given the need for high air purity, the turbocharger employs air bearings instead of regular lubricated bearings. These air bearings use aerodynamic profiles to create a pressure gradient when the shaft spins, requiring some

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bleed air recirculation to cool the bearings. In this turbocharger, packaging is optimized, reducing complexity, weight, and footprint.

The compressed air must be cooled to prevent damage to the stack and humidifier membranes. A water-to-air charge air cooler was designed specifically for this application, allowing for tight integration within the fuel cell system chassis. This component delivers high effectiveness, ensuring precise air temperature control across the entire operating range.

The proton-conductive membrane in the fuel cell stack facilitates proton exchange between anode and cathode electrodes, and the ease of this molecular transport affects each cell's performance. Water molecules enable this process, so the membrane must be constantly hydrated, but excess water can block membrane pores and cause flooding. Therefore, precise humidity control is crucial during operation.

To achieve this, an air-to-air humidifier is used in the cathode subsystem, leveraging the ability of Nafion™ compounds to transfer water between two flows based on concentration gradients. The selected humidifier is the result of intensive benchmarking, aimed at reducing its footprint while ensuring performance. A humidifier bypass is included for precise humidity regulation, integrated into the water separator body. Several rounds of CFD simulations to optimize the shape and hose size and minimize the footprint of the bypass valve.

To protect the turbine from damage caused by water droplets impacting its high-speed blades, a droplet separator is installed in the exhaust to remove condensed water. A proprietary design was developed in-house, leveraging the company's expertise in turbulent motion simulations to create a custom solution that optimizes pressure drop and separation efficiency while maintaining a compact footprint.

Several different control valves are employed in the system.

Isolation valves ensure system protection during transitions, providing very low internal leakage (<0.1 sccm @ 0.8 bar) through a dedicated sealing design. This guarantees airtight isolation of the stacks after shutdown, preventing aging due to hydrogen starvation.

As stack efficiency is closely related to air inlet pressure, it is essential to optimize this parameter under all operating conditions. In FPT's system, pressure regulation is managed by a back pressure valve integrated into the water separator body, characterized by fast response times to help maintain optimal stack conditions.

3.2.4 Thermal Module

In the FPT system the thermal management is split into two separate sub-systems: a "high-temperature" cooling circuit and one "low-temperature" circuit. The purpose of the "high-temperature" cooling circuit in the fuel cell system is to evacuate the excess heat and control the temperature of the coolant before and across the stack to ensure optimal operation, as well as cooling down the compressed air flow in the air-to-water heat exchanger. This is achieved through a high-voltage electric pump that controls the coolant flow rate to keep the temperature increase over the stacks at a predefined value dependent on the operative point, while an electronically operated 3-way bypass valve enables precise coolant recirculation to achieve constant inlet temperature to the stacks at their nominal temperature. This configuration allows dynamic thermal management during critical phases such as startup, shutdown, and transient conditions. The heat exchanger is mounted in parallel to the stack, with flow split between the two paths controlled by flow restrictors, optimizing heat transfer as needed. Excess heat absorbed by the coolant from the stack and heat exchanger is dissipated through the vehicle or test-bench radiator.

The pump is sourced to be able to deliver the flow needed at the maximum power operating point, considering the estimated pressure drop of the entire circuit, obtained via simulation considering the fuel cell system layout and a reference vehicle cooling circuit.

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The ion exchanger, placed in parallel to the radiator bypass, continuously removes ionic contaminants from the coolant, preserving the system's electrical insulation properties. The placement of the ion exchanger was done after examining different solutions via simulations and evaluating the impact on pump power consumption and temperature control. The component has been selected and positioned to be easily serviceable because the cartridge will need to be replaced at regular intervals.

Additionally, a coolant filter, located upstream of the stack, safeguards against potential occlusion of the cooling channels of the stack plates, ensuring uninterrupted coolant flow and system reliability.

In parallel, the "low-temperature" cooling circuit ensures the efficient and reliable operation of high-voltage components such as the e-turbo and DCDC converter, which require lower coolant temperatures than the fuel cell stack. This separate circuit, driven by an electric coolant pump within the vehicle or test-bench setup, maintains these components at their optimal operating temperature, ensuring overall system performance and durability.

