

Marine – Megawatt Charging Systems

Paving the way to Waterborne Charging Systems, based on solutions already implemented in-field

An industry whitepaper with lessons-learnt, specifications and recommendations for standardization bodies and marine stakeholders

Company	Authors	Contact
Wabtec Corp.	Álvaro Reina Guido Gommer Pietro Grippi	FSG-sales@wabtec.com
Damen Shipyards	Peter Rampen	Info@damen.com
Siemens eMobility	Dr. Thomas Gerrits	Tender.benelux.si@siemens.com
Valencia Port Fund.	Arnau Asensio Mar Vicente Aurelio Lázaro	Acampos@fundacion.valenciaport.com

Table of Contents

Executive summary – Why Marine-MCS?	1
1. Marine Stakeholders Requirements	2
1.1. Vessel Offshore Requirements	2
1.2. Port Onshore Requirements	4
1.3. M-MCS Electrical Vehicle Supply Equipment (EVSE) Requirements	5
2. Proposed solution for manual & automated M-MCS	5
2.1. EVSE System Specifications	5
2.2. Vessel System Specifications	6
2.3. Manual M-MCS Specifications	7
2.4. Automated M-MCS Specifications	8
2.5. M-MCS Charging Site and Test setup	8
3. Port Interoperability, Scalability and Replicability	9
3.1. Interoperability and Replicability Framework	9
3.2. Scalable and Industry 4.0-Enabled Port Electrification	9
3.3. Return of Investment (RoI) and Economic Viability	10
4. Conclusions – Towards M-MCS Standardization	11

Authors:



Industry Acknowledgement:

Part of this whitepaper's outcomes were developed under EU project ©HYPOBATT. Partially funded by European Union's Horizon Europe Programme under Grant Agreement N° 101056853. The initiative has been framed within the Zero-Emission Waterborne Transport (ZEWT) partnership HYPOBATT - waterborne.eu. The views expressed are solely those of the authors and do not necessarily reflect those of the European Union or other companies – Copyright© contributing authors.



Co-funded by the
European Union

Executive summary – Why Marine-MCS?

Marine electrification is a key enabler of maritime decarbonization, supporting European climate objectives while reducing emissions and improving air quality in ports and coastal areas. To enable widespread deployment of high-power vessel charging, standardized and interoperable solutions are required. Building on the Megawatt Charging System (MCS) standard developed for heavy-duty transport, the industry and marine companies authoring this whitepaper have conceptualized, developed and tested in real-life environments marine megawatt-scale charging solutions for electric vessels, validating fast, safe, and scalable charging. These actions have contributed to the development of the **Marine-Megawatt Charging System (M-MCS)**, which extends MCS principles to address the specific operational, environmental, and safety requirements of marine applications. This whitepaper provides **implementation-oriented guidance for ports, charging infrastructure operators, system integrators, and other stakeholders**, presenting key requirements and recommendations for deploying interoperable, modular, and future-proof maritime charging systems based on MCS technologies and relevant international standards.

- **Standardization philosophy:** M-MCS is envisaged as the MCS standard applied to the maritime environment, with the upcoming IEC/IEEE 80005-4 [1] as the marine system framework and with specific marine requirements added only where the regular MCS approach is not sufficient. Therefore, this Whitepaper recognizes IEC/IEEE 80005-4 as the natural maritime home for the DC shore-connection system requirements. Supported by CharIN MCS whitepaper [2], IEC61851 series [3] and ISO15118 series [4] framed within the waterborne sector, since they provide established charging and safety basis. Therefore, IEC/IEEE 80005-4 shall define the marine application framework, while the upcoming MCS standard, IEC 61851 and ISO 15118 provide the applicable technical building blocks. Combined, these standards can establish a solid, future-proof foundation for the much-needed Marine MCS standard.
- **Communication insights:** marine application adds constraints rather than creating a separate MCS system. For high-level charging communication, 10BASE-T1S should remain the preferred/common M-MCS approach, aligned with applicable recommendations and standards [2], [3], [4]. The authors achieved communication success using this approach, based on the system specification showcased within this whitepaper.
- **Market implementation:** The proposed Marine MCS is not a competing connector or independent standard. Instead, the whitepaper describes it as a marine application profile of MCS, scaling-up common MCS communication and safety principles while adding marine-specific requirements that are mandatory to vessels and ports. Examples are vessel motion and risk of drifting, environmental robustness, cable and automated connection device (ACD) handling, charging redundancy, port integration and longer communication distances.

1. Marine Stakeholders Requirements

1.1. Vessel Offshore Requirements

Vessels vary significantly in terms of application, size and range. These characteristics determine their onboard power demand and, consequently the shore-side power required both to supply load profiles while berthed and to charge the battery systems [5], [6]. Onshore power supply (OPS) infrastructure is increasingly being deployed in ports and along the main inland shipping routes [7]. Today, OPS is typically available in high-voltage AC (HVAC) for high power levels and low-voltage AC (LVAC) for power levels up to 1MVA. Battery charging requirements for electric and hybrid vessels range from several hundred kilowatts up to multiple megawatts, depending on vessel type and operational and/or charging profiles. Larger vessels, such as RoPax ferries, cruise ships and offshore service vessels, generally have sufficient space and technical capabilities to accommodate onboard high-voltage conversion systems and certified crews. However smaller and medium-size vessels often lack the space and economic justification for such crew and equipment, while LVAC typically provides insufficient power for rapid charging. For these vessels, locating the charging equipment onshore and transferring via low-voltage DC (LVDC) offers a more practical solution. As no widely adopted maritime standard currently exists for high-power LVDC, MCS provide a promising basis for maritime roll-out through the M-MCS concept. Furthermore, some vessel categories, especially ferries operating on fixed routes, have only limited time available for charging. Time lost for making the connection directly impacts in higher power charging to keep its operational timetable. For vessels with a short time for charging, or with a limited crew size, an ACD can improve charging

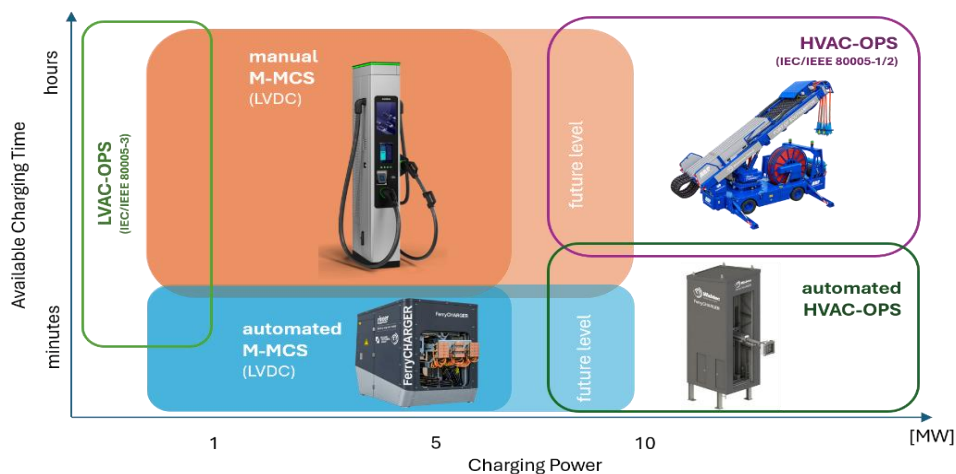


Figure 1 - Need for MCS based LVDC shore power connection in relation to other OPS types, positions on charging required power and available time (manual based on dual dispensers).

efficiency and operational reliability. Figure 1 illustrates the relationship between available shore power supply categories and vessel charging requirements, ranging from overnight charging to high power automated M-MCS charging solutions. The Manual M-MCS showcased here uses a dual-dispenser configuration to support dual power circuits and vessel connectors while enabling scalable power delivery.

