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Specification and architectural design of multipoint MCS



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EXECUTIVE SUMMARY

This deliverable defines the specification framework and architectural design principles for interoperable and scalable multipoint Megawatt Charging System (MCS) hubs within the MACBETH project. Its objective is to establish a common conceptual baseline for the design, planning, and evaluation of high-power charging infrastructure for heavy-duty electric vehicles, while remaining adaptable to different site constraints, grid conditions, and evolving standards.

Building on system-level requirements identified in WP2, the document translates operational, spatial, grid-integration, and user-centric needs into a set of representative multipoint MCS concepts. These include alternative site layouts, shared and modular power cabinet architectures, and automation-ready designs. The concepts are intended to support high utilisation, minimise operational complexity, and enable future scalability without prescribing site-specific engineering solutions.

The deliverable further defines high-level technical specifications covering electrical infrastructure, vehicle-to-charger communication, cybersecurity, and environmental and operational requirements. Communication assumptions are aligned with ISO 15118-20, including the MCS profile, while cybersecurity considerations follow secure-by-design principles and established best practices. These specifications establish clear boundary conditions for subsequent design, optimisation, and pilot implementation activities in later work packages.

Interoperability and standardisation aspects are analysed by mapping the proposed concepts to relevant ISO and IEC standards. Remaining gaps are identified, particularly with regard to multipoint and shared-power operation, automated conductive connections, mixed CCS and MCS deployments, and site-level effects such as noise and thermal impacts. These gaps are not considered blockers for pilot deployment but highlight areas where further validation and feedback to standardisation bodies are required.

To ensure evaluation readiness, the deliverable also defines harmonised data and monitoring requirements for multipoint MCS hubs. These requirements are aligned with the KPI framework and data collection protocol defined in Deliverable D2.3 and integrate a minimum technical dataset to enable consistent performance assessment across pilot sites. This alignment ensures that pilot deployments will generate comparable and actionable data related to operational performance, grid impact, quality of service, and environmental aspects.

Overall, this deliverable provides a coherent and future-oriented foundation for the deployment and assessment of multipoint MCS hubs within the MACBETH project. By combining architectural concepts, high-level technical specifications, interoperability considerations, and data-driven evaluation requirements, it supports the development of interoperable, scalable, and grid-compatible megawatt charging infrastructure for heavy-duty transport in Europe.

LIST OF ABBREVIATIONS AND ACRONYMS

Acronym	Meaning
ACD	Automated Connection Device
B2B	Business-to-business
B2C	Business-to-Consumer
BESS	Battery Energy Storage System
CCS	Combined Charging System
CoW	Coalition of Willingness
CRA	Cyber Resilience Act
DSO	Distribution System Operator
EC	European Commission
EMS	Energy Management System
EV	Electric Vehicle
EVSE	Electrical Vehicle Supply Equipment
FDIS	Final Draft International Standard
HDEV	Heavy-Duty Electric Vehicle
HDV	Heavy-Duty Vehicle
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LDV	Light Duty Vehicle
MCS	Megawatt Charging System
NC DCC	Network Code Demand Connection Code
RfG	Requirements for Generators
SoC	State of Charge
WP	Work Package

1 INTRODUCTION

The electrification of heavy-duty transport requires charging infrastructure capable of delivering megawatt-level power in a reliable, interoperable, and scalable manner. Multipoint MCS hubs represent a key enabler for long-haul freight electrification, but their deployment introduces challenges related to space constraints, grid integration, operational safety, and interoperability across manufacturers.

Task 4.1 addresses these challenges by defining a shared conceptual framework for multipoint MCS hubs. The objective is to establish a consistent understanding of how such hubs should be structured, what minimum capabilities they must provide, and how they can remain adaptable to evolving standards and operational practices. This deliverable therefore serves as a bridge between high-level requirements defined in WP2 and the concrete design, manufacturing, and pilot activities in later work packages.

1.1 Purpose of the document

This deliverable defines the specification framework and architectural design principles for multipoint Megawatt Charging System (MCS) hubs within the MACBETH project. Its primary objective is to translate system-level requirements identified in WP2 into a coherent set of conceptual architectures, functional boundary conditions, and high-level technical specifications that can guide subsequent design, optimisation, and pilot implementation activities. The document deliberately focuses on interoperable, scalable, and future-proof concepts rather than detailed engineering or site-specific solutions, ensuring applicability across different deployment contexts and alignment with evolving standards.

1.2 Structure and logic of the report

The report is structured to guide the reader from general context and requirements toward concrete architectural concepts, technical specifications, and evaluation-ready data definitions. Following this introduction, Chapter 3 summarises the key input and system-level requirements derived from WP2 that form the foundation for all subsequent design decisions. These requirements frame the operational, spatial, grid-related, and user-centric challenges addressed in the document.

Chapter 4 builds on these inputs by presenting alternative architectural concepts for multipoint MCS hubs, including site layout options, power cabinet configurations, and automation-ready designs. These concepts illustrate how multipoint MCS hubs can be structured to address different use cases and constraints without prescribing specific implementations. Chapter 5 then translates the identified use cases and concepts into high-level technical specifications covering electrical, communication, cybersecurity, and environmental and operational aspects.

Interoperability and standardization aspects are addressed in Chapter 6, which maps the proposed concepts to relevant ISO and IEC standards, identifies remaining gaps—particularly for multipoint operation and automation—and highlights regulatory considerations relevant for deployment. Chapter 7 complements the architectural and technical work by defining harmonised data and monitoring requirements, ensuring that the pilots can be evaluated consistently against the KPI framework defined in WP7. Finally, Chapter 8 summarises the key conclusions and positions the deliverable within the overall MACBETH project roadmap.

1.3 Scope of deliverable

This document defines conceptual architecture and high-level specifications for multipoint MCS hubs within the MACBETH project. Its scope covers site-level layout concepts, power-distribution architectures,

functional boundary conditions, and key technical assumptions related to electrical infrastructure, communication, cybersecurity, environmental robustness, and operation. The deliverable also addresses interoperability and standardisation aspects and identifies remaining gaps relevant for multipoint MCS deployment.

The document deliberately does not prescribe detailed engineering designs, component sizing, supplier-specific solutions, or site-specific installation plans. National permitting procedures, detailed grid-connection engineering, and procurement-level specifications are considered out of scope. Instead, the deliverable provides a common conceptual and technical baseline that can be adapted to different deployment contexts and used as input for subsequent design, optimisation, pilot implementation, and evaluation activities within the project.

1.4 Relation to other work packages

This deliverable builds directly on the system-level requirements and use cases identified in WP2 and translates them into architectural concepts and technical boundary conditions for multipoint MCS hubs. It provides a shared reference framework for WP4 design activities and serves as a foundation for WP5 hub optimisation and WP6 pilot implementation at the selected demonstration sites.

