D1.4 Testing and validation plan

ENLIGHTEN

nExt geNeration 1200V eLectric hIGH volTage powErtraiN

Horizon Europe | HORIZON-CL5-2024-D5-01

Integration and testing of next generation post-800V electric powertrains

(2ZERO Partnership)

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PROJECT ABSTRACT

ENLIGHTEN aims at developing, integrating and testing a next generation post 800V electric vehicle powertrain with an indicative voltage level of 1200V. It targets a higher performing, cost optimized and more sustainable drivetrain layout that is also backwards compatible to the existing charging infrastructure with 1000V or 500V respectively. Determining exactly how high the new voltage level should be, to enable expected advantages in a systemic and systematic way is also part of the project. A new voltage level affects the entire sphere of electric mobility, both horizontally (vehicle, charging infrastructure, users, manufacturers) and vertically (OEM, tier1, tier2, single component supplier), hence a deliberate decision is required. To accomplish this an advanced electrical system architecture is presented by the ENLIGHTEN consortium in this proposal on whose basis a specific electric vehicle drivetrain will finally be developed and demonstrated in a C-segment vehicle. The at TRL5 delivered powertrain will consist of a dual voltage battery system and an integrated motor-inverter E-drive system, complemented by an intermediate DCDC converter, an AC and DC capable onboard charger and a power distribution. All power electronic devices will exploit low loss, ultra-fast switching gallium nitride (GaN) semiconductors for highest efficiency and to minimize cooling demand and component size. The dual voltage battery can be switched dynamically from one battery voltage into the other while driving. Through these and other measures, the ENLIGHTEN system delivers significant advances over the 2024 State of the Art. The ENLIGHTEN consortium includes 2 automotive companies, 1 Tier1 supplier and 2 SMEs. Their expertise is leveraged by the partnership with 2 research institutions and 4 academia/universities, constituting an ideal setup for strengthening the competitiveness of the European automotive industry.

PARTNERS

Participant no.*	Participant short name	Participant organisation name	Country
1. Coordinator	**AIT**	Austrian Institute of Technology GmbH	Austria
2.	**EAT**	Eaton	Czech Republic
3.	**POLITO**	Politecnico di Torino (Polito)	Italy
4.	**IFP**	IFP Énergies nouvelles	France
5.	**AU**	Aarhus University	Denmark
6.	**THI**	Technische Hochschule Ingolstadt	Germany
7.	**MAT**	Manifattura Automobili Torino	Italy
8.	**CGD**	Cambridge GaN Devices	United Kingdom
9.	**LT**	Leadtech	Italy
10.	**FMF**	FPT Motorenforschung AG	Switzerland
11.	**ETH**	Eidgenössische Technische Hochschule Zürich	Switzerland

LIST OF ABBREVIATIONS

Acronym / Short Name	Meaning
AC	Alternating Current
BMS	Battery Management System
CAN	Controller Area Network
CCS	Combined Charging System
CMTI	Common-Mode Transient Immunity
DC	Direct Current
DCDC	Direct Current to Direct Current Converter
EMF	Electromotive Force (Back-EMF)
EV	Electric Vehicle
GaN	Gallium Nitride
HIL	Hardware-in-the-Loop
HMI	Human–Machine Interface
HPC	High-Power Charging
HVAC	Heating, Ventilation and Air Conditioning
HV	High Voltage
i-DCDC	Intermediate DCDC Converter
KPIs	Key Performance Indicators
LV	Low Voltage
MS	Milestone
OBC	Onboard Charger
PDU	Power Distribution Unit
PWM	Pulse Width Modulation
R&D	Research & Development
SiC	Silicon Carbide
SOC	State of Charge
SOH	State of Health
SoA	State of the Art
TSEP	Thermal Sensitive Electrical Parameter
THD	Total Harmonic Distortion
VCU	Vehicle Control Unit
WLTP	Worldwide Harmonized Light Vehicles Test Procedure

EXECUTIVE SUMMARY

Deliverable D1.4 – the Testing and Validation Plan – lays out how the ENLIGHTEN project will prove the performance and reliability of its ~1200 V dual-voltage powertrain. The plan sets a clear path, starting with component testing and moving all the way up to full vehicle trials, to make sure the technologies achieve three main goals: seamless dual-voltage switching in under 30 milliseconds, ultra-fast charging from 20 to 80 percent state of charge in just 10 minutes at 350 kW, and a 25 percent reduction in WLTP energy losses compared to today's best systems.