Vessel size and design vary, preventing a fixed charging inlet

location. Waves, wind, loading and tides also cause vessel movement relative to the quay, making connection more demanding than on-road transport (see Figure 2). Cable management must therefore adapt to vessel and port conditions while remaining MCS-compliant. Two complementary approaches are considered: **Manual and Automated M-MCS**, both requiring robust and safe designs to handle high charging power, vessel movement, harsh marine conditions and long quay-to-vessel connection distances.

1.1.1. Manual M-MCS requirements

Manual Marine-MCS should combine safe operation, cable ergonomics, low lifecycle cost and long-term durability.

Cable Handling: For manual MCS charging, cable weight, stiffness and cooling needs require cable support solutions to reduce operator strain and improve safety, while limiting bending, twisting and tensile loads.

Cable Length, Cooling and Cost: Longer cables increase losses, conductor size, weight and cooling needs. Cable length should therefore be minimized through charger placement and berth design, with cable management being often more cost-effective than larger conductors and cooling systems.

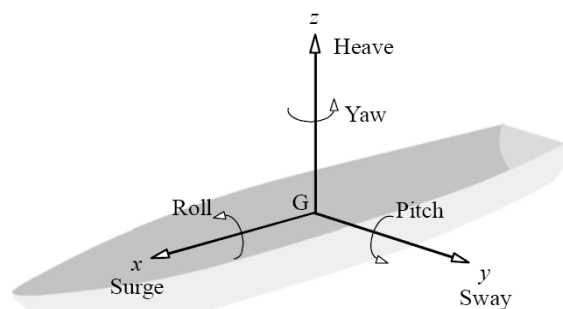


Figure 2 - Six-degrees-of-freedom for ship motion

Protection and Locking: The connector shall remain de-energized until insertion, communication and safety checks are complete. Mechanical locking shall prevent disconnection, confirm engagement, allow emergency release and enable power only when securely connected. Cable tension monitoring and fast emergency disconnect are also required in case of vessel drift. **Corrosion and Marine Environment.** Marine charging equipment must withstand salt spray, humidity, rain, UV and temperature variations. Marine-grade, corrosion-resistant components, high ingress protection, drainage and easy maintenance access are essential for reliability and low downtime.

1.1.2. Automated M-MCS requirements

For fully electric vessels, where the onboard Battery Energy Storage Systems (BESS) constitute the primary source of energy, the vessel shall be equipped with two independent BESS, in accordance with the applicable IMO, flag-state, classification society, certification, and maritime safety requirements (see Figure 3). The authors identified the need to formalize automation-specific safety criteria while maintaining compliance with IEC 80005 Series requirements [8].

Live conductive parts shall remain inaccessible or de-energized until validated contact, actuation/ insertion/ retraction forces shall be limited, and human presence in the active area shall be excluded by barriers, inspection and interlocks. Finally, each installation should include a vessel-shore compatibility assessment covering berth layout, tidal conditions, weather, loading operations, and local hazards. Automated connection shall ensure the following: (1°) reduce connection /disconnection times, (2°) eliminate cable cooling requirements by avoiding manual handling, (3°) facilitate handling of the longer and heavier cables typical of maritime applications, (4°) compensate for vessel-quay position variations and distances, (5°) enhance operational safety, and (6°) enable dual charging circuitry to enable both BESS' simultaneous charging. However, date-to-day connectors are not suitable for automated connection systems, requiring the development of a new technological solution.

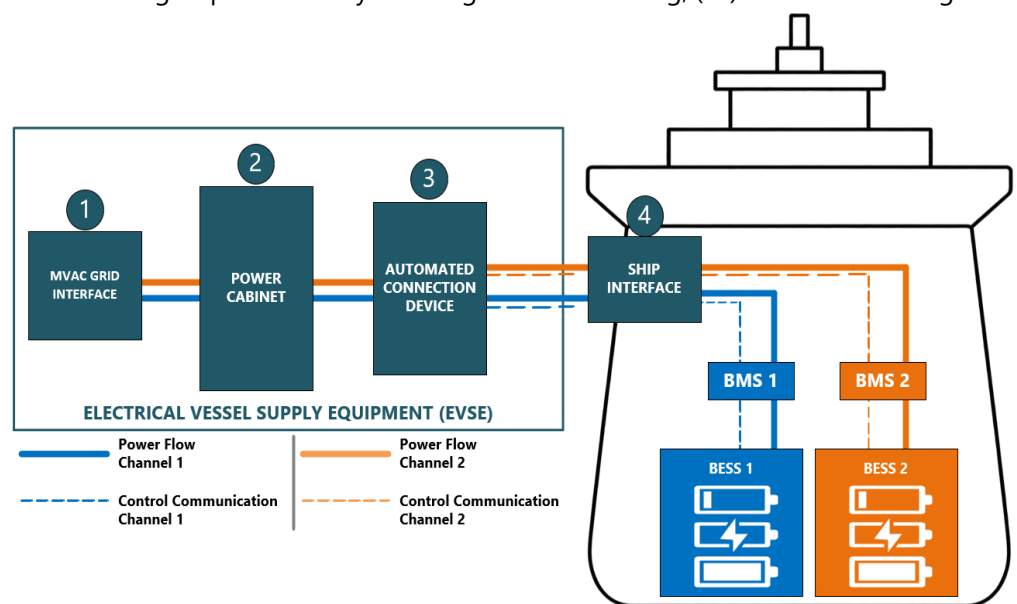


Figure 3 System overview for automated M-MCS requirements definition

For automated Marine-MCS charging, the standardization must remain on the **minimal complexity, interfaces and mass on vessels side**, that can satisfy a product design with competitive Total Manufacturing Cost (TMC), rather than prescribing fixed mechanical architecture. In-line with already proven reliable concepts (see Figure 4), the vessel-side interface must remain passive, robust and interoperable, while port-specific infrastructure and the ACD compensate alignment, distance and vessel-motion effects before enabling power transfer.

Table 1 - M-MCS Automation requirements

Need	Minimum automation requirement
Vessel Detection	Detection and identification of the vessel in charging position.
Control	Auto-align mate–monitor–retract; no manual plug handling.
Sensing	Real-time position, contact, motion and misalignment detection.
Compensation	Active. Infrastructure pre-alignment dimensions
Force	Vessel pushing force minimised; ideally near zero.
Ship interface	Passive, robust, low-maintenance, standardised.
Envelope	Baseline $\approx 1.5 \times 1.5 \times 0.3$ m; adaptable side/top.
Disconnect	Fast safe release under departure or abnormal motion.
Interlocks	Energise only after position, contact and Control Pilot / Communication verified.