In addition, the data and monitoring requirements defined in this deliverable are aligned with the KPI framework and data collection protocol developed in WP7 (Deliverable D2.3). This alignment ensures that design decisions made in WP4–WP6 are evaluation-ready and that the pilot deployments can generate harmonised, comparable data for performance assessment, grid-impact analysis, and overall project evaluation.

1.5 Key words

Megawatt Charging System, MCS, multipoint charging, heavy-duty vehicles, interoperability, hub architecture, grid integration

2 INPUT FROM WP2 REQUIREMENTS

The concepts and specifications presented in this deliverable are based on system-level requirements identified in WP2, including stakeholder needs, and pilot site constraints. WP2 highlights the need to support a range of heavy-duty vehicle categories with significantly different charging power demands, while ensuring predictable and safe user journeys.

From an operational perspective, requirements include minimizing queuing, enabling reliable high-power charging for long-haul operations, and ensuring compatibility with evolving vehicle interfaces. Grid-related requirements emphasize the need for load management, and coordination with DSOs to mitigate peak power impacts. These inputs form the foundation for the multipoint MCS concepts defined in this deliverable.

The use cases addressed in this deliverable are selected based on system-level requirements identified in WP2 and represent the most relevant operational, and grid-related scenarios expected for early deployment of multipoint MCS hubs. They reflect recurring challenges observed across stakeholder input, including high-power charging for different heavy-duty vehicle categories, limited space availability, high site utilisation, and operation under challenging environmental conditions. From an operational perspective, the selected use cases focus on minimising queuing and maneuvering complexity and enabling reliable long-haul charging. In parallel, grid-related considerations such as flexibility, and coordination with DSOs are embedded in the use-case selection to ensure relevance for real-world implementation. Together, these use cases form a foundation for developing and assessing multipoint MCS concepts.

Table 1 Use case overview

Use case	Title	Requirement
3	Charge without decoupling trailers	A charging bay should support multipoint dual charging for refrigerated and e-trailers
4	Charging on a highly utilised site with maximised charging infrastructure capacity under spatial limitations	Minimise the charging hardware (the size of the equipment or modular design)
4	Charging on a highly utilised site with maximised charging infrastructure capacity under spatial limitations	The up time of the chargers needs to be high
5	Safe LDV charging at an integrated and flexible multipoint truck charge point	The flexible charge point should have accessibility in mind when being designed, including availability for people in wheelchairs
7	Charging in challenging operational conditions	The charging equipment is designed for winter conditions with heating elements where necessary
7	Charging in challenging operational conditions	Charging experience is designed to minimise the drivers' required time outside
7	Charging in challenging operational conditions	Well-designed cooling system to maintain sufficient charging power
7	Charging in challenging operational conditions	The chargers are designed to withstand vandalism
8	Managing site power peaks	The charging site's EMS can throttle chargers' output power

3 CONCEPT OVERVIEW FOR MULTIPOINT MCS HUBS

Multipoint MCS hubs are conceived as charging sites where multiple vehicles of different types like Heavy Duty Vehicles (HDV) and Light Duty Vehicles (LDV) can be charged simultaneously or sequentially using shared or modular power resources. The concepts defined in this section are intended to be adaptable to different site sizes, grid connection capacities, and operational priorities.

3.1 Drive through design

The drive-through charging site design is based on a linear, fuel-station-like layout that enables heavy-duty vehicles to enter, charge, and exit the site without reversing or complex maneuvers (Figure 1). Charging lanes are arranged to support forward-only traffic flow, with MCS dispensers positioned on the left-hand side of the vehicle in line with current standards, while CCS may be added flexibly for mixed or overnight charging. This concept prioritises high throughput, short dwell times, and operational simplicity, making it well suited for motorway and corridor locations with high utilisation, while requiring careful optimisation of space, cable length, and substation placement to avoid power losses.

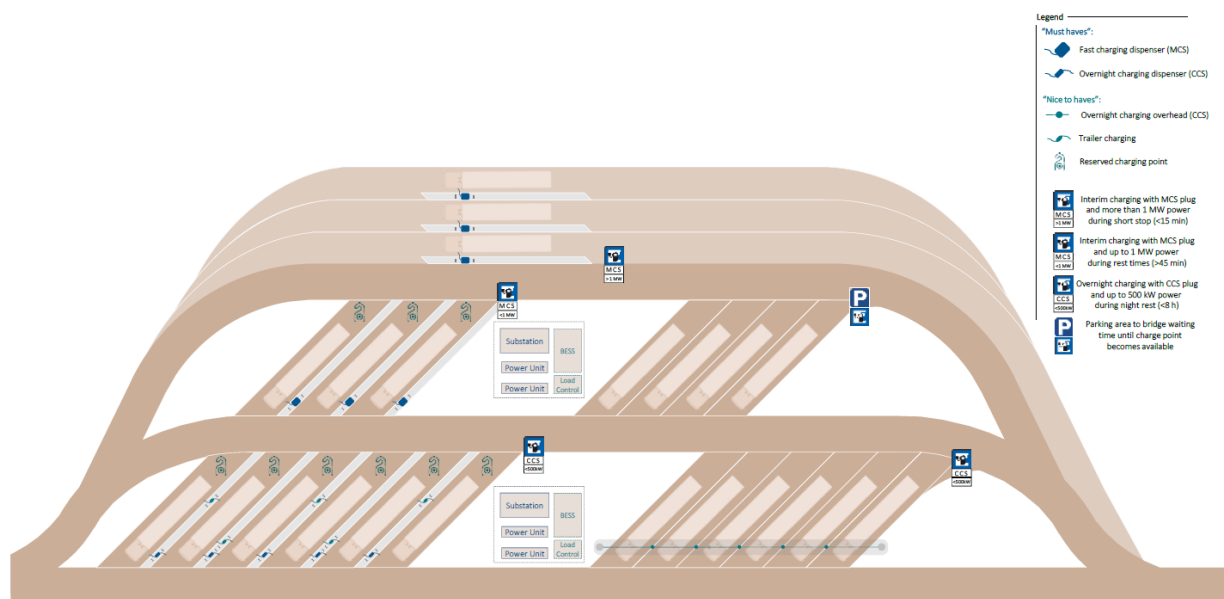


Figure 1 Charging site design with drive through capability Source: HoLa consortium [1].

3.2 Charging site design with dedicated waiting area

The site design with a dedicated waiting or queuing area extends the charging layout by adding a clearly defined buffer zone where vehicles can wait safely before accessing charging points (Figure 2). Vehicles are directed either to an available charger or to the waiting area, from which they are released in a controlled manner as capacity becomes available. This concept improves safety and traffic management under high utilisation, supports future features such as reservations or prioritisation, and increases scalability of the site, but more complex internal traffic planning, making it particularly relevant for future-proof HDV charging hubs with growing demand.