The testing is structured as a phased roadmap. At the component stage, the project's key innovations—such as the GaN multi-level inverter, the high-efficiency motor, the dual-voltage battery, the advanced combo-charger, the intermediate DCDC (i-DCDC) converter, and the power distribution unit (PDU)—are validated in the lab. These tests check for safety, thermal stability, and efficiency under specified conditions. Once validated, the components are integrated into- and tested as subsystems like the E-drive and the predictive control platform. The final step takes place at the vehicle level, where the Hyundai Ioniq 5 donor car first establishes baseline performance. The ENLIGHTEN systems are then integrated, and their impact is verified through chassis dynamometer measurements, fast-charging tests, and road testing.

The tests are being carried out in the ENLIGHTEN beneficiaries' laboratories across Europe, with each project partner focusing on the areas that match their expertise. This setup allows for thorough validation, steady progress, and reduced risks throughout the process. The results will proof a technology that can deliver longer driving range, faster charging, positioning ENLIGHTEN as an important step forward in the development of next-generation electric vehicles.

A testing and validation plan is also available for internal use in Excel table format on the ENLIGHTEN SharePoint.

1 INTRODUCTION

Deliverable D1.4 – Testing and Validation Plan defines the framework for testing and demonstration in the ENLIGHTEN project. It sets out how testing at component-, subsystem- and system level will be organized, scheduled, and carried out to verify the technical solutions developed during the project.

The plan links system-level demonstration in the donor car with single-component testing. This structure ensures validation against the project's key performance indicators (KPIs) and objectives.

Verification will follow a stepwise process. Partners will first test individual elements in their facilities. Then, subsystems will be assembled and verified. Full vehicle testing will follow, both on roller test bench and in on-road trials. Each phase is aligned with project milestones to confirm progress and reduce risk.

Figure 1 shows the phased testing and validation approach. The process starts with component-level testing of the GaN multi-level inverter, motor, battery system, combo-charger, i-DCDC converter, and PDU. Lead partners validate each in their laboratories. Subsystem testing follows, covering the integrated E-Drive (motor, inverter, and control software), battery validation, and dual-voltage switching. The final stage is vehicle-level testing, beginning with baseline measurements, powertrain testing in the lab, and road trials.

The figure also assigns responsibilities. IFP leads motor and inverter development and validation. AIT manages i-DCDC, dynamic dual voltage solid-state switching, and integration. ETH handles modelling and combo-charger. THI leads on the battery system. MAT manages vehicle integration and testing. AU focuses on control and algorithms. FMF and POL contribute to motor and inverter design. CGD supplies GAN switching devices.

This layered approach shows how each technology moves from concept to component testing, through subsystem integration, and finally to full vehicle demonstration.