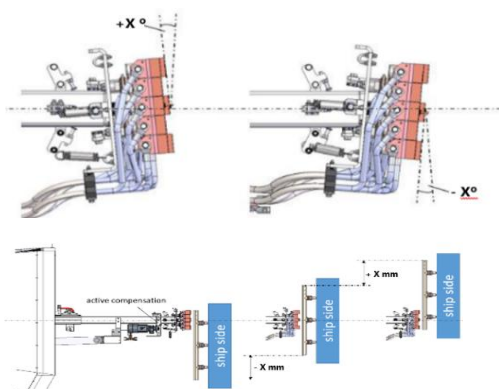


Figure 4 Key angles and lengths to be defined for an automated telescopic arm

From a standardization perspective, the automated M-MCS interface requires definition of the **basic signalling sequence** and operative control procedure, contact confirmation, energization, charging, fault reaction and disconnection. Beyond mechanical alignment, the standard should require continuous basic signalling and digital communication supervision, verified contact quality before voltage enable, and fail-safe behaviour under signal loss, premature vessel departure or abnormal motion.

1.2. Port Onshore Requirements

The transition towards battery-electric vessels goes well beyond installing charging equipment, requiring long-term planning of electrical networks, berth layouts and Energy Management Systems (EMS) (see Figure 5 Electrical Ecosystem at ports visualizing different M-MCS use-cases). As electrification progresses, charging infrastructure will become as strategic as traditional bunkering facilities. The first applications expected to adopt battery-electric propulsion are those operating on fixed and predictable routes where charging occurs naturally during regular port calls: passenger ferries, Ro-Ro vessels, port service vessels, tugboats and offshore support vessels. With docking times typically ranging from a few minutes to less than one hour, megawatt-scale charging becomes an operational necessity, without it, operators would require either significantly larger batteries, battery swapping, or longer turnaround times. As battery technology evolves, this can progressively expand to coastal cargo and offshore construction vessels. Ports therefore require modular and scalable solutions, allowing power levels and charging points to grow alongside demand.

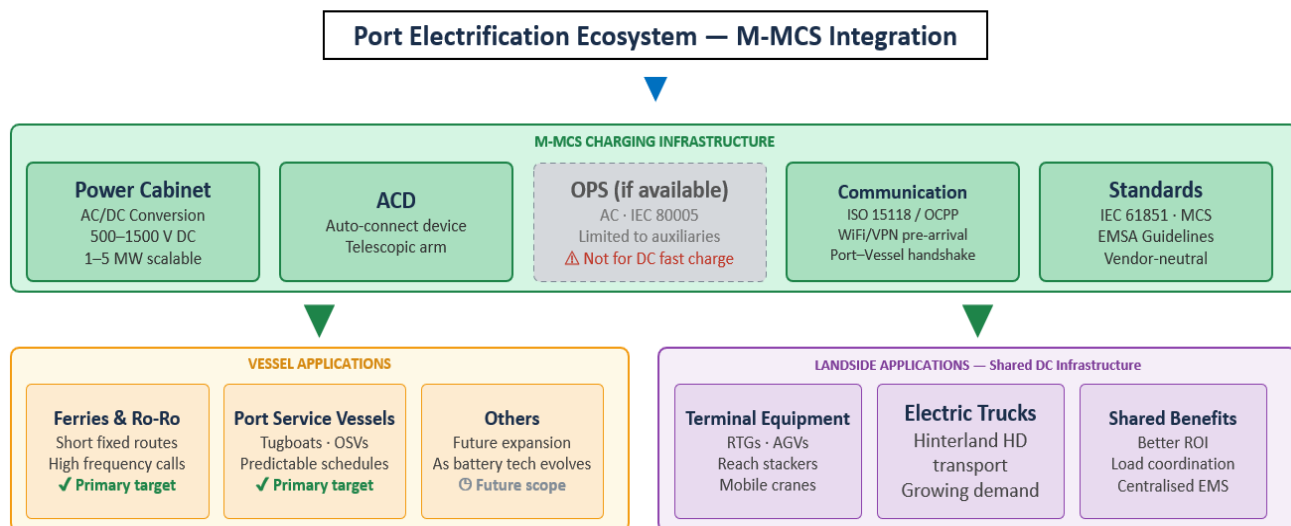


Figure 5 Electrical Ecosystem at ports visualizing different M-MCS use-cases

Beyond vessel charging, ports are also electrifying terminal equipment and hinterland transport, which require similar power levels and complementary operating schedules, enables shared use of high-power DC infrastructure, improving utilisation and reducing overall electrification costs. It also supports centralised energy management, load balancing, and more efficient integration of renewable energy and battery storage, capabilities that become increasingly critical as ports evolve into complex electricity and multi-energy hubs. Finally, interoperability remains a key requirement for port infrastructure. Ports cannot invest in charging systems tied to individual vessel manufacturers or proprietary technologies. In line with EMSA recommendations [9] and the ongoing evolution of IEC standards, a standardised Maritime Megawatt Charging System provides the common framework needed for different vessel types, equipment suppliers and future heavy-duty applications to operate safely over shared infrastructure. This standardization will reduce investment uncertainty, simplify future expansions and accelerate the deployment of battery-electric vessels and port equipment across European ports [10].

1.3. M-MCS Electrical Vehicle Supply Equipment (EVSE) Requirements

As opposed to regular MCS, which is aimed at megawatt-class charging infrastructure for heavy-duty road transport vehicles [11], and R-MCS, which is aimed at Ruggedized MCS charging connections [12], M-MCS has 2 distinctive key-difference requirements; 4&7 in below Table 2. The risk of a vessel drifting away from the quayside due to a mooring failure, wind, or unintended (tidal) movement requires a fast emergency disconnect system. For Automated M-MCS systems this translates to the requirement that the time between Charge Enable (CE), and power contacts (DC+/-, PE) disconnection should be longer than the emergency shutdown and optionally unlocking stages to prevent arcing. For manual M-MCS systems this requires that a cable tension exceedance leads to a fast emergency disconnect consisting of emergency shutdown, unlocking and tension relief by disconnection in advance of damage. For both solutions the timing depends on the defined maximum allowed dynamic movement, which could vary per application. Another important aspect is the power interface redundancy as motivated in section 2.2; sea-worthy vessels require a fall-back to assure safely reaching the shore in case of a failure in one of the propulsion systems. Referring to the charging system, this can be achieved with full-redundancy using 2 equal parallel EVSE-plug EV-inlet circuits, or partly redundant with shared communication and/or power.