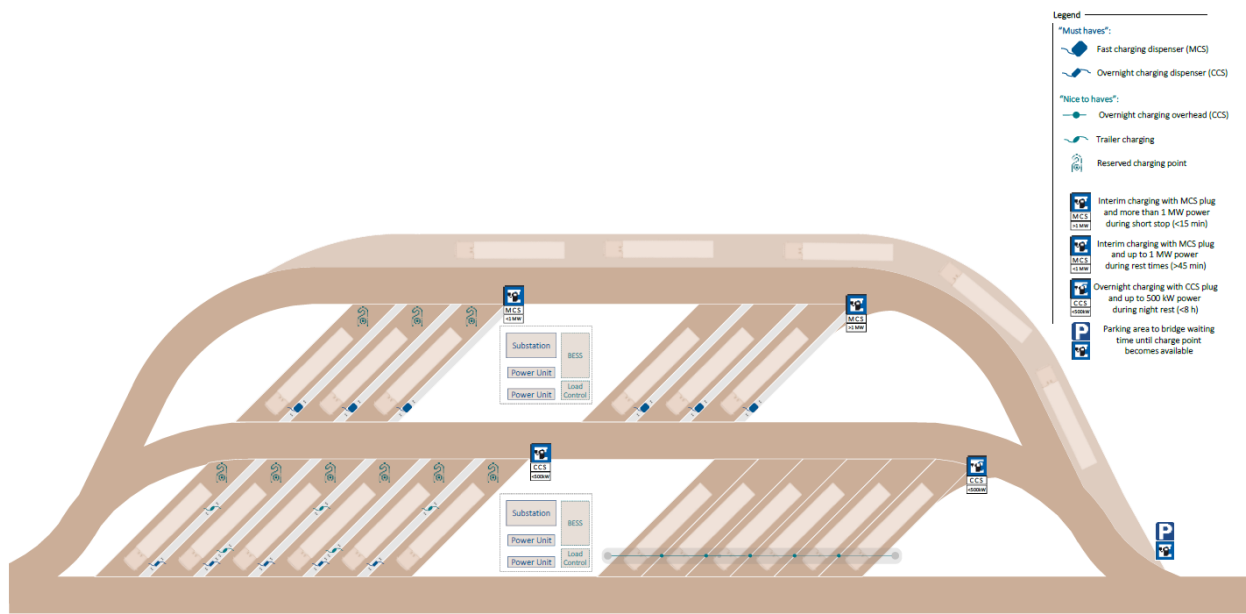


Figure 2 Charging site design with waiting area Source: HoLa consortium [1]

3.3 Shared power cabinet concept

The shared power cabinet concept is based on one centralized power conversion system that supplies multiple charging points simultaneously. All power electronics are aggregated in a single cabinet, and power is dynamically distributed across connected chargers according to vehicle demand, charging priorities, and grid constraints.

This concept maximizes utilisation of a limited grid connection and minimizes duplicated hardware. It is best suited for compact sites with multiple charge points clustered close together, where chargers operate under coordinated control and predictable usage patterns. For smaller sites, it is typically applied where grid capacity is constrained but charger count is expected to grow, allowing additional charge points to be added without installing new power cabinets.

3.4 Modular multi-cabinet concept

The modular multi-cabinet concept distributes power conversion across multiple physically independent cabinets, each supplying one or a small number of charging points. Power is expanded by adding complete cabinet modules rather than connecting additional dispensers to a central unit.

This approach prioritizes incremental scalability, redundancy, and layout flexibility over maximum power sharing efficiency. It is particularly suitable for small sites or early-stage deployments, where only one or two charge points are initially required and future expansion is uncertain. For smaller sites, this concept avoids over-dimensioning a central power unit and allows capacity increases to be directly linked to demand growth.

3.5 Automated connection integration

Automation-ready concepts are considered as an extension to both shared and modular architectures. Right now, automated conductive connection systems can reduce manual handling of heavy MCS cables, reducing damage due to misuse, reducing driver-time needed, and improve operational consistency under different environmental conditions. However, the biggest gain is being prepared for partial- and full autonomy of trucks. While full standardization of automated charging is still evolving, the concepts defined here maintain clear



interfaces between charging systems, vehicles, and automation components to ensure future compatibility. Therefore, the current deployment status is not further progressed than pilot projects such as in MACBETH.

4 HIGH-LEVEL TECHNICAL SPECIFICATIONS

This section maps the use cases to the subcategories and create specs:

4.1 Electrical

Building on the electrical design principles outlined above, Table 2 translates these boundary conditions into concrete, verifiable requirements for MCS hub implementation. The Table 2 captures whether the charging equipment supports a modular design (S4.1), which is essential for scaling multipoint hubs beyond 1 MW while managing space and grid constraints. Environmental and thermal requirements are reflected in S7.1 and S7.2, ensuring reliable operation under winter conditions and sufficient cooling performance for high-power MCS cables, where cable length and thermal limits directly affect usable charging power. Finally, S8.1 links the electrical hardware to site-level control by confirming that the Energy Management System (EMS) can throttle charging power, enabling effective load management and the integration of optional BESS to improve grid compatibility.

Table 2 List of electrical specifications

No.	Description	Specification
S4.1	Is there a modular design for the charging equipment?	Yes / No
S7.1	Does the charging equipment have heating elements to withstand winter conditions?	Yes / No
S7.2	Does the cooling equipment deliver a min. of 10% of the charging power for the cooling?	Yes / No
S8.1	Charging site EMS can throttle output power of charging station	Yes / No

4.2 Communication

Communication between the vehicle and the charging infrastructure is based on ISO 15118-20, including its MCS profile, enabling secure service negotiation, high-power charging control, and streamlined session handling. The system design assumes a 10BASE-T1S physical layer as the underlying communication medium to ensure robust, automotive-grade connectivity with simplified wiring and multidrop support. In addition, a standardized EVSE–automation interface is envisaged, providing only high-level control and status signals to external automation systems. Overall, the concepts rely on harmonized interfaces for both manual and automated charging scenarios, minimizing the need for proprietary extensions wherever possible.

4.3 Cybersecurity

Cybersecurity is addressed at a conceptual level, focusing on secure authentication, integrity of communication, and protection against unauthorized access. Authentication requirements build on established mechanisms within ISO 15118-20, ensuring mutual authentication between EV and EVSE and supporting certificate-based trust models. All communication channels are expected to use state-of-the-art cryptographic protection, with TLS 1.3 serving as the baseline protocol to guarantee confidentiality, integrity, and resistance against known attack vectors.

For automated systems, integrity and safety considerations extend to safeguarding automation-related control paths. This includes preventing manipulation of high-level movement or positioning signals and ensuring that safety-critical commands cannot be spoofed or injected. These measures help avoid unsafe system states and support reliable operation of robotic or automated charging processes.