3.2.5 HV Management System

In the context of fuel cell systems and vehicles, what is considered as high voltage (HV) system is the subsystem of the FCS comprising components and circuitry operating at 60 VDC and higher. Figure 8 presents an overview of the main parts of the current fuel cell system HV management system.

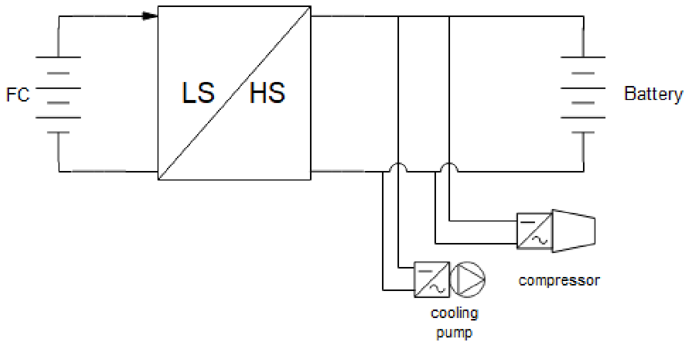

Figure 8: General schematic of the HV system.

The stacks (left in Figure 8) operate at a varying voltage depending on the load while the inverter of the traction electric motor of the eAxle (D2.1) is operated in the voltage range set by the batteries (right in Figure 8), depending on their operating conditions. To couple these two sides operating at different voltages, a DCDC converter is used (depicted as LS/HS in the picture), that has the capability to work in buck and boost mode[1] to have the maximum flexibility in terms of high voltage circuit sizing and configuration. A power distribution unit (PDU) on the HV bus side (HS) serves as interface to the HV components of the FC system, namely the e-turbocharger and the electric coolant pump.

The HV system has the following important operating, functional and safety Tasks to perform:

3.2.5.1 Provide interfaces and power supply for all components operating at HV, including the vehicle's battery

All HV components, i.e., the stack, pump, compressor, and the vehicle's HV bus (otherwise DC-Link) are connected compliant to regulations (R100.3 etc) and the vehicle manufacturer's requirements and norms HV

[1] "Buck" and "boost" are specific DC/DC topologies that decrease or lift the output voltage of the converter. Current modern power electronics offer a broader variety of options with improved performance than the original back and boost. Nowadays, we use the term to refer to the general categories of DC/DC converters that increase or decrease voltage.

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connectors and cables. Both connectors and cables are dimensioned for the maximum expected currents and temperatures during operation.

3.2.5.2 Active regulation of the FCS's power output

Based on the VCU's requirements and the FCS actual state, the FCCU (§3.3) is sending to the DC/DC converter a power output or current output request that the FCS may deliver. The power or current configuration may refer to the input (LS) current coming from the FC stack, or the output (HS) current, based on the vehicle request and the HV components (compressor and pump) consumption. In both cases, a relevant signal is sent to the DC/DC ECU and the DC/DC is adapting appropriately the HV voltage to allow for the requested power flow from the FC stack to the vehicle's HV bus.

This is done by adapting the switching frequency of its power electronics and thus adapting the electrical resistance that the FC stack "sees". The stack behaves in this sense as a passive electric source and the lower the resistance at its output the higher the current and the power it provides. The reactivity of the DC/DC to the current or power request in the order of magnitude of a few milliseconds.

3.2.5.3 Passive and active protection of components and personnel

Both personnel and components are protected with a series of relevant measures such as:

- Floating HV electrodes.
- Fuses against overcurrent.
- Isolation monitoring[2].
- Power electronics circuitry against counter current (protection of the stack).
- Electric filters against current ripple.
- Electromagnetic Compatibility (EMC) filters.
- Protection of the power electronics against liquids and dust.
- Cumulated charge discharging mechanisms.