Table 2 Main requirements for a Marine Megawatt Charging System

1. MCS requirements according to IEC 61851-23-3 [13], ISO 15118-20 [14], and applicable marine standards [10].	2. MV AC supplied, wherein OPS (6.6/11 kV and 50/60 Hz) must be a possible supply solution
3. The M-MCS voltage specifications should cover the DC voltage range: 500-1500 V DC (equal to R-MCS proposed)	4. Fast emergency disconnect solution preventing arcing and/or cable rupture in case of unintended vessel movement
5. Compliance with the port mechanical, electrical, and communication requirements; IEC/IEEE 80005-1 [15], & -3 [16].	6. Minimized quayside space usage, requiring slim dispensers or ACD housing, and cable management.
7. To assure maximum redundancy, a dual-circuit solution exists for the complete LV section to separately charge the 2 EV batteries	8. Fully self-supplying system; supply of ancillary power to auxiliary loads such as cooling and dispensers should be provided (no additional LV AC supply needed)
9. Scalability with multiple converters to increase DC output power capabilities according to Figure 1	10. Connection to Port operator's back-office according to OCPP
11. Full system suitable for -30 to +50 °C ambient temperature	12. Sea-climate proof system; IP65/IK11 protection and C5-M environmental conditions suitable
13. <i>Highly recommended</i> : BESS integration to reduce MV AC grid peak loads and support the grid when EV charging is off.	14. <i>Highly recommended</i> : the possibility to enable MV AC grid power quality (PQ) services.

2. Proposed solution for manual & automated M-MCS

M-MCS charging solutions using manual plugging and automated connection will be provided in the following, which are proven by practical validations. Having showcased both solutions – physically unique but electrically equal – on the same vessel, **exchangeability and applicability are demonstrated for maritime use**.

2.1. EVSE System Specifications

As listed in Figure 1, an M-MCS charging solution should cover a wide voltage- and current-range to be interoperable with the mentioned interfaces. This should be combined with an efficient and modular power conversion concept to assure minimized CapEx in the form of raw-material use, and Operational Expenses (OpEx) resulting from e.g. energy loss reduction and MV grid services by enabling requirements 13 & 14, from Table 2.

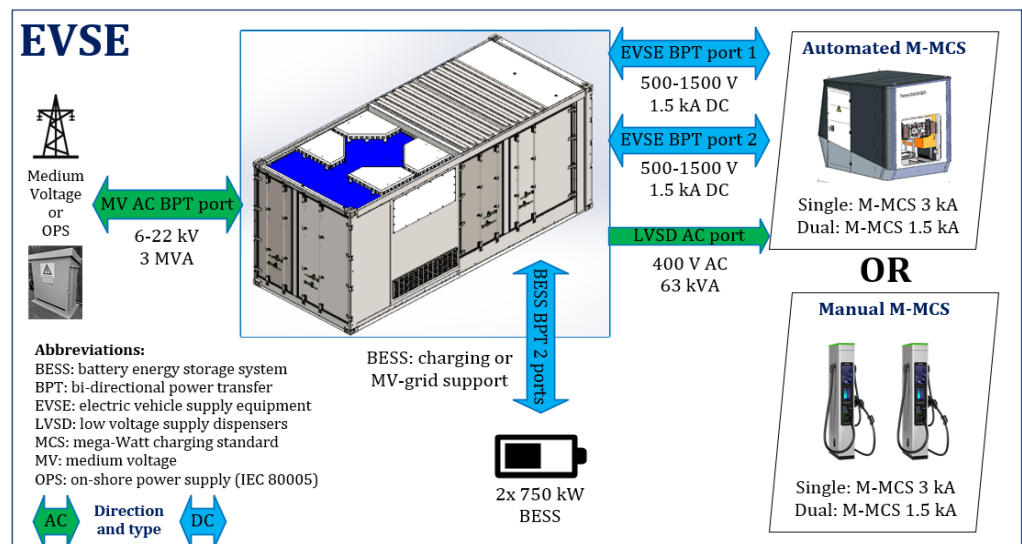


Figure 6 Proposed M-MCS suitable EVSE system with different EV connection options

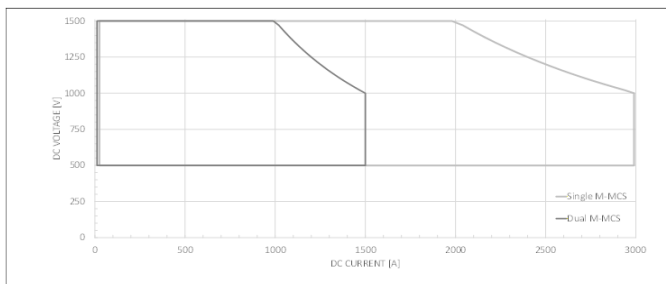


Figure 7 Current – voltage relation scalable DC power curve envelopes for the respective M-MCS types as shown in Figure 6.

To enable such solution, a 3 MW power container, Figure 6, has been developed within the HYPOBATT project [17], capable of providing the DC power curve envelopes as, indicated in Figure 7, therewith capable of scaling with the shown connection interfaces, from 1.5 to 3kA per channel (although HYPOBATT team implemented this up to 2.5kA to fulfil the in-field requirements). To allow for the connection of multiple power containers to an MV AC grid feeder, each container is equipped with a 3-field MV switchgear set (RRL); 2 ring fields (R) for cascaded connection of multiple containers and/or connect it in an MV-ring, and 1 load field

(L) to which the EVSE power conversion equipment is connected. On LVDC side (EVSE BPT ports), multiple containers can be paralleled to increase the DC power to multiples of 3 MW in-line with the needs defined in Figure 1.

2.2. Vessel System Specifications

Several interfaces must be considered, including power, mechanical, ergonomic, control, earthing & EMC, safety and cooling. Further information about them is here below provided.

Power interfaces: Fully electric vessels require two independent BESS and electrically separated power sections in accordance with applicable classification and maritime safety requirements. M-MCS should therefore support two independent charging paths, each supplying its respective BESS/LVDC section, directly or through DC/DC converters (see Figure 8). The proposed reference architecture uses two separate charger connections, each rated up to 3 MW (MCS Level 3), enabling up to 6 MW (2×3 MW) while maintaining electrical separation between both power paths. If a bus-tie is provided, it must remain open during charging, subject to the vessel's electrical and safety requirements.