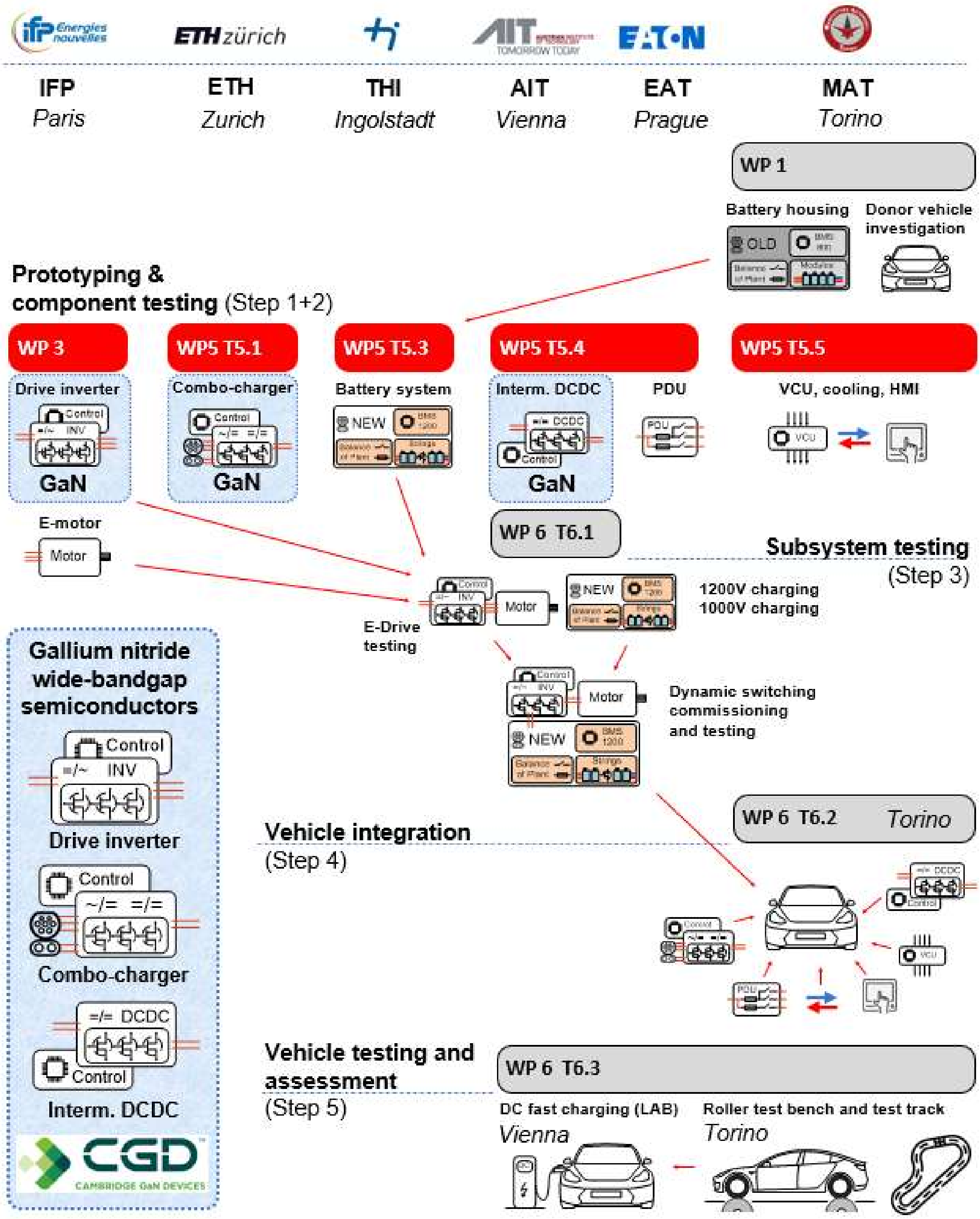

Figure 1 –Partner activities and prototyping, testing and assessment procedure

2 COMPONENT TESTING

2.1 GAN MULTI-LEVEL INVERTER (IFP)

GaN multi-level inverter is one of ENLIGHTEN's technology bricks where high switching frequency, lowest losses, and high power density are enabled for traction application cases.

Testing of the component is performed at IFPEN.

Verification of the GaN-based multi-level inverter is planned in sequential stages of testing for safe, efficient, and robust operation:

- **GaN power-stage switching (no current)** – Double-pulse and step-switching tests on a clamped DC bus validate dv/dt (up to 100 kV/µs), overshoot, and ringing to protect devices and insulation.
- **Control integration (multi-level PWM + robust controllers)** – Control board flashing and HIL/simulator checks ensure correct modulation and state-machine stability at up to 50 kHz switching frequency (vs. 20 kHz SoA).
- **Inductive-load operation (no active power)** – Passive inductor testing at low/medium bus voltage validates PWM modulation, current ripple, harmonics, and switching loss indicators without stressing the DC bus.
- **Cooling / thermal performance of GaN switches** – Thermography, TSEP, and SOA checks confirm junction temperatures <150 °C under rated load, ensuring safe lifetime margins.
- **Full functional test at full power (active load)** – Using a programmable active load, speed/torque profiles are swept to log efficiency (>98%), THD, and DC ripple, validating power density up to 60 kW/L.
- **Safety strategies & failure modes** – Faults (sensor loss, over/under-voltage, short, over-temp) are injected to verify safe shutdown (vs. 100 ms for contactors).

2.2 ELECTRIC MOTOR (IFP, ETH)

ENLIGHTEN PMSM motor is developed and tested in a next-generation ~1200V e-drive system. Stress is on early reliability of key components, pre-final assembly, verification of performance, and verification of anticipated efficiency and loss reduction compared to the 800V state-of-the-art. IFP and ETH labs perform testing, with a combination of full-size vehicle assembly and scale-model verification.