3.3 Control System

The control unit, sensors and software play a critical role in the achievement of high stationary and dynamic performances of a fuel cell as well as lifetime targets. Advanced state machines control the critical procedures of start-ups and shut-downs, monitoring functionalities protect the integrity of the system, and the safety of the users and advanced control logics operate the system to achieve high power and efficiency. During the project, FPT has developed the entire control software for the fuel cell system, starting from pre-existing experiences in innovation projects and developing to follow the ISO26262 to ensure functional safety requirements. Extensive testing campaigns with Model in the Loop (MiL), Hardware in the Loop (HiL) and at system level are planned and implemented to calibrate and validate the control system.

3.3.1 Control Unit, Sensors and LV topology

Fuel Cell Control Unit (FCCU)

An FCCU for a fuel cell system is necessary for optimizing and ensuring compatibility, and it should be selected based on several aspects. The system actuators and sensors should be chosen to define the input and output interfaces of the control unit. The main requirement is to fully develop the control application software within FPT, taking responsibility for generating code, compiling, and flashing the software to the control unit. Additionally, a list of requirements has been defined, and a scouting campaign for an FCCU has been initiated.

[2] Active on the DC/DC only when the internal contactors are open to avoid interference with the vehicle's isolation monitoring device (IMD).

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The main requirements are:

Table 4: FCCU Features

ID	FCCU Feature
1	Voltage Supply compatibility to the vehicle
2	High protection class
3	High lifetime
4	Operating temperature flexibility
5	Fast communication for development
6	Functional Safety according to FPT requirements (HW and BSW)
7	Different I/O interfaces
8	Diagnostic capability
9	High computational power

The selected control unit complies with FPT requirements and has been tested on Hardware-in-the-Loop and on the fuel cell system.

3.3.2 SW Architecture and Functionalities

The Software architecture is developed using System Composer a Mathworks Matlab/Simulink product. The software architecture consists of 6 main divisions, System Inputs, System Outputs, Power manager, Monitoring and Diagnosis, and each subsystem controller. Each part can be described as follow:

System Inputs:

Receiving all the sensors (analogue or digital) or actuator messages through CAN network

System Outputs:

Actuating all the actuators through PWM, analogue output or CAN network.

Monitoring and diagnosis:

Monitoring and diagnosis, often called the safety layer in control architecture, are essential for automotive systems to ensure the safety of both occupants and the vehicle or powertrain from potential hazards. This function continuously monitors fuel cell system components (such as sensors and actuators) and system parameters for any malfunctions or anomalies. If a malfunction is identified, corrective actions can be taken to prevent further damage or hazards. The system may then attempt to recover from the fault; if successful, the failure flag is reset, i.e. system is healed. If recovery is unsuccessful, a fault code is reported, detailing the nature and location of the fault. The system will take appropriate measures according to the fault level associated with the detected fault code.

Power Management:

The power management function receives real-time net power demand data from the vehicle. As the fuel cell system operates based on current demand, this demand is estimated using a semi-physical model. To ensure that the system's output matches the power demand, a closed-loop current control is implemented. Power delivery may be limited by the stack control function due to insufficient reactants or unachieved operating conditions. The power manager can also reduce/limit the power. The currently available power is then sent to the DC-DC converter. The system prioritises, whenever possible, meeting the power demand according to the

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target transient rate of the system, meaning that if the available current matches the current demand, power will be delivered promptly.

Stack Control:

The stack control function is essential for ensuring the fuel cell system operates efficiently and safely. The stack control receives the current demand from the power manager. It defines all the setpoint of the operating conditions following to the current demand such as anode and cathode pressures, cathode air flow, thermal subsystem setpoints, etc. It evaluates in real time the current available based on the actual conditions of the reactants and temperature. Once the current available is defined, it will be communicated to the power manager in order to proceed with the power demand delivery.

Air Supply Control:

The air supply control consists mainly of three control strategies:

1. The air flow on the stack inlet is controlled to ensure the amount of oxygen required to ensure a safe/reliable the chemical reaction. The air flow is achieved by actuating the turbocharger speed.
2. The cathode inlet pressure is controlled in order to maintain a certain pressure during operation. The pressure is regulated by actuating the back pressure valve position.
3. The relative humidity at the cathode inlet is controlled in order to provide a sufficient humidity to the membrane which ensure reliable chemical reaction. The relative humidity is achieved by actuating the humidifier bypass valve position.