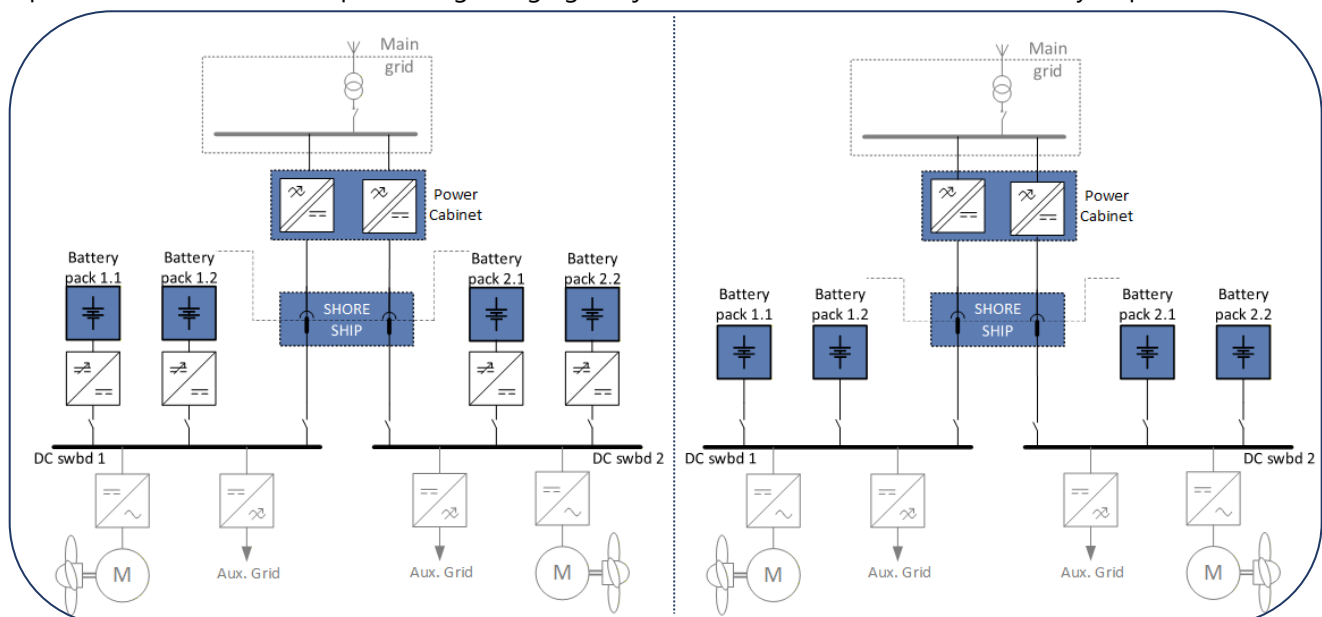


Figure 8 Proposed charger connections for electric vessel basic power system topologies containing at least 2 sections; fixed DC-bus with batteries via DC/DC converters (left), or floating DC-bus with batteries directly connected (right).

The fixed and floating DC-bus architectures in Figure 8 constitute the cornerstone reference architecture for M-MCS, representing the fundamental BESS-to-LVDC integration approaches and establishing the basis for charging, redundancy and electrical separation requirements. As per specific use-cases requirements and electrical providers specifications, alternative SLD configurations remain possible, provided they preserve equivalent safety, redundancy, electrical separation, interoperability and shore-interface principles.

Mechanical and Ergonomics: The M-MCS power connection can be either made by the manual MCS plugs (suitable for marine environment) or by the ACD. Figure 9 showcases the implementation of both typologies on the same ship. Due to the diversity of ship appearances, a fixed location cannot be determined, but the inlet should be close to the (normal) quay side and easily accessible by the operator in case of manual connection. For larger distances between dispenser and ship inlet, cable support systems should be considered. For safety reasons the inlet locations should not be accessible to the public. Special attention should be given to the mooring position and ship motions, in case an ACD connection is used.



Figure 9 Same ship (dual) connection mated with manual connection (left) and temporary HYPOBATT ACD connection (right)

Control interfaces: The MCS communication is required for a safe and optimal power transfer. For each charger inlet, an Electric Vessel Charge Controller (EVCC) should be implemented, acting as the communication interface between the EVSE and the

ships' Power Management System (PMS). In the HYPOBATT project the standard MCS EVCC communication and control functions have been used based on T1S, where some changes were made on the PMS interface towards the EVCC.

Earthing & EMC: For safety reasons, both the MCS standard and the maritime shore power standard require equipotential bonding between shore and ship. A galvanic isolator should be considered to reduce the risk of galvanic corrosion. The galvanic isolator should be connected between ships PE connection (to hull) and shore/EVSE PE. The risk of electrolytic corrosion due to stray currents from this LVDC shore power is low, because a charging session will be stopped in case of an earth fault. Loss of the equipotential bonding is, due to the conductive connection through the water (incl. fresh water), difficult to detect by means of the basic signalling. Regular inspection of the PE connections is advised. For safety reasons and IMD timing the power system capacitance to earth is limited by the MCS standards. This Y-capacitance limit allows lower values at higher voltage levels dependent, which needs attention especially for larger ships power systems. Therefore, attention is required to meet the Y-capacitance limits and related common mode voltage emissions. **Cooling:** The MCS current will generate significant heat dissipation. For MCS level 2 (< 1.5 kA), only passive colling is required for the inlet thermal design. For MCS Level 3 (1.5 - 3 kA), cooling requirements differ between manual and automated M-MCS. Manual connections require active liquid cooling, whereas automated solutions can enable higher-current connections with passive cooling, as manual cable-handling constraints are removed. **Safety:** Fundamental M-MCS requirement due to high-power electricity, vessel movement and harsh marine conditions. Power transfer shall only start after communication, connector verification and safety interlock activation, with insulation, temperature, contact quality and communication continuously monitored. Manual and automated solutions shall be fail-safe, triggering controlled shutdown and safe disconnection upon communication loss, abnormal vessel movement or equipment faults. Mechanical locking shall prevent unintended disconnection while allowing emergency release, thereby excluding the R-MCS approach [12]. Energized and automated areas shall be protected by barriers and interlocks, with emergency stops accessible from vessel and shore. Site-specific risk assessments shall cover berth layout, environment, vessel characteristics and port operations.

2.3. Manual M-MCS Specifications

The [Frisia E-I](#) fully electric ferry has its dedicated LVDC shore power connection. Consisting of two galvanically separated LVDC supplies, where the connections are made by means of MCS (level 2) connectors (see Figure 1). While other aspects like communication are not on according MCS charging standards. A special tower was developed to achieve an easy and relative quick connection operated from the ship bridge area.



Figure 10 Manually operated dual-MCS plugging into the vessel

2.4. Automated M-MCS Specifications

Considering the automatic connector requirements (see section 1.1.2), the Automated M-MCS product required a dedicated design. The connector was designed and validated to work for either charging one BESS up to $1500\text{V}/6000\text{A}_{\text{Peak}} - 5000\text{A}_{\text{Contr}}$ or two independent battery systems up to $1500\text{V}/3000\text{A}_{\text{Peak}} - 2.5\text{A}_{\text{Cont}}$ each, in accordance with the scalability indicated in Figure 1. External I/O multiplexers enable dynamic switching between the two configurations. A fully passive ship interface compensates vessel heave, while all shore-side operations are fully automated (compensating all the other movements). Fail-safe operation is ensured through continuous monitoring of connection status, communications (MCS low-level and T1S-SPE high-level), vessel dynamics, temperatures, and equipment faults, enabling controlled shutdown and safe disconnection when required, disabling electrical disconnection before mechanical disconnection as safety procedure to prevent arcing (see section 1.3).