Testing of the electric motor is performed primarily in IFP's laboratories, using dedicated magnet, rotor, and stator characterization equipment, as well as full-scale automotive test benches. FMF contributes scalable motor design and digital modelling expertise, while ETH provides high-frequency loss analysis and thermal modelling support. The activity is embedded in WP4 (E-motor design and development) and closely linked with WP3 (Inverter design and verification), with critical validation steps aligned to milestone MS5 (motor prototypes available for subsystem testing) and MS7 (vehicle integration and commissioning):

- **Magnet, Rotor, and Stator (Elementary Test) -** Key motor aspects are derisked early and material quality is confirmed. Lab testing includes histograph testing on magnets, induction rotor tester testing, MTC stator testing, and age acceleration to confirm baseline manufacturing robustness.
- **Electrical Performance -** Key electrical figures—back-EMF, short-circuit currents, and flux mapping—are measured. They represent inputs for WP3 digital twin verification. A 25–30% reduction in partial load losses relative to the 800V state-of-the-art will be demonstrated.
- **Thermal & Mechanical Performance -** Thermal sensors and torque/speed characterization are utilized for motor estimation under different cycles of loads. It is seen from the measurement data that winding and stator temperatures are well within the safe limit of the 180 °C insulation class, validating durable operation under stress situations and input for lifetime estimation.
- **Control Setup & Base Calibration -** Control and speed/torque schemes are validated via IFP's 800V SiC inverter. Base calibration is utilized for matching with the digital twin models and facilitates optimization towards efficiency. It is also a starting point for system-level project objective of reducing WLTP consumption in energy from 26.6 Wh/km to 19.9 Wh/km (–25%).

2.3 BATTERY SYSTEM (THI)

The ENLIGHTEN battery system is engineered as a dual-voltage platform with advanced safety, high efficiency, and ultra-fast charging capability. It integrates a modular architecture, solid-state switching, optimized cabling and busbars, advanced thermal management, and a sophisticated BMS to ensure stable operation under demanding driving and charging conditions.

Verification of the battery system takes place mainly at the Ingolstadt facilities of THI, with AIT providing the solid-state switches. This task is rooted in WP5 (Battery system, charging technology and ancillary systems), with milestones linked to MS5 (components ready for subsystem verification) and MS7 (vehicle integration and commissioning).:

- **Battery Modules -** Battery modules will be tested for safe operation in a single configuration including the full characterization of all electrical parameters needed for modelling such as internal resistance, OCV curve, power capability, etc. In addition, modules will be stringed together in a testing configuration to form switchable sets of modules as intended in the final system, with the limitation of testing voltage of maximum up to 800 V based on the test bench capabilities. After this reduced testing voltage scenario, the final system will be built for 1200 V whereas in the final configuration no full electrical tests can be performed at THI facilities. However, the BMS functionality including proper communication and operation of safety measures and switches will be demonstrated at final configuration level.
- **Strings & Solid-State Switches (Dual Voltage) -** Stringed battery modules enable dual voltage operation (1200 V ↔ 600 V). Solid-state semiconductor switching allows fast and safe switching from one mode to another, with switching times aimed to be below 30 ms.

- **Busbars & Cabling -** will be engineered for low-loss, lightweight distribution with advanced busbar and cabling engineering. Electrical contact verification, safety checks, and mechanical connections ensure robust and efficient power transmission.
- **Cooling System -** Advanced thermal management maintains safe operating conditions, extends battery life, and enables ultra-fast charging. Verification for a range of flow rates and various temperature profiles scaled down to (interconnected) module level to validate the operational scenarios with 350 kW (full system power level) chargers with a corresponding thermal safety margin.
- **Battery Management System (BMS) -** It monitors state-of-charge (SOC) and state-of-health (SOH), prevents over-charge/discharge, and regulates switching functions. Embedded testing will confirm correct tracking and safe ultra-fast charging.
- **Fast Charging on Emulated ≤1000V (Parallel Mode) -** Verification at a scaled module level according to final system design demonstrating the 20–80 % SOC in 10 minutes operation in parallel mode (~600 V, related to full system level), presenting backwards compatibility with existing HPC charging infrastructure.
- **Fast Charging at 1200V (Serial Mode) -** Verification at a scaled module level according to final system design demonstrating the 20–80 % SOC in 10 minutes operation in series mode (1200 V, related to full system level). Full 1200 V fast charging will be demonstrated at AIT.