Fuel Path Control:

The fuel path control consists mainly of three control strategies:

1. The anode inlet pressure is controlled in order to maintain a certain pressure during operation. The pressure is regulated by actuating the injector opening.
2. The amount of nitrogen concentration in the anode is controlled in order to maintain a low nitrogen concentration in the anode loop. The nitrogen concentration is controlled by actuating the purge valve position.
3. The amount of water accumulated in the anode is controlled in order to remove the water from the anode loop. The water removal is achieved by actuating the drain valve position.

Thermal Circuit Control:

The thermal circuit control consists mainly of two control strategies:

1. The coolant stack inlet temperature is controlled in order to maintain the requested temperature and operate the stack at its higher efficiency. The coolant stack inlet temperature is reached by actuating on the three-way valve.
2. The temperature difference between stack coolant inlet and outlet is controlled in order to maintain a specific temperature difference based on stack requirements. The temperature difference is achieved by actuating on the coolant pump.

High Voltage Control:

The high voltage control consists of operating the DCDC including the power distributor unit. It has four main functions:

1. Set the current to be drawn from the Fuel Cell.
2. Precharge the stack side when voltage starts build up on the stack side.

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3. Discharge the stack side and battery side.
4. Emergency shutdown to open the contactors.

Supervisory:

The supervisor, is also know but the state machine, is the brain of the fuel cell system. The supervisory controls each subsystem individually and preselect the operating condition required at each state.

After powering off the vehicle, the fuel cell system software goes into the following sequences.

Standby; where the FCCU verify that all components are operating correctly, and high voltage is detected from battery and hydrogen supplied from the tank.

Startup, which consists of running each subsystem at its specific operating conditions in order to get voltage and then drawn current from the stack.

Run, which consists of operating each subsystem following to the operating conditions.

Shutdown, which consists of removing the water from the stack and cool down the stack before complete shutdown.

Emergency Shutdown, which consists on isolating the system in few milliseconds and discharge the stack side.

3.4 Safety and Functional Safety

3.4.1 Fuel Cell System Safety

During the fuel cell system development, the industrial standards and regulations applicable for hydrogen-fuelled vehicles as well as electric powertrains, were considered.

In general, regulation R10 provides requirements related to electromagnetic compatibility, which is a common regulation for electronic devices of vehicles. The fuel cell system components consider the internal FPT standards, which is compliant to this regulation.

Similarly, the regulation R100.3 provides requirements related to electric powertrains, in particular protection against direct as well as indirect contact. To avoid direct contact, certain measures were applied such as e.g., the usage of sufficient HV cables including the connectors or the stack enclosure which can be not removed without usage of special tools. The protection against indirect contact is achieved by monitoring the isolation resistance. The monitoring operates only during disconnected fuel cell system state to avoid any interferences with the vehicle isolation resistance monitoring, which is considered as active in all operating conditions.

Regulation R134 provides requirements related to the usage of hydrogen-fuelled vehicles. The fuel cell system needs to be protected against overpressure situations. Therefore, the system is equipped with a shut-off valve at the system inlet, which will isolate the system from H_2 supply if the pressure is above the intended operation pressure. Another requirement applicable to the fuel cell system is the allowed H_2 concentration in the exhaust line. At any time, critical H_2 concentrations must be avoided. Therefore, a H_2 concentration exhaust monitoring has been implemented and isolate the system if the concentration is above the safety threshold.

SAE J1766 provides recommended practice for electric, fuel cell and hybrid electric vehicles crash integrity testing. The fuel cell system needs some time to be fully discharged, therefore the system is designed as “one box”, where the system up to its HV interface can be considered as one electrical protection barrier. With this concept, the system can be easily and fast enough disconnected by opening the HV contactors.

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3.4.2 Functional Safety

During the fuel cell system development, the industry standard regarding functional safety ISO26262 applicable to road vehicles, was considered. To identify the hazardous events a hazard and risk assessment was performed to derive the safety goals applicable to the fuel cell system.