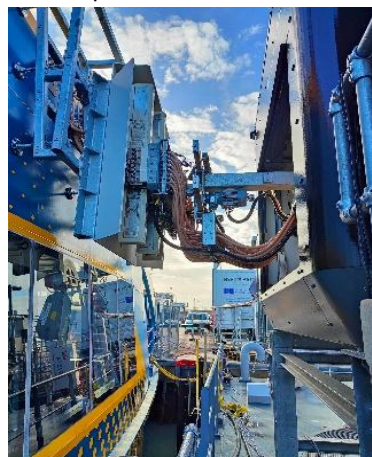


Figure 11
One out of the two temporary commissioned installations for the FRISIA Demonstration site (both charging 2 independent BESS at $995\text{V} - 875\text{A}$ each, with both MCS & T1S-SPE communications active)

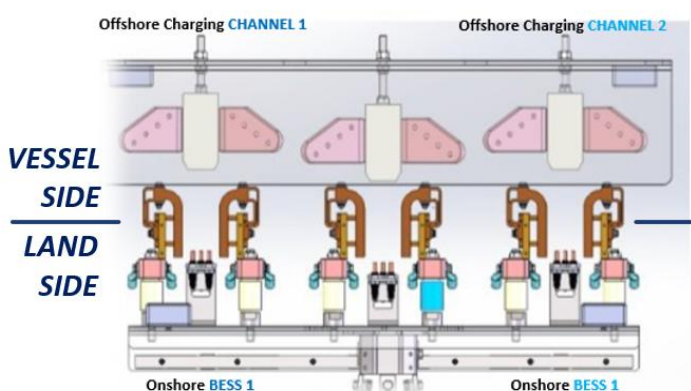


Figure 12 Automated M-MCS dual-circuitry concept in disconnected phase

With these conceptual approaches, the vessel's two redundant BESS are charged independently, maintaining full electrical and functional separation between them. While the mechanical parts of the three charging connectors are integrated into a single moving frame, galvanic isolation is preserved between the two independent battery systems and their respective charging circuits, centralizing PE and CE signals in the product (see Figure 12 Automated M-MCS dual-circuitry concept in disconnected phase). As a result, the charging voltage and current can be optimized individually according to the specific requirements of each BESS. This represents a major step forward on smart marine charging systems.

2.5. M-MCS Charging Site and Test setup

To verify different charging system configurations, the test site was set up as shown in Figure 13. Therein, the distributed supply equipment structure consisting of the 3 MW charger power conversion container and EVSE connector is shown. The demonstrated manual and automated EVSE connector and ship interface for this correspond to those indicated in

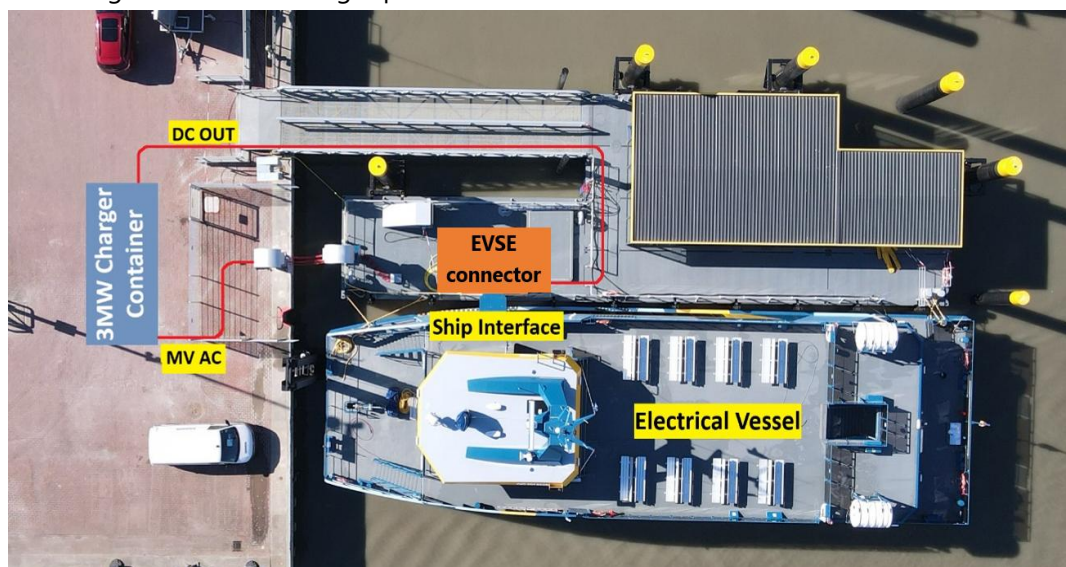


Figure 13 Overview of the test system installation at Frisia site with indicated components

Figure 10 and Figure 11, respectively. An approximate trajectory of 40 meters DC OUT cabling is installed which can be extended up to 100 meters but should be minimized from cost and efficiency perspective.

3. Port Interoperability, Scalability and Replicability

The integration of M-MCS into ports requires coordination between multiple stakeholders, including port authorities, terminal operators, vessel operators, grid operators and technology providers. A key limitation for the deployment of M-MCS is currently the relatively small number of vessels equipped with battery systems and capable of megawatt-scale charging, although battery-hybrid and fully electric vessels are becoming increasingly relevant in the market. Beyond vessel availability, deployment also depends on sufficient electrical capacity, proximity of the grid connection to the berth, space for charging equipment, and integration with existing port operations.

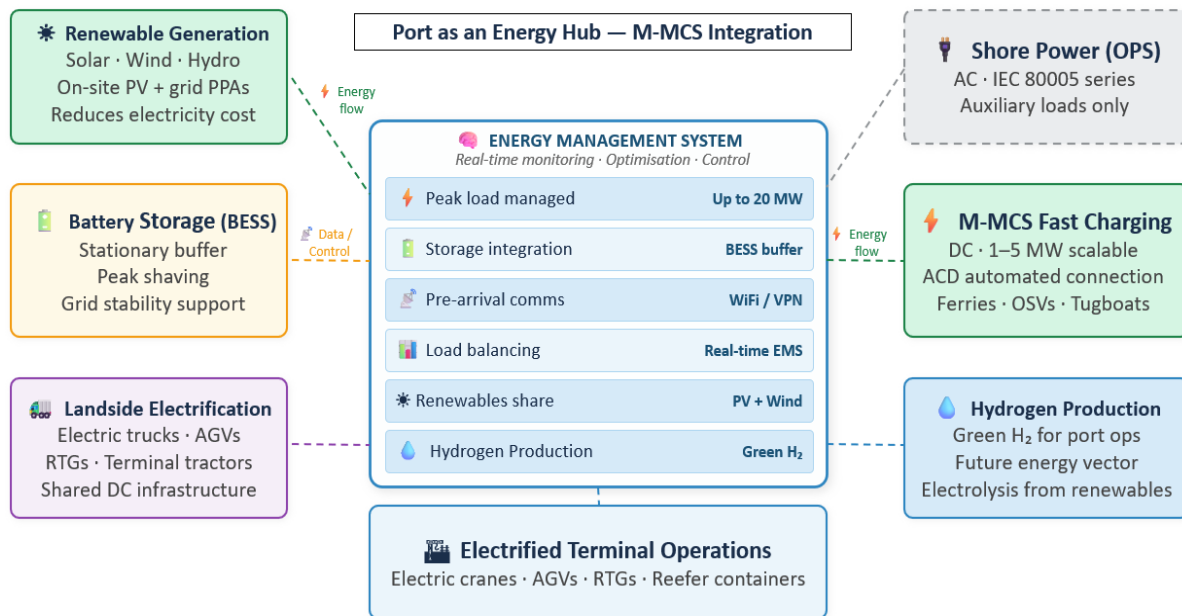


Figure 14 Energy usage at ports

The HYPOBATT solution can be integrated into the port energy system as a high-power energy hub, rather than being limited to vessel charging. The same electrical infrastructure can supply energy to different users within the terminal, including vessels at berth, electric trucks, terminal tractors and other cargo-handling equipment. This shared use increases the utilisation of the installed charging capacity and allows the infrastructure to support the progressive electrification of both maritime and landside operations. Integration with a port's EMS (see Figure 14) can further improve the use of available energy and grid capacity by forecasting demand, coordinating charging with other port loads and limiting simultaneous power peaks. Combined with renewable generation and BESS, this optimisation can reduce the underlying cost of electricity and improve the economic performance of the charging service.