2.4 COMBO-CHARGER (ETH)

ENLIGHTEN combo-charger is developed as a multi-function onboard charger for AC and DC inputs with backwards compatibility with the existing charging infrastructure. Employing wide-bandgap GaN devices and a multi-level topology, the target of the project is a more efficient and compact system compared to current state-of-the-art chargers. Verification of the basic function is carried out at ETH's High Power Electronic Systems Lab in Zürich on AC and DC operation of the charger. The design, construction and commissioning of the onboard combo-charger is part of WP5 (Battery system, charging technology and ancillary systems), specifically required for milestones MS5 (components ready for subsystem verification) and MS7 (vehicle integration and commissioning). These are the specific objectives, methods, KPIs, collaborators, and facilities:

- **AC Input Charging (400V 3-Phase) -** Qualified for normal 400V three-phase AC grid use at an output power of 11 kW, the target efficiency and the thermal performance will be verified with corresponding measurements. The compliance with relevant EMI, grid, and safety standards is also investigated.
- **DC Input Charging (<500V CCS 1.0) -** For first-generation DC fast chargers backward compatibility, the charger is tested for DC input up to 500V (CCS 1.0). Again, efficiency and thermal performance will be tested, ensuring compatibility with the "old" Charging Infrastructure.
- **Multi-Level Topology & GaN Switching -** The charger utilizes an advanced multi-level topology and high-speed GaN switches (target switching frequency: ~50 kHz) in order to minimize switching losses, voltage stress, and electromagnetic emissions. A prototype will be built and tested to demonstrate that the efficiency and the power density targets are met as expected.

- **Thermal & Cooling System -** An appropriately designed water cooling system will ensure safe operation over the entire output voltage range. Operation at various loads is expected to validate the thermal performance of the charger.
- **Total Efficiency & Power Density –** Based on a verification with a prototype, the combo-charger is expected to achieve ≈98% efficiency and a power density of 5 kW/L for both AC and DC input operation, thereby advancing beyond today's leading onboard charging systems.

2.5 INTERMEDIATE DCDC CONVERTER (AIT)

ENLIGHTEN intermediate i-DCDC converter is designed as a high-efficiency, space-compact interconnect for the ~1200 V traction battery and the donor vehicle's existing 800 V subsystems, such as HVAC compressor and 12V DCDC converter. Based on a GaN multilevel topology, the converter mitigates switching losses, reduces size and cost, and preserves stable operation in harsh driving and charging conditions. Verification is carried out at AIT's Vienna labs, focusing on voltage conversion functionality, dynamic switching and thermal stability. The task is assigned in WP5 (battery system, charging technology and ancillary systems) and aligned against milestone MS5 (components ready for subsystem verification) and MS7 (vehicle integration and commissioning). Specific targets, methods, KPIs, collaborators, and facilities are presented as follows:

- **Voltage Conversion (1200V → donor vehicle's 800V domain) -** It provides for a stable voltage conversion from the high voltage traction battery to the available 800V donor vehicle interface, supplying subsystems such as HVAC compressor and the 12V DCDC converter. Its power output is 7 kW rated and validated in donor vehicle subsystem integration.
- **GaN multilevel topology -** Switching losses and system size are minimized by using a GaN-based multilevel topology. Lab testing corroborates high frequency switching operation with efficiency enhancements over industry designs, allowing for cost and volume reduction.
- **Dynamic Switching Compatibility -** It is compatible with the dynamic switching capability of the dual-voltage battery. Verification confirms safe switching of the converter on power-off switching events (<30 ms), in synchronism with solid-state switch operation, with no subsystem stability compromise.
- **Thermal Performance & Cooling -** Thermal monitoring for various load cases proves the converter's cooling solution and design margins. Results are consistent with stable operation when the junction temperatures are kept under 150 °C at rated full load for ensured GaN device reliability with continuous operation.