Overall, the specifications are intended to be consistent with established cybersecurity frameworks and standards commonly applied in industrial and critical-infrastructure environments, such as the IEC 62443 series for industrial automation and control system security and ISO/IEC 27001 for information security management at the organizational and system level. In addition, this document includes a non-binding reference to emerging regulatory frameworks, notably the EU Cyber Resilience Act (CRA), to reflect alignment with principles such as secure-by-design, vulnerability handling, and lifecycle transparency.

Concrete technical implementations and conformity assessments are explicitly deferred to later project stages, where system-specific risk analyses will determine applicable controls, profiles, and compliance approaches based on the chosen architecture, operational model, and regulatory context.

4.4 Environmental and operational requirements

Multipoint MCS hubs must operate reliably under diverse environmental conditions, including temperature extremes and adverse weather. Operational requirements include clear traffic flows, minimization of pedestrian–vehicle interaction, and support for predictable charging processes. Space efficiency and noise emissions are key considerations, particularly in densely populated areas.

During high-power charging, significant heat is primarily generated by power electronics (e.g. converters, rectifiers, transformers), cooling systems, and high-current components such as cables and connectors, where resistive losses increase with charging power. Additional heat sources include active cooling components themselves, such as pumps and fans, which are required to maintain safe operating temperatures at power levels of 1 MW and above. The magnitude of heat generation depends on factors such as charging power, efficiency of power electronics, ambient temperature, cable length, and cooling concept.

Effective thermal management is therefore essential but can also become a relevant source of noise, especially in high-power EVSEs with forced air or liquid cooling. Noise may originate from cooling fans, pumps, compressors, and auxiliary equipment, as well as from vehicle-side systems operating during charging. To reduce energy losses and mitigate noise emissions, multiple measures can be applied, including optimized charging hub layouts, adapted cooling concepts (e.g. low-noise or liquid cooling), noise barriers, and operational strategies [2].

In line with the requirements introduced in Task 4.1, the topic of waste heat recovery is explicitly recognized as a future consideration. Waste heat generated during high-power charging may be captured and reused locally (e.g. for building heating or ancillary systems), contributing to improved energy efficiency and reduced environmental impact at MCS hub sites.

Table 3 summarizes the key environmental and operational requirements that translate these considerations into verifiable criteria. These include provisions for specialized charging needs (e.g. refrigerated or e-trailers), high charger availability, accessibility requirements, user interaction aspects, and operational robustness.

Table 3 environmental and operational requirements

No.	Description	Specification
S3.1	Is there a separate charging opportunity for refrigerated or e-trailers?	Yes / No
S4.2	The up time of the chargers needs to be high	Uptime >97%
S5.1	Does the charging site consider availability for people in wheelchairs?	Yes / No
S7.3	Quick initiation of charging possible with payment terminal or Plug and Charge?	Yes / No
S7.4	Scratch proof display available?	Yes / No

5 INTEROPERABILITY & STANDARDIZATION CONSIDERATIONS

5.1 Relevant existing and upcoming standards

The deliverable aligns with ISO 15118-20 for communication and security and with ongoing IEC standardization activities for MCS conductive charging. These standards provide the foundation for interoperability across vehicles and charging equipment from different manufacturers. The main standards are presented in Table 4. Where appropriate, European harmonised standards have been recommended. Many of them are also national standards with additional prefixes, such as DIN (Germany), BS (the UK), SS (Sweden), SFS (Finland), NBN (Belgium) and NEN (the Netherlands).

Table 4 Relevant standards.

Standard name	Contents	Relevance
EN IEC 61851-1	EV charging systems (Conductive charging)	General requirements
EN IEC 61851-21-1	EV charging systems (Conductive charging)	On-board charger EMC requirements
EN IEC 61851-21-2	EV charging systems (Conductive charging)	Off-board EMC requirements
EN IEC 61851-23	EV charging systems (Conductive charging)	DC EV supply equipment
IEC 61851-23-1:2026 PRV	EV charging systems (Conductive charging) – Pre-release version	DC electric vehicle supply equipment – Requirements for Automated Connection Devices (ACD)
EN IEC 61851-23-3 FDIS	EV charging systems (Conductive charging) – final draft	DC EV supply equipment for MCS
EN IEC 61851-24	EV charging systems (Conductive charging)	Digital communications between DC charging station and vehicle
IEC 61851-27	EV charging systems (Conductive charging) – under development	EV supply equipment with automated docking of a vehicle coupler
IEC 61851-28	EV charging systems (Conductive charging) – under development	Communication between automatic EV supply equipment and vehicles
EN ISO 15118-1	Communication standards	General requirements
EN ISO 15118-8	Communication standards	Physical layer and data link layer requirements for wireless communication (possibly relevant for ACD)
EN ISO 15118-9	Communication standards	ISO 15118-8 conformance test plan
EN ISO 15118-10	Communication standards	Physical and data link layer requirements for Ethernet connections

Standard name	Contents	Relevance
ISO/AWI 15118-11	Communication standards – under development	ISO 15118-10 conformance test plan
ISO/AWI PAS 15118-12	Communication standards - under development	Requirements regarding message exchange between EVCC and SECC
EN ISO 15118-20	Communication standards	2nd gen network and application layer requirements
EN ISO 15118-21	Communication standards	ISO 15118-21 conformance test plan
ISO 15118-23	Communication standards - under development	2nd gen network and application layer requirements – DC charging
ISO/PAS15118-202	Communication standards	Additional functionality for V2G
EN IEC 62196-1	Connectors and inlets	General requirements related to EV plugs, socket-outlets, vehicle connectors and inlets
EN IEC 62196-3	Connectors and inlets	Dimensional compatibility requirements for DC pin and contact-tube vehicle couplers
IEC TS 62196-3-1	Connectors and inlets	Vehicle connector, inlet and cable assembly for DC charging with thermal management system
ISO 5474-1	Power transfer – Functional and safety requirements	General requirements for conductive power transfer
ISO 5474-3	Power transfer – Functional and safety requirements	DC power transfer
ISO 5474-5	Power transfer – Functional and safety requirements	Automatic conductive power transfer (relevant to ACD)
EN IEC 63110	Communication standards	Managing charging and discharging of infrastructure by focusing on backend functions
EN IEC 63119	Communication standards	Information exchange for EV charging roaming services
IEC 62351 Series	Data and communications security	Grid and power systems cybersecurity
EN IEC 60204-1	General safety – Safety of machinery	Electrical equipment – General requirements
IEC 60364 series	Low-voltage electrical installations	Safety requirements for electrical installations (General)
IEC 60364-7-722	Low-voltage electrical installations	Specific requirements for circuits of EV charging installations