The safety goals are mainly related to the following hazardous events:

- Avoid H_2 release within/around the fuel cell system
- Avoid unintended H_2 release into the vehicle exhaust line
- Avoid exposure to HV live parts of the fuel cell system
- Avoid exposure of pressurized components from the fuel cell system

The safety goals must be satisfied by the fuel cell system functional safety concept. A qualitative fault tree analysis (FTA) supported the concept development, where root causes for potential violation of the SGs were identified and safety measures accordingly defined. The general approach of the functional safety concept is to introduce dedicated safety measures instead of covering the needs as part of the primary functionality. This allows a less complex solution while ensuring a better fault coverage. Furthermore, this approach will allow better structure of the software architecture, where functional safety related functions, like e.g., monitoring can be executed on a separate safety core to ensure freedom from interference to other functions.

The functional safety concept will define the functional safety requirements which are considered as input for the technical safety concept. As part of the technical safety concept, the defined safety measures were allocated to physical components. The components, like actuators and sensors, were chosen to fulfil the required diagnostic coverage. The same applies to the fuel cell system control unit, which is developed according to ISO26262. A further breakdown to software functions and hardware elements was performed to allocate the identified needs accordingly.

3.5 Simulated Performance

In order to predict the performance of the fuel cell system, an empirical, zero-dimensional simulation model has been developed. All main system components have been implemented zero-dimensionally and have been coupled. For this, experimental and/or simulated supplier data has been used. This allows the estimation of the stack performance, the BoP component's power consumption and thus the system power and efficiency.

Results were computed with different combinations of stacks and BoP-components to select the most suitable combination. Through the simulations it was demonstrated that the KPIs set for the project could be achieved.

3.6 Prototype Build

A first prototype has been built and installed on the fuel cell system test bench to perform the initial system and SW commissioning as well as calibration and validation activities. The first built has been completed in Q4/2024 and it includes all components but the enclosure (Chapter 3.2.1); the system build up with the enclosure will be performed ahead of the final system validation and performance targets demonstration.

4 Conclusion and next steps

The EMPOWER project has made significant strides in the development of scalable and modular fuel cell systems for Zero-Emission Heavy-Duty Vehicles (ZE HDVs). The extensive design and integration work performed in Task 2.2 has resulted in the creation of a highly efficient and flexible fuel cell system that will help in meeting the stringent performance targets set for the vehicles. Chapter 1 provides an introduction to the project and the task; Chapter 2 focuses on the vehicle definition and its impact on the requirements for the fuel cell system in relation to the work performed in D1.1; Chapter 3 describes in detail the design choices and

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driving principles behind the definition of the system and its components as well as the SW developed for this system and the safety and functional safety implications.

The next steps in this activity are particularly related to Task 2.4, which involves the experimental validation of the system. This phase will be crucial in verifying the performance and reliability of the fuel cell system under real-world conditions. The outcomes of Task 2.4 will be documented in Deliverable 2.3, providing valuable insights and data to further refine and optimize the system.

The successful completion of these tasks will pave the way for the commercialization of ZE HDVs, contributing to the reduction of CO_2 emissions in the transport sector and supporting the transition to a more sustainable and eco-friendly future.

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Project Partners:

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Participant No*	Participant short name	Participant organisation name	Country
1 Coordinator	**AIT**	AIT Austrian Institute of Technology GmbH	AT
2	**IVECO**	IVECO SPA	IT
3	**FPT**	FPT Industrial SPA	IT
4	**IFPEN**	IFP Énergies nouvelles	FR
5	**POLITO**	Politecnico di Torino	IT
6	**LT**	Lead Tech SRL	IT
7	**VIL**	Villinger GmbH	AT
8	**CID**	Fundación CIDETEC	ES
9	**CTE**	CT Engineering GmbH	AT
10	**GLO**	GRUBER Logistics S.p.A.	IT
11	**BRE**	BREMBO SPA	IT
12	**IIT**	Istituto per Innovazioni Tecnologiche Bolzano S.c.a.r.l.	IT
13	**ALFI**	Air Liquide	FR

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