2.6 POWER DISTRIBUTION UNIT (EAT)

The ENLIGHTEN Power Distribution Unit (PDU) is developed to manage the safe and reliable distribution of high-voltage power from the ~1200 V traction battery to all major subsystems. Designed with advanced switching, protection, and monitoring functions, the PDU ensures robust operation under normal and fault conditions while enabling seamless integration with the vehicle control system. Verification is carried out primarily at Eaton's R&D laboratory in the Czech Republic, focusing on fault tolerance, thermal stability, and communication reliability. This task is embedded in WP5 (Battery system, charging technology and ancillary systems) and aligned with milestone MS5 (components ready for subsystem verification) and MS7 (vehicle integration and commissioning). Key validation areas are:

- **High-Voltage Power Distribution -** PDU is qualified for 1200V service ratings to offer a safe and efficient power distribution for supplying the drivetrain and auxiliary networks.
- **Switching and Protection Functions -** Enhanced protection functions are integrated for safety against fault and over-load conditions. It is subjected to over-current and fault situations to demonstrate the switching elements' reliability and response time in operation.
- **Thermal Performance -** Thermal sensors monitor system operation through steady and peak load cycles. Test results will confirm stable thermal operation ensured by the PDU.
- **CAN-Based Control & Monitoring -** It combines CAN-based communication for compatibility with the vehicle control unit (VCU). Communication reliability verification, diagnostic accuracy, and fault indication are found to be correct through testing, facilitating real-time monitoring and system-level safety coordination.

3 SUBSYSTEM TESTING

3.1 E-DRIVE (MOTOR + INVERTER) (IFP)

ENLIGHTEN ~1200V E-drive integrates high-performance motor and GaN-inverter, targeting ultra-high efficiency and robust control. Thorough verification secures improvements in speed/torque output, efficiency, heat removal, and system robustness in general compared to today's 800 V state-of-the-art. Verification is carried out at IFP's laboratories in France, with system-level validation supported at AIT. This activity is rooted in WP6 (Testing, demonstration and vehicle integration) and aligns with milestone MS6 (subsystems validated) and MS7 (vehicle integration and commissioning). Key validation areas include:

- **Speed & Torque Capabilities -** To assess performance for the whole operating range, the motor is subjected to an e-motor testbench under stationary and transient load cycles.
- **System Efficiency (Motor + Inverter) -** E-drive efficiency is characterized through complete efficiency maps for torque/speed points and representative drive cycles. Using GaN multilevel inverter technology, peak inverter efficiency is greater than 99%, with up to a 25–30% reduction in partial-load losses compared to 800 V state-of-the-art. It benefits range extension and lower thermal loads directly.
- **Thermal Performance of Joint Cooling System -** The motor and inverter combined cooling loop will be tested under various load circumstances. Measurements confirm safe thermal operation for both peak and steady loads, temperatures for winding and for junction remaining in the 150–180 °C range for reliability and durability.
- **Control System Behavior (Full Voltage & Power) -** Higher-level algorithms for controls are tested through full power operation, transients, and fault situations. Results confirm robust and stable torque control, smooth voltage and mode switching, and fault-tolerant operation.

- **Integrated Motor-Inverter Robustness -** Endurance cycles validate subsystem reliability prior to vehicle assembly. Via performance, thermal, and safety verification in conjunction, the E-drive achieves a systemic contribution to total powertrain efficiency.

3.2 MOTOR + INVERTER + CONTROL SOFTWARE (PREDICTIVE CONTROL) (AIT)

The E-Drive subsystem integrates the motor, multilevel inverter, and predictive control software in a compact, efficient, and rugged package. Testing is carried out mainly at AIT's laboratories in Austria, with assistance from IFP and FMF for motor testing, and AU for advanced control algorithms. The activity is rooted in WP6 (Testing, demonstration and vehicle integration) and aligns with milestone MS6 (subsystems validated) and MS7 (vehicle integration and commissioning). Key validation areas include:

- **Speed & Torque Capability with Predictive Control -** Validation on AIT's e-motor testbench under stationary and transient load cycles. Predictive control algorithms ensure stable and responsive torque even under high-voltage operation and rapid transitions.
- **Robustness & Fault Handling -** Subsystem robustness is also validated in endurance testing with intentional fault inputs. The predictive control assures fail-operational stability, safe shut-off when necessary, and smooth switching to dual voltage in less than 30 ms. These results confirm both the safety and longevity of the E-Drive subsystem