Standard name	Contents	Relevance
EN 61000 series	EMC compatibility	Detailed guidelines for testing, measuring and limiting electromagnetic emissions
EN IEC 60068 series	Environmental testing	Environmental testing of E/E products (incl. temperature, humidity, shock and vibration)
PD IEC TS 63379	Connectors and inlets	Vehicle connector, vehicle inlet and cable assembly for MCS
EN 61439-7	EMC compatibility	Low-voltage switchgear and control gear assemblies for application incl. EV charging stations
EN IEC 62052-11	Metering	General requirements for metering equipment
EN IEC 62053-41	Metering	Particular requirements for static meters for DC energy
EN 50470-4	Metering	Particular requirements for static meters for DC active energy
EN 60529	Enclosures - Safety	Degrees of protection provided by enclosures (IP Code)
EN 62262	Enclosures - Safety	Degrees of protection provided by enclosures for electrical equipment against external mechanical impacts (IK code)
EN 62477-1	Power conversion	General safety requirements for power electronic converter systems and equipment
EN 60664 series	Insulation	Insulation coordination for equipment within low-voltage systems

The charging infrastructure for MCS conductive charging must be compliant with a range of EU and UK standards across multiple topic areas to ensure safety, interoperability and regulatory acceptance. In addition to the IEC 61851 series of core standards related to EV charging systems, standards and regulations related to:

- Electrical safety and grid connections (incl. insulation, earthing, fault protection and power quality)
- Vehicle to charger communication
- EMC (electromagnetic compatibility) requirements to control emissions
- Mechanical and environmental standards (incl. connector designs, cooling systems, ingress protection and durability among others)
- Functional safety standards and cybersecurity requirements

To enable reliable operation, accurate billing and cross-border interoperability in both EU and UK markets, regulations around energy metering and billing must also be considered. Ensuring alignment with these standards is critical for regulatory approval and reliable deployment of MCS charging at scale.

Considering that Macbeth trial sites are located in specific EU countries (Belgium and Sweden), engineering standards (related to EVSE installation) from each of the above countries should be considered for compliance purposes. Regarding electrical installations, for example, Belgium follows the NBN C15-100/RGIE (AREI) code while Sweden has its own rules in SEK Handbook 444.

WP4 focuses on European and international standards, so national guidance and standards will not be examined as part of this deliverable (out of scope). That said, both Belgium and Sweden generally adopt and

are aligned with CENELEC/IEC standards. The expansion of MCS charging infrastructure to other countries should of course be compliant with each country's requirements and regulations.

5.2 Identified gaps

Despite significant progress in MCS standardisation, several gaps remain that are particularly relevant for multipoint and high-utilisation MCS hubs. These gaps are not blockers for pilot deployment but require further validation through projects such as MACBETH and ongoing work in standardisation bodies.

5.2.1 Multipoint and shared-power operation

Current IEC and ISO MCS standards focus primarily on single EV–single EVSE charging sessions and do not fully address multipoint hub architectures with shared or dynamically allocated power resources.

While ISO 15118-20 supports advanced energy transfer control, standardised concepts for power sharing, prioritisation, and arbitration between multiple simultaneous MCS charging sessions are not yet defined. This includes:

- Coordination between multiple EVSE ports connected to a shared power cabinet
- Transparent communication of temporary power limitations to vehicles
- Standardised behavior under grid- or site-level power constraints

The CharIN MCS Whitepaper acknowledges the increasing complexity of large charging sites and fleet use cases but does not yet define normative requirements for multipoint power allocation strategies, leaving this as an open area for further development and validation. [3]

5.2.2 Automated and robotised MCS connections

Although MCS has been designed with automation readiness in mind, including geometric suitability and communication support, full standardisation of automated conductive MCS connections is still incomplete.

The CharIN Whitepaper [3] explicitly states that automated coupling is possible but remains optional and subject to further standardisation, particularly for:

- Interfaces between EVSE, vehicle, and automated coupling systems
- Safety concepts for automated connection and disconnection
- Harmonisation with emerging standards for automated charging devices (e.g. IEC 61851-27 / 28)

For multipoint hubs where cable handling, ergonomics, and uptime are critical, and where building future-proof infrastructure is key (considering quick advances of vehicle autonomy), the lack of fully standardised automated MCS solutions represents a relevant gap that must be addressed through pilot testing and feedback to standardisation bodies.

5.2.3 Mixed CCS and MCS installations

The coexistence of CCS and MCS charging points within the same hub is expected in early deployment phases and at mixed-use sites.

However, harmonised guidance is missing on:

- Electrical and safety separation between CCS and MCS systems
- Operational rules for mixed vehicle classes (LDV and HDV)

- Traffic flow, accessibility, and user interface consistency

While the CharIN Whitepaper provides extensive requirements for MCS hardware and communication, it does not yet define best practices for mixed CCS/MCS hub operation, especially in multipoint, high-power environments.

5.2.4 Noise, thermal impacts, and site-level effects

MCS introduces significantly higher currents and cooling requirements than existing DC charging systems.

CharIN MCS Whitepaper addresses thermal limits for connectors, cables, and EVSE components, and they are also defined in the MCS standards. Site-level impacts such as cumulative noise, waste heat, and cooling system interactions are not covered in existing MCS standards, although they are addressed in CharIN Acoustic Functions Whitepaper.

For dense or urban deployments, this gap is particularly relevant and must be addressed through site design, layout optimisation, and additional local mitigation measures, as already indicated by recent project experience and research activities (e.g. ESCALATE, HoLa). [2])

5.3 Regulatory considerations

Regulatory considerations include compliance with electrical safety regulations, grid-connection rules, and emerging cybersecurity legislation. For MCS-based charging hubs, harmonization with EU network codes—particularly the Network Code Requirements for Generators (RfG) and the Network Code Demand Connection Code (NC DCC)—is needed to ensure consistent grid-integration behavior, fault-ride-through expectations, and load-management capabilities across different operators and countries. These aspects are essential when deploying high-power charging clusters that may have notable grid impact.

Cybersecurity- and software-related obligations are increasingly influenced by the EU CRA, which, although not legally binding for this deliverable, provides relevant guidance regarding secure-by-design principles, vulnerability handling processes, and software lifecycle transparency. In addition, products used within charging systems must comply with applicable safety and radio frameworks, such as the Low Voltage Directive (LVD) for electrical safety and the Radio Equipment Directive (RED) for components incorporating wireless communication modules or radio interfaces.

Local permitting and environmental requirements remain highly site-specific. These may include zoning rules, building permits, fire-safety approvals, environmental impact assessments, and grid-capacity confirmation from the local DSO. While these are acknowledged as critical for real-world deployment, they are not elaborated within this deliverable, as detailed procedures vary significantly by region and installation type.

6 DATA AND MONITORING REQUIREMENTS

This chapter defines the data and monitoring requirements for multipoint MCS hubs to ensure (i) operational observability, (ii) cross-site comparability, and (iii) KPI-ready evaluation in WP7. The requirements align with the KPI framework and data protocol described in Deliverable D2.3, including its emphasis on data ownership, data availability risks, confidentiality handling, and practical data exchange formats.