3.1. Interoperability and Replicability Framework

Frameworks holding the most of potential for replicability belongs to Ports with predictable and concentrated charging demand. Ferry terminals are particularly attractive due to their regular schedules, short port calls and high-power charging requirements, which facilitate energy forecasting, infrastructure sizing and system utilisation. Ro-Ro terminals offer similar advantages while also enabling charging services for landside applications such as electric trucks, terminal tractors and operational fleet vehicles, as showcased in the HYPOBATT Replication & Scale-up Handbook [18].

3.2. Scalable and Industry 4.0-Enabled Port Electrification

The large-scale deployment of high-power charging systems presents challenges that vary according to port characteristics. Smaller ports often face limitations related to grid availability and installed electrical capacity, while larger ports must manage additional loads that compete with existing energy-intensive operations such as cranes, refrigerated terminals and cargo-handling equipment. Future electrified ports will require an integrated energy ecosystem combining upgraded substations, EMS, BESS and local renewable generation. A phased deployment strategy, starting with pilot installations and progressively expanding capacity, represents the most realistic pathway towards large-scale adoption.

Scalability can be further enhanced through the shared use of electrical infrastructure for both maritime and landside applications. While ferry terminals mainly serve passenger vehicles, Ro-Ro and container terminals can also support

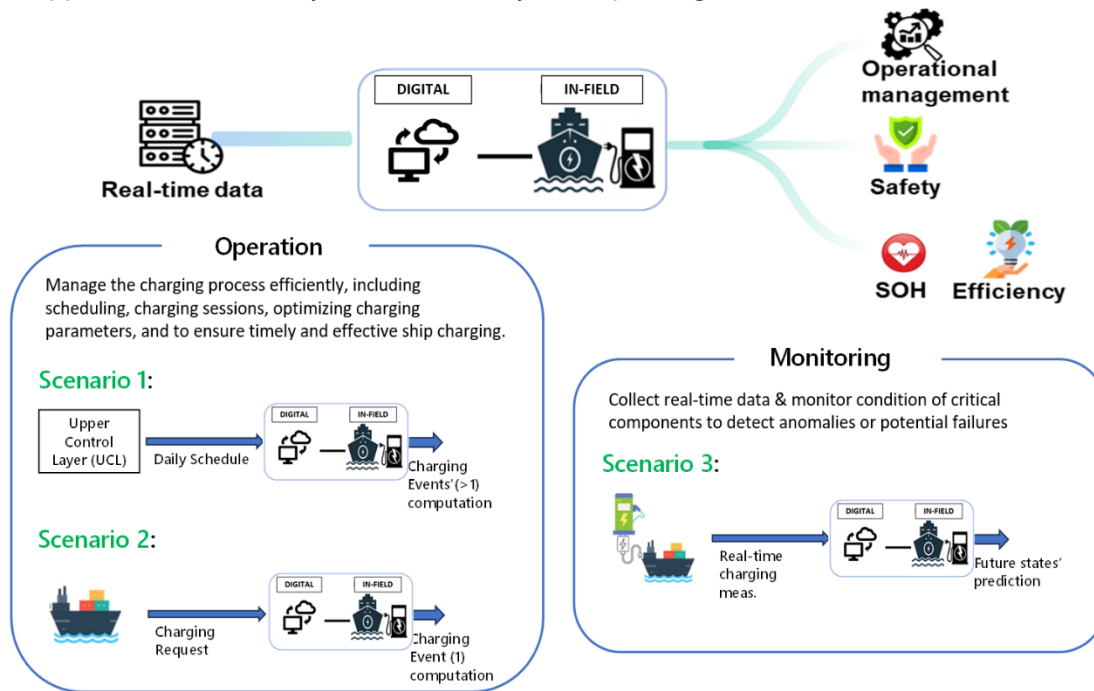


Figure 15 Architecture framework for Control and Optimization of electric vessel charging events and energy at the port's premises

operations, based on the following, but not limited to, benefits: Optimized vessel charging schedules, smart energy usage, decreased electricity OpEx for ports, increased lifetime of BESS for vessels charging at a port (through optimized charging profiles according to the BESS's State of Energy (SoE) and available mooring times– which in turns increase port usage attractiveness for regional ships' operators, and stakeholders [19].

3.3. Return of Investment (RoI) and Economic Viability

The economic viability of M-MCS depends on investment, energy throughput, asset utilisation, electricity and grid costs, and the charging business model, requiring assessment for each port and vessel operation. Predictable, recurring charging demand, particularly on fixed routes, improves infrastructure utilisation and planning. Further benefits arise when grid connections, power conversion, BESS and EMS are shared with landside applications, increasing utilisation and reducing duplicated infrastructure. HYPOBATT Deliverable D6.5, Full HYPOBATT and Hyper Charging Business Plan and Scaling Strategy [20], assessed several project-specific use cases. For the analysed Gandía use case, the business-case model indicates strong sensitivity to the charging-service mark-up: a 10% mark-up results in an estimated 13-year payback, while 20% reduces payback to approximately 5 years. Importantly, this RoI excludes potential additional port revenues from offering ship operators a more competitive charging solution. These results are specific to the scope, assumptions and operating profile of the analysed use case. They should not be interpreted as generally applicable equipment pricing or as guaranteed payback periods for other M-MCS installations. The reported calculations exclude government incentives and penalties. Across the use cases analysed in Deliverable D6.5, optimisation measures including BESS integration, local renewable generation and alternative infrastructure configurations reduced the modelled average energy cost by between 5% and 33%, depending on the scenario. The benefits achievable in an individual project will depend on local electricity tariffs, grid conditions, vessel schedules, annual energy demand and infrastructure utilisation.

Table 3 Considerations for project-specific economic assessment

1. Expected vessel calls and annual charging energy.	2. Charging duration, peak power and infrastructure utilization.
3. Charging equipment, connection equipment, grid connection and civil-work investment.	4. Electricity prices, grid fees and peak-demand charges, charging-service pricing, business ownership.
5. Maintenance, inspection, service & component-replacement costs.	6. Integration of BESS and local renewable generation. Applicable public funding or port-electrification incentives.
7. Potential shared use by maritime and landside applications.	8. Applicable public funding or port-electrification incentives.