3.3 BATTERY FINAL VALIDATION (AIT)

Final verification of the ~1200 V battery system assures ultra-fast charge capability alongside infrastructure compatibility for today, safe thermal operation, and durable BMS management. Verification through testing proves the system can reliably hit the project's fast-charge objectives in real-world operation. Testing is carried out mainly at THI's facilities in Ingolstadt and at AIT's laboratory in Vienna, with both partners collaborating on validation of solid-state switches, cooling, and BMS operation. The activity is embedded in WP6 (Testing, demonstration and vehicle integration) and aligned with milestone MS6 (subsystem validation) and MS7 (vehicle integration and commissioning). Key validation areas include:

- **Charging at 1200 Vdc -** The battery pack is charged at ~1200 Vdc to validate performance. Testing confirms safe operation through charge cycles and demonstrates charging from 20–80% in just 10 minutes.
- **Charging at 600 Vdc / 1000 Vdc -** Backward compatibility for currently available infrastructure is ensured through low voltage 600 Vdc and up to 1000 Vdc charging. Testing shows full compatibility with current 350 kW CCS chargers, ensuring flexibility and usability on today's infrastructure with safe and efficient operation.
- **SOC 20–80% in 10 Minutes -** Several consistent tests on different SOC start points confirms the system consistently achieves the 20–80% SOC in 10 minutes. Voltage and current profiles are stringently monitored, confirming ultra-fast charging as repeatable and stable for use cases.

- **Cooling System -** The cooling system is tested for steady-state high power charging with varying coolant flow rates. Cell and module thermocouples confirm the stable operation where each parameter is safe in every instance. Data indicate safe thermal performance for the system under extended high C-rate charging.
- **BMS Behavior & Safety Checks -** Verification of BMS behavior is assured with a set of safety-driven tests, including fault injection, over-current, and over-temperature events. Events are appropriately noted in the BMS, and alarms are appropriately triggered.

3.4 BATTERY + E-DRIVE + I-DCDC + SWITCH (DUAL VOLTAGE) (AIT)

The ENLIGHTEN powertrain combines the dual-voltage battery, E-Drive, intermediate DCDC converter, and solid-state switches to show that switching between 1200 V and 600 V is possible during driving operation. The validation work aims to make this switching smoothly under load, properly coordinated by the control logic. The testing will be carried out at AIT's laboratory in Vienna, with important contributions from IFP, and THI. This effort is part of WP6, which focuses on testing, demonstration, and vehicle integration, and it directly supports milestone MS6 on subsystem validation and MS7 on vehicle integration and commissioning. The validation looks closely at several key aspects to confirm performance and reliability:

- **Switching Logic -** Control coordination between the inverter, intermediate DCDC converter, and battery management system is verified. Results confirm seamless communication and interaction. Load demand and battery safety functions work together to maintain reliable operation.
- **Dynamic Switching under Load -** Tests confirm safe and efficient switching between 1200 V and 600 V in driving mode. Transitions are stable, loss-free, and consistent.
- **Battery–E-Drive Connection -** Validation ensures the dual-voltage battery connects reliably to the inverter and motor. Electrical and thermal interfaces are monitored continuously.
- **Switching Time -** High-speed data acquisition shows switching events always meet time limits. Transitions should take less than 30 milliseconds.

4 VEHICLE TESTING & DEMONSTRATION (MAT)

4.1 BASELINE DONOR VEHICLE INVESTIGATION (ORIGINAL VEHICLE) (MAT)

The ENLIGHTEN project sets a full baseline for the donor vehicle. This baseline is the reference for efficiency, energy use, and system integration impacts. Measurements take place at MAT's facilities in Italy. The work uses full-vehicle metrology, alignment tools, chassis dynamometers, and public charging stations. This task is part of WP1 Requirements and Specifications. It links to Tasks T1.2 and T1.3, deliverables D1.1 and D1.3.2, and milestone MS2 on baseline vehicle data.

Key reference measurements include:

- **Vehicle Mass -** The curb mass is measured with ±0.5% accuracy using a 4-corner scale under full-fluid conditions. These values are the basis for WLTP normalization and efficiency checks.
- **Ride Height, Toe, Camber -** Suspension and steering geometry are recorded on an alignment rack. Toe, camber, and ride height at both axles are documented to allow repeatable setup after system integration.
- **Tire Make, Model, and Pressures -** Tire make, model, and size are documented. Cold and hot inflation pressures are measured to normalize rolling resistance.
- **12V DCDC, HVAC, OBC -** Loads from auxiliary systems are benchmarked by monitoring components in the donor vehicle via OBD and external instrumentation.
- **Fast Charging -** Charging is benchmarked under real conditions at public CCS stations. CARSCANNER logs current, voltage, SOC, and time to establish a 20 to 80 percent charge profile at up to 1000 V.
- **Energy Consumption, WLTP -** Chassis dynamometer testing under WLTP provides the baseline Wh/km. CARSCANNER and metrology logs support the results. These values anchor the KPI of reducing energy losses by 25 percent.
- **Constant-Speed Consumption, Road (Optional) -** Public-road steady-cruise tests are optionally performed to cross-check chassis dynamometer data. Stable energy traces are recorded.
- **Constant-Speed Consumption, Dyno -** Chassis dynamometer testing under controlled steady-state speeds of 80, 100, 120, and 140 km/h is performed. Results are repeatable and map speed-dependent energy use.
- **Custom Driving Cycle, Track "Normal Driving" -** A realistic duty cycle is defined and executed on a test track in Italy. CARSCANNER logs representative energy use and performance profiles.

4.2 VCU & HMI (MAT)

The ENLIGHTEN Vehicle Control Unit and Human–Machine Interface manage powertrain coordination, driver interaction and diagnostics. Validation will be performed at MAT in Turin using bench setups with simulated inputs, HV and LV connections, and full subsystem integration. The task is part of WP6 on testing, demonstration, and vehicle integration. It links to Task T6.3, deliverable D6.3, and milestone MS7 on vehicle integration and commissioning.

- **VCU Basic Functions -** Bench testing verifies ignition, forward, reverse, neutral, and park. Simulated pedal and switch inputs are checked through CAN communication with all subsystems.
- **VCU Integration with Battery and Powertrain -** Validation covers the battery, inverter, i-DCDC, PDU, and combo-charger. Tests confirm command coordination and correct fault handling in HV and LV domains.
- **HMI Display -** A 10-inch touchscreen is tested to show SOC, drive modes, and fault status. CAN communication ensures reliable data exchange with the VCU.

- **User Interaction -** Tests confirm safe and intuitive operation for gear selection, drive mode changes, and fault handling.
- **Safety and Diagnostics Communication -** Fault injection confirms alarms, logging, and fail-safe actions reach the driver through the VCU and HMI.

4.3 VEHICLE LAB TESTING (MAT)

The ENLIGHTEN powertrain is validated at vehicle level with chassis dynamometer, supported by AIT. The task is part of WP6. It links to Task T6.3, deliverable D6.3, and milestone MS7. The program confirms efficiency gains, dual-voltage operation, ultra-fast charging, and subsystem coordination.

- **WLTP Cycle Testing -** Results confirm the 25 percent loss reduction target from 26.6 to 19.9 Wh/km including driving and charging.
- **Dynamic Switching Roller Test -** Dual-voltage switching is validated on dyno. Transitions remain under 30 milliseconds with no overshoot or spikes.
- **Constant Speed Simulation -** Dyno runs between 80 and 140 km/h generate repeatable efficiency curves aligned with subsystem targets.
- **Performance -** Acceleration, top speed, and torque response confirm C-segment performance.
- **Inverter and Motor Control -** Real driving cycles confirm torque and speed handling with stable subsystem coordination.
- **Thermal Profiling and BMS Coordination -** During charging, sensors and logs confirm stable pack temperature and correct protection actions.

4.4 VEHICLE ROAD TESTING (MAT)

The ENLIGHTEN demonstrator undergoes road testing at MAT proving grounds and public roads in Turin. Activities are part of WP6, Task T6.3, deliverable D6.3, and milestone MS7. Testing validates robustness, efficiency, charging, and benchmarking against a production EV.

- **On-Road Driving under Varied Conditions –** Mixed driving scenarios including stop-and-go traffic, highway cruising, and hill climbs confirm stable operation in real driving environments.

- **Dynamic Switching between 600 V and 1200 V –** Telemetry verifies coordinated inverter and BMS behavior during voltage transitions. Switching times remain <30 ms under real driving conditions.

5 CONCLUSION

The ENLIGHTEN testing and validation program covers components, subsystems, and full vehicle demonstrations. Laboratory verification and road trials confirm that the 1200 V dual-voltage powertrain is technically feasible, safe, and efficient. Results show ultra-fast charging, reliable subsystem coordination, and a 25 percent reduction in WLTP energy losses. The outcome supports higher range, shorter charging times, and stronger user confidence in future EVs.