The purpose of this chapter is to define what data needs to be available and monitored, not to prescribe in detail how data is technically collected, stored, or contractually shared. The definition of concrete data collection architectures, storage solutions, access rights, and data-sharing mechanisms is addressed in other parts of the project, building on the requirements specified here.

In particular:

- WP2 / Deliverable D2.3 defines the overarching data governance approach, including roles and responsibilities for data ownership, access, and confidentiality, as well as guidance on data formats and interfaces.
- WP6 addresses implementation-related aspects, including how monitoring data can be technically integrated into site-level systems, EMS platforms, and backend solutions.
- WP7 uses the data defined in this chapter to calculate KPIs and perform cross-site analysis, but does not define data collection or sharing mechanisms itself.

In addition, the chapter adopts Coalition of Willingness (CoW) Annex B – List 1 [4] as a technical minimum dataset for energy and control-related signals, ensuring that essential EV–EVSE–grid interaction variables are captured in a harmonised way.

6.1 Objectives and Principles

Multipoint MCS hubs shall provide data that supports:

1. WP7 KPI calculation across economics, operational performance, QoS, grid integration, environment and investment friendliness, as defined in D2.3.
2. Operational monitoring for uptime/availability, fault diagnosis, and performance issues (e.g., power derating, thermal constraints).
3. Cross-pilot consistency: data must be comparable between Belgium and Sweden pilots (and future sites) using common identifiers, units, timestamps and minimum required fields.

6.2 Data categories and minimum datasets

D2.3 distinguishes between session-level datasets (per charging event), timeseries datasets (e.g., 1-min power logs), and site-level electrical/environmental datasets, with explicit data owners and risk levels discussed in the pilot data sources annexes and the data protocol workflow.

Accordingly, MACBETH hubs should provide data in three layers. The minimum datasets in Sections 6.2.1 to 6.2.3 were derived by mapping the WP7 KPIs defined in Deliverable D2.3 to the minimum data required for their calculation and validation. This was crosschecked against pilot data availability and aligned with CoW Annex B to ensure feasibility, comparability, and consistency across sites.

6.2.1 Layer A — Charging session dataset (event-based)

Purpose: supports the majority of operational KPIs (utilisation, session duration, energy per session, unique users' proxy, revenue proxies, reservation/no-show analysis).

- Minimum fields (per session) (aligned with D2.3 pilot data inventories):
- Charging station ID, charging point/connector ID
- Session start timestamp, session end timestamp
- Energy delivered (kWh)
- Connector type (MCS/CCS), current type
- Reservation flag (if applicable)
- Payment method category and session cost (where permitted)
- Pseudonymized vehicle/user identifier (where permissible)

6.2.2 Layer B — Power and status time series (device-level)

Purpose: supports charging curve KPIs, efficiency/loss estimation, peak-load duration, and a subset of grid-integration KPIs. D2.3 examples indicate 1-min (preferred) or 5-min resolution, depending on availability.

Minimum time series (per charging point / connector):

- Active power output (kW) at defined interval (target 1-min; acceptable 5-min if constrained)
- EVSE status / availability state (e.g., available, occupied, faulted) to support availability and reliability KPIs

Recommended additions (where available):

- Temperature of charging station / relevant components (D2.3 includes temperature logging expectations for pilots)
- Automation-related timeseries for robotic systems (Belgian pilot relevance noted in D2.3)

6.2.3 Layer C — Site-level electrical & environmental dataset

Purpose: supports grid integration KPIs (hosting capacity indicators, power-to-energy ratio, simultaneity factor proxies), environmental KPIs (renewable fraction, noise), and resilience indicators.

Minimum site-level signals:

- Grid import power at site (kW) (time series)
- Site grid capacity (static value)
- Voltage at point of common coupling (time series)
- Renewable energy indicators where applicable (e.g., energy source ratio / renewable fraction)
- Noise measurement dataset where applicable (D2.3 includes noise as an evaluation item)

6.3 Integration of further data points

To strengthen technical comparability and prepare for future smart/grid-interaction functionality, MACBETH adopts CoW Annex B – List 1 as a minimum technical dataset for EV–EVSE power transfer capability and control boundaries. CoW defines this list as technically essential and part of a common data language.

6.3.1 How List 1 fits into MACBETH monitoring

List 1 data points are integrated as follows (examples shown; full list remains in the annex referenced):

A) Power transfer capability and measurement

- Max/min possible power and current of EV and EVSE when connected (#1–#4, #7–#10)
- Present power/current measured at EV and EVSE interface (#5–#6, #9–#10)

B) Session constraints / energy bounds

- Planned departure time (#11), SoC display (#12)
- Required/available energy boundaries (#13–#17)

C) Operational enablement / mode

- Smart/bidirectional enabled flags (#19), EV connected and available (#20), use case mode indicator (#21)

D) Grid and market context

- State-of-grid signal (#25), DSO tariffs (#26), flexibility activation (#27), metering identifiers (#28), commodity price (#29)

E) Traceability / constraints

- Vehicle identifier concept (#24), location (#18), bidirectional limitation concepts (#22–#23)

6.4 Data quality, resolution, and traceability rules

To ensure D2.3 KPI calculation is feasible and comparable, the following cross-site rules apply:

- **Timestamps:** all datasets must include a consistent timestamp standard (recommended: UTC) and unambiguous interval definitions.
- **Identifiers:** every record must be linkable via a consistent set of IDs:
 - site ID → station ID → charging point/connector ID → session ID (pilot-defined)
- **Units:** use SI units consistently (kW, kWh, V, A, °C), documented per dataset.
- **Completeness flags:** missing values must be flagged; partial coverage should be explicitly described in the data inventory and reflected in KPI data risk.

- **Minimum sampling:** follow D2.3 expectations (typical 1-min for power logs, session-level event records per charging transaction; allow 5-min where limitations exist and document it).

7 CONCLUSIONS

This deliverable consolidates the conceptual, technical, and methodological foundations required for the successful deployment of multipoint MCS hubs within the MACBETH project. Building on the system-level requirements from WP2 and aligning with the evaluation framework of D2.3, the work presented in D4.1 defines how multipoint MCS hubs should be structured, how they can operate efficiently under real-world constraints, and how they will be assessed once deployed at the Belgian and Swedish pilot sites.

This deliverable consolidates the conceptual, technical, and methodological foundations for multipoint MCS hubs within the MACBETH project. Rather than prescribing a single target architecture or operational model, D4.1 presents reference concepts, identifies relevant standards, and outlines key design, operational, and evaluation considerations that frame how multipoint MCS hubs can be structured. Building on system-level requirements from WP2 and aligned with the KPI framework of Deliverable D2.3, the document highlights current capabilities, constraints, and standardization gaps, establishing a common basis for implementation decisions and for the assessment of the Belgian and Swedish pilot deployments.