The HYPOBATT results indicate that M-MCS may provide an economically viable pathway under suitable operating and commercial conditions. However, economic performance is strongly influenced by infrastructure utilisation and the characteristics of the local energy ecosystem. A site-specific assessment is therefore required to determine the appropriate technical configuration and commercial model.

4. Conclusions – Towards M-MCS Standardization

The work presented in this whitepaper demonstrates that MCS provides a viable foundation for interoperable megawatt-scale DC vessel charging when adapted to maritime requirements. Manual and automated M-MCS solutions have been developed and validated under representative operating conditions, demonstrating a common electrical and communication architecture that supports different physical connection concepts, modular power scaling and independent vessel BESS sections. The practical experience from HYPOBATT provides evidence of technical feasibility and, critically, identifies the remaining gaps to be addressed by future standards.

The key conclusion is that M-MCS should not become a separate charging ecosystem, but a maritime implementation of MCS. Established MCS principles for power transfer, communication and functional safety should be preserved, adding only requirements specific to marine operation. These include vessel motion and environmental exposure, variable berth geometry and connection distances, cable management, BESS redundancy, emergency disconnection and automated connection. For automation, standards should define functional interfaces, operating envelopes, connection sequences, sensing, interlocking and fail-safe behavior, without prescribing a single mechanical ACD design.

At port level, M-MCS should form part of a scalable and integrated energy ecosystem, combining modular power conversion, EMS, BESS, renewable generation and shared infrastructure with other heavy-duty applications. Site-specific vessel-shore compatibility assessments will remain necessary to address berth, grid and local operating conditions. Overall, the demonstrated solutions and lessons learned establish a practical industry baseline for safe, interoperable, scalable and replicable M-MCS deployment, while providing concrete input to the upcoming **IEC 80005-4 and related MCS, IEC 61851 and ISO 15118 standards. The goal is not to reinvent MCS for marine applications, but to build on its foundation, standardize what is marine-specific, and enable one globally interoperable M-MCS charging framework.**

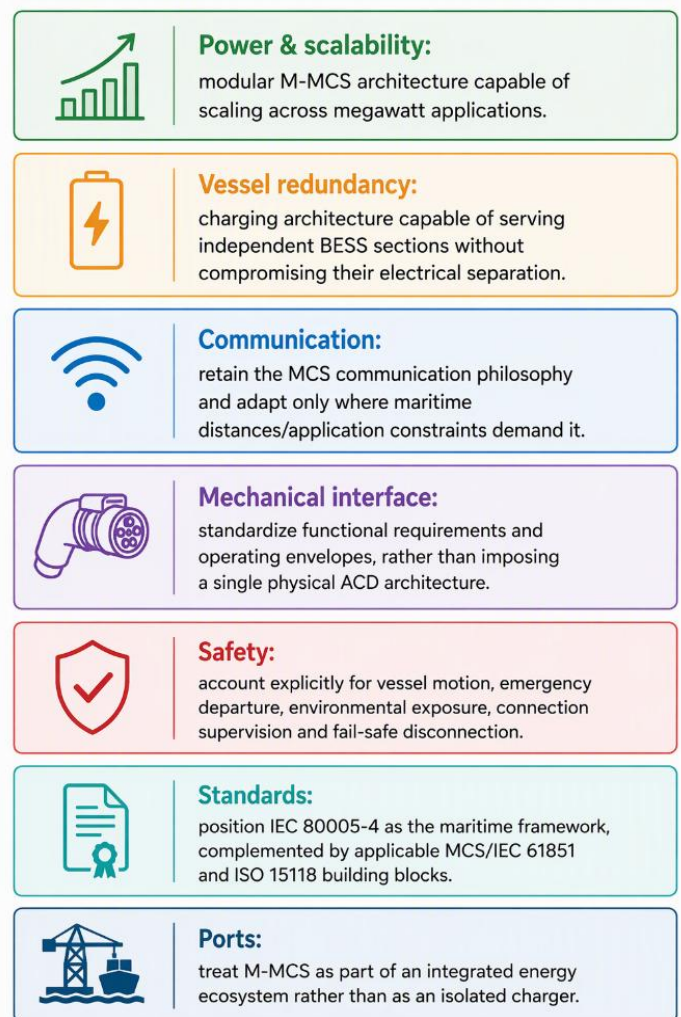


Figure 16 M-MCS Whitepaper-Conclusion Blocks

References

- [1] IEC/IEEE P80005-4, "Utility Connections in Port - Part 4: DC shore connection (DCSC) systems - General requirements".
- [2] Charging Interface Initiative e.V. (CharIN) , "Megawatt Charging Systems - Whitepaper under development (work in progress)".
- [3] IEC 61851 series, "Electric vehicle conductive charging system. International Electrotechnical Commission (IEC)".
- [4] ISO 15118 series, "Road vehicles — Vehicle to grid communication interface." [Accessed 2026].
- [5] HYPOBATT Project, "High power charging technology overview - Report" [Accessed 2026].
- [6] HYPOBATT Project, "Marine hyper charging application overview, KPI's and specifications - Report" [Accessed 2026].
- [7] HYPOBATT Project, "Port integration and grid interface requirements - Report" [Accessed 2026].
- [8] IEC/IEEE, "80005 standard series".
- [9] EMSA (European Maritime Safety Agency), "Shore-Side Electricity (SSE) - 19 July 2022. [Online]. Available.
- [10] HYPOBATT Project, "Regulatory recommendations for enhanced marine standardization - Report" [Accessed 2026].
- [11] IEC - TC69, *Electric vehicle conductive charging system -- Part 23-3: DC electric vehicle supply equipment -- Megawatt charging systems*, Geneva, Switzerland: International Electrotechnical Commission, 2026.
- [12] Ruggedized MCS Task Force (CharIN and ICMM), *Ruggedized Megawatt Charging System (R-MCS)*, 2024.
- [13] IEC 61851-23-3, "Electric vehicle conductive charging system - Part 23-3: DC electric vehicle supply equipment - Megawatt charging systems" [2026].
- [14] ISO 15118-20, "Road vehicles — Vehicle to grid communication interface — Part 20: 2nd generation network layer and application layer requirements. Amd 1: Amendment 1: AC DER service, MCS service, and improved security concept)" [2022/Amd 1:2026].
- [15] IEC/IEEE 80005-1, "Utility connections in port – Part 1: High voltage shore connection (HVSC) systems – General requirements".
- [16] IEC/IEEE 80005-3, "Utility connections in port – Part 3: Low voltage shore connection (LVSC) systems – General requirements".
- [17] HYPOBATT "Hyper powered vessel battery charging system" Project [Online]. Available: www.hypobatt.eu. [Accessed 2026].
- [18] HYPOBATT Project, "Replication & Scale-up Handbook" [Accessed 2026].
- [19] G. Elezgarai et al., "Cloud-Based Digital Twin for Optimized Multi-Megawatt Charging Control Strategies in Maritime Applications," ESARS-ITEC. Naples, Italy, pp. 1-6, doi: 10.1109/ESARS-ITEC60450.2024.10819875, 2024 IEEE International.
- [20] HYPOBATT Project, "Full Hypobatt and hyper charging business plan and scaling strategy" [Accessed 2026].