The architectural concepts developed—drive-through layouts, queuing-area-based designs, shared and modular power cabinets, and automation-ready interfaces—provide a versatile toolbox for designing scalable, grid-compatible and interoperable high-power charging sites. They reflect the diverse operational realities of heavy-duty transport along TEN-T corridors and incorporate requirements for safety, accessibility, usability, and future-proofing. These concepts deliberately avoid prescriptive, site-specific engineering and instead deliver a flexible conceptual baseline for WP5 optimization activities and WP6 pilot implementation.

From a technical specification standpoint, the deliverable defines clear boundary conditions for electrical infrastructure, communication (ISO 15118-20 including the MCS profile and its 10BASE-T1S assumptions), cybersecurity (TLS 1.3 and secure-by-design principles), environmental robustness, user accessibility and operational requirements such as uptime, winter readiness, thermal performance, EVSE automation interfaces, and cable management. Interoperability considerations further ensure alignment with relevant IEC/ISO standards while identifying remaining gaps—particularly for multipoint power allocation, automation interfaces, mixed CCS/MCS operations, noise and waste-heat management—that the pilots will help address.

Complementing the architectural work, the chapter on data and monitoring requirements creates a direct bridge to the KPI-based evaluation framework in D2.3. By defining harmonised data categories, minimum datasets, timeseries requirements, and compliance with CoW Annex B List-1 technical data points, the deliverable ensures that pilot sites will generate the information necessary to evaluate economic performance, operational efficiency, quality of service, consumer acceptance, grid impact and environmental performance. This early alignment between design and evaluation is essential for ensuring that the real-world pilots yield actionable, comparable, and reproducible insights for future MCS deployments.

Overall, this deliverable provides a coherent foundation for the next stages of MACBETH. It offers a unified conceptual architecture, aligns technical specifications with emerging standards, and embeds data-driven evaluation into the design of multipoint MCS hubs. As pilot deployment progresses, the concepts and specifications presented here will be further refined based on practical experience, evolving standards, and stakeholder feedback. Together, these elements position MACBETH to demonstrate interoperable, scalable, and future-ready megawatt charging solutions that can accelerate the electrification of heavy-duty transport across Europe.

8 REFERENCES

- [1] P. Plötz, D. Speth und L. Kappler, „Megawatt charging in long-haul trucking: First findings on challenges and solutions,“ Fraunhofer ISI, Karlsruhe, 2024.
- [2] M. Antila, V. Naumanen, A. Mladek, C. Kollik, A. Stoiber und M. Häußler, „ESCALATE project: megawatt charging and its,“ in *38th International Electric Vehicle Symposium and Exhibition (EVS 38)*, Gothenburg, Sweden, 2025.
- [3] CharIN e.V., „Recommendations and Specification for MCS related standards bodies and solution suppliers,“ 08 05 2025. [Online]. Available: https://www.charin.global/media/pages/technology/knowledge-base/0c2cc2c8da-1747654352/250508_whitepaper_megawatt_charging_system_2.0.pdf.
- [4] „Joint Report by European Working Group 1 “Car Charging and Aggregators” and European Working Group 2 “Energy and Grid Topics” in the “Coalition of the Willing on Bidirectional Charging”,“ On behalf of the Coalition of the Willing on Bidirectional Charging (CoW), Germany, 2024.

9 ANNEX

9.1 Evaluation Framework and Data Collection Protocol D2.3

No	Cluster	KPI no.	KPI	Unit/Metric
1	Economics	1.1	Mean revenue of site per day	Euro
		1.2	Mean revenue of site per month	Euro
		1.3	Mean revenue of site per year	Euro
		1.4	Mean revenue per CCS session	Euro
		1.5	Mean revenue per MCS session	Euro
		1.6	Purchase cost per MCS recharging station	Euro
		1.7	Purchase cost per MCS recharging point	Euro
		1.8	Purchase cost per CCS recharging station	Euro
		1.9	Purchase cost per CCS recharging point	Euro
		1.10	Operation & Maintenance cost per MCS recharging station per year	Euro
		1.11	Operation & Maintenance cost per MCS recharging point per year	Euro
		1.12	O&M per CCS recharging station per year	Euro
		1.13	O&M per CCS recharging point per year	Euro
		1.14	Mean electricity cost at site incl tax + VAT	Euro/kWh
		1.15	Mean electricity price at CCS plug	Euro/kWh
		1.16	Mean electricity price at MCS plug	Euro/kWh
		1.17	Mean charged energy per CCS session	kWh
		1.18	Mean charged energy per CCS recharging point per day	MWh
		1.19	Mean charged energy per CCS recharging point per month	MWh
		1.20	Mean charged energy per CCS recharging point per year	MWh
		1.21	Total charged energy across all CCS recharging points at the site per day	MWh
		1.22	Total charged energy across all CCS recharging points at the site per month	MWh
		1.23	Total charged energy across all CCS recharging points at the site per year	MWh
		1.24	Mean charged energy per MCS session	kWh
		1.25	Mean charged energy per MCS recharging point per day	MWh
		1.26	Mean charged energy per MCS recharging point per month	MWh
		1.27	Mean charged energy per MCS recharging point per year	MWh
		1.28	Total charged energy across all MCS recharging points at the site per day	MWh
		1.29	Total charged energy across all MCS recharging points at the site per month	MWh
		1.30	Total charged energy across all MCS recharging points at the site per year	MWh
		1.31	Mean purchased energy of site per day	MWh

2	Operational performance	1.34	Mean purchased energy of site per month	MWh
		1.35	Mean purchased energy of site per year	MWh
		1.36	Maximum purchased energy of site per day	MWh
		1.37	Maximum purchased energy of site per month	MWh
		1.38	Maximum purchased energy of site per year	MWh
		1.39	Ratio of mean MCS charged energy per recharging point per day to CCS charged energy per recharging point per day	%
		1.40	Ratio of mean MCS charged energy per recharging point per month to CCS charged energy per recharging point per month	%
		1.41	Ratio of mean MCS charged energy per recharging point per year to CCS charged energy per recharging point per year	%
		2.1	Mean energy utilisation per CCS recharging point per day	%
		2.2	Mean energy utilisation per CCS recharging point per month	%
		2.3	Mean energy utilisation per CCS recharging point per year	%
		2.4	Mean energy utilisation per MCS recharging point per day	%
		2.5	Mean energy utilisation per MCS recharging point per month	%
		2.6	Mean energy utilisation per MCS recharging point per year	%
		2.7	Mean energy utilisation of all recharging points on site per day	%
		2.8	Mean energy utilisation of all recharging points on site per month	%
		2.9	Mean energy utilisation of all recharging points on site per year	%
		2.10	Mean MCS session duration	minutes
		2.11	Mean CCS session duration	minutes
		2.12	Fraction of MCS sessions (> 100 kWh) completed within 45 minutes	%
		2.13	Ratio of time spent per CCS session to MCS session	%
		2.14	Total number of unique MCS users	numeric
		2.15	Average number of unique MCS users per day	numeric
		2.16	Average number of unique MCS users per month	numeric
		2.17	Average number of unique MCS users per year	numeric
		2.18	Total number of unique CCS users	numeric
		2.19	Average number of unique CCS users per day	numeric
		2.20	Average number of unique CCS users per month	numeric
		2.21	Average number of unique CCS users per year	numeric
		2.22	Ratio of mean power over session to maximum power available at recharging point	%
		2.23	Ratio of mean power over session to maximum power available at recharging point under grid curtailment	%
		2.24	Ratio of time spent per session plugged-in not charging full battery	%
		2.25	Mean duration of time spent per session plugged-in not charging with full battery per session	min/ hours
		2.26	Mean duration of time spent per session plugged-in not charging with full battery per day	hours

		2.27	Mean duration of time spent per session plugged-in not charging with full battery per month	hours/days
		2.28	Mean duration of time spent per session plugged-in not charging with full battery per year	hours/days
		2.29	Mean total losses of electricity at site level per day	kWh
		2.30	Mean total losses of electricity at site level per month	MWh
		2.31	Mean total losses of electricity at site level per year	MWh
		2.32	Resilience	scorecard
		2.33	Ratio of total sessions that were reserved in advance and resulted in charging	%
		2.34	Ratio of total sessions that were reserved in advance and did not result in charging	%
3	Quality of Service	3.1	EU's Safe and Secure Truck Parking Areas level	Bronze/ Silver/ Gold/ Platinum
		3.2	Mean queue length	number of vehicles per hour
		3.3	Maximum queue length	number of vehicles per hour
		3.4	Mean waiting time per vehicle	mins
		3.5	Maximum waiting time per vehicle	mins
		3.6	Mean annual downtime	hours/days per year
		3.7	Mean duration of operation at site grid capacity per day	minutes
		3.8	Mean duration of operation at site grid capacity per month	hours
		3.9	Mean duration of operation at site grid capacity per year	days
		3.10	Software interoperability across HDVs, LDVs and CPs	scorecard
		3.11	Design best practice	scorecard
		3.12	Signage	scorecard
		3.13	Price transparency	scorecard
		3.14	Automation of charging	scorecard
		3.15	Flexibility	scorecard
4	Consumer acceptance	4.1	Driver satisfaction	survey/ interview result
		4.2	LSP/Carrier satisfaction	survey/ interview result
		4.3	Willingness to pay of LSP/ Carrier/ Shipper	interviews
5	Ease of grid integration	5.1	Hosting capacity	%Voltage drop/ kW added
		5.2	Power to energy ratio	kW/kWh

		5.3	Ratio of sum of individual charge capacities to grid connection limit (Simultaneity factor)	%
		5.4	Power factor	
6	Environmental	6.1	Renewable energy self-consumption	%
		6.2	Renewable energy fraction	%
		6.3	Electricity supplied is 100 % renewable	yes/no
		6.4	Land use/footprint of the site per charging bay	sq.m.
		6.5	Recharging station efficiency	%
		6.6	Standby electricity use	W
		6.7	Noise generated	dB
7	Investment friendliness	7.1	Time for site identification	months
		7.2	Time for site permitting	months
		7.3	Data availability related to future grid connection	scorecard
		7.4	Time for grid connection	months/ years
		7.5	Time for installation and commissioning	weeks

9.2 Further data points by CoW

Joint report by European Working Group 1 “Car Charging and Aggregators” and European Working Group 2

#	Data Point	Source	Proposed definition
1	Max. possible charging/discharging power of EV (AC & DC) when connected to the charging point [W]	EV	Maximum charge/discharge power supported by the EV [W]
2	Max. possible charging/discharging current of EV (AC & DC) when connected to the charging point [A]	EV	Maximum charge/discharge current supported by the EV [A]
3	Min. possible charging/discharging current of EV (AC & DC) when connected to the charging point [A]	EVSE	Minimum charge/discharge current supported by the EVSE [A]
4	Min. possible charging/discharging power of EV (AC & DC) when connected to the charging point [W]	EVSE	Minimum charge/discharge power supported by the EVSE [W]
5	Present charging/discharging power [W]	EV	Present active power measured by the EV [W]
6	Present charging/discharging current [A]	EV	Present charge/discharge current measured by the EV [A]

7	Max. charging/discharging power of the EVSE (AC & DC) [VA]	EVSE	Maximum charge/discharge power supported by the EVSE [VA]
8	Max. charging/discharging current of the EVSE (AC & DC) [A]	EVSE	Maximum charge/discharge current supported by the EVSE [A]
9	DC + AC continuous/actual power [W]	EVSE	Present active power measured by the EVSE at EV–EVSE interface [W]
10	DC + AC continuous/actual current [A]	EVSE	Present charge/discharge current measured by the EVSE at EV–EVSE interface [A]
11	Time of planned departure [hh:mm]	EV / User	Departure time indicating when energy transfer should be finished
12	Current SoC [%]	EV	Present State of Charge (for display only)
13	Available/chargeable energy till customer-defined minimum SoC [Wh]	EV	Energy difference between present energy level and max BPT energy level [Wh]
14	Available/chargeable energy till customer-defined maximum SoC [Wh]	EV	Energy difference between present energy level and min BPT energy level [Wh]
15	Available energy till battery minimum SoC [Wh]	EVSE	Energy difference between present energy level and EV minimum energy level [Wh]
16	Required energy till target SoC [Wh]	EVSE	Energy needed to reach target SoC at departure time [Wh]
17	Energy till max. battery SoC [Wh]	EV	Energy difference between present energy level and EV maximum energy level [Wh]
18	Location [address or GPS]	EV	Location of the EV
19	Smart charging / bidirectional charging enabled [yes/no]	EVSE	BPT enabled [yes/no]; FPT enabled [yes/no]
20	EV connected and available for bidirectional (dis-)charging	EVSE	BPT enabled [yes/no]; FPT enabled [yes/no]
21	UC mode [V2H / V2G] (static)	EVSE	Static indication whether grid injection is possible

22	Specifications on limitations on bidirectional charging (e.g. virtual mileage)	EV	OEM-defined limits on bidirectional charging
23	Current limitations on bidirectional charging (e.g. virtual mileage)	EV	Current remaining limits on bidirectional charging usage
24	Vehicle ID	EV	Unique EV identifier (e.g. EVCCID, lifetime)
25	State of the grid (local congestion / redispatch need)	DSO / MPO	Grid state information (e.g. power envelope, LPC signals)
26	DSO grid tariffs	DSO	Applicable distribution grid tariffs
27	Flexibility service activation signal	FSP / DSO / TSO	Signal activating contracted flexibility services
28	Meter-ID / MaLo	User / DSO	Unique metering or market location identifier
29	Commodity price	User / Energy supplier	Time-of-use / variable electricity price [ct/kWh]