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D3.1 BlueBARGE: Power supply modules and microgrid specifications

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Acronyms and Abbreviations

Acronym/Abbreviation	Meaning
BMG	Barge Micro Grid
BMS	Battery Management System
CHB	Cascaded Half-Brigde
DCMG	DC Micro Grid
DER	Distributed Energy Resource
EDLC	Electrochemical Double-layer Capacitor
EMS	Energy Management System
ESS	Energy Storage System
FC	Fuel Cell
FFR	Fast Frequency Response

HT	High Temperature
HV	High Voltage
HVSC	High Voltage Shore Connection
ICE	Internal Combustion Engine
LNG	Liquefied Natural Gas
LV	Low Voltage
LVSC	Low Voltage Shore Connection
MCFC	Molten Carbonate Fuel Cell
MGO	Marine Gas Oil
MMC	Modular Multilevel Converter
MV	Medium Voltage
NaS	Sodium-Sulfur
NiCd	Nickel-Cadmium
NiMH	Nickel-Metal Hydride
NPC	Neutral-Point Clamped
OPS	Onshore Power Supply
PEM	Proton Exchange Membrane
Pb-A	Lead-Acid
PMS	Power Management System
PSM	Power Supply Module
RTE	Round Trip Efficiency
SoC	State of Charge
SoS	State of Storage
SOFC	Solid Oxide Fuel Cell
SSE	Shore Side Electricity
VSC	Voltage Source Converter
VRFB	Vanadium Redox Flow Battery
QoS	Quality of Service

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Executive Summary

The primary aim for Task 3.1 is to establish specifications for a barge-based power system that can effectively store and supply adequate energy to meet the needs of connected vessels, operating safely and efficiently within the challenging marine environment.

Power Supply Modules

The sizing of commercial containerized marine Power Supply Modules (PSM) from partners Corvus (Lithium-ion Lithium Iron Phosphate, Li-ion LFP) and CellCube (Vanadium Redox Flow Battery, VRFB) has been conducted based on performance specifications. Expected degradation near the end of life, power losses, and efficiencies were used to estimate the number of 20-foot Equivalent Unit (TEU) containerized PSMs needed to fulfill Project Key Indicator (PKI) 1.4, providing 3 MW power and 35 MWh capacity per PSM.

- **Li-ion LFP:** Requires at least 54 containerized PSMs from Corvus.
- **VRFB**: Requires at least 125 containerized PSMs from CellCube.

For alternative designs, the PSMs of interest include:

- **Fuel Cells**: Promising for large-scale energy storage and zero-emission using carbon-free fuels, though fuel storage poses challenges.
- **Supercapacitors**: Suitable for rapid discharges, such as peak shaving.

Power Inverter

To interface the barge with both Shore-Side Electricity (SSE) and loads with bidirectional power flow, a single grid-tied power inverter system was chosen for its commercial availability and simplicity. To handle maximum power output, two commercial power inverter solutions were identified:

- **Single Central Inverter**: Achieves up to 98.6% efficiency, enabling simple implementation.
- **15 Smaller Synchronized Parallel Inverters**: Achieve up to 99% efficiency, offering redundancy.

Basic features such as automatic output synchronization, dual-frequency operation, and power flow control are necessary. Application-based features may also be required to meet specific performance needs.

Power Management System

For the overall Power Management System (PMS), a hierarchical structure is proposed, consisting of a top layer with an Energy Management System (EMS), a middle layer with a PMS, and a bottom layer for essential converter control and fault detection.

- The **IEEE 1709** standard for Medium Voltage Direct Current (MVDC) ships requires the PMS to be designed such that it can at least manage power, maintain Quality of Service, and maximize survivability during disruptions.

Control and Monitoring

For the control and monitoring system of the barge's power system, it is recommended to:

- Follow **IEEE 1709** standards for maritime Medium Voltage Direct Current Microgrids (MVDC MG):
  - Implement real-time monitoring of PSMs and loads, achievable through sensors and communication links, e.g., to the Battery Management System (BMS).
  - Perform fault management verification studies to confirm post-fault reconfiguration and stable recovery, ensuring system stability under all configurations.
- Provide Protective Devices or equivalent measures for alarms or tripping:
  - Protection of power connections between the shore, barge, and vessels should follow **IEEE 8005-1** for high voltage connections and **IEEE 8005-3** for low voltage connections.
  - Protection of the barge electrical system should comply with **IEC 60092:202**.

Power Connection

The barge's power connection with vessels, ports, and the local grid ensures safe and compatibility by following standards:

- **IEC 61936:** Governs general requirements for the design and installation of high-voltage electrical installations, ensuring safety and reliability.
- **IEC 62613**: Specifies requirements for plug-in connectors, providing secure and compatible connections between the barge and shore or vessel.
- **IEC/IEEE 80005-1** and **80005-3:** Establish standards for onshore power supply (OPS) connections to the barge, ensuring safe and efficient power transfer in both high-voltage and low-voltage scenarios. Furthermore, this should be followed for power connections at sea between a barge and a vessel.

To ensure a flexible and adaptive connection the following equipment should be implemented:

- **Cable Management System:** Enables secure and efficient handling of connection cables, supporting remote-operated/automatic connection and disconnection under varying conditions. Furthermore, a plug adjustment system should be used, enabling seamless compatibility with different vessel types

Purpose of the Document

The primary purpose of this document, "D3.1: Power Supply Modules and Microgrid Specifications," is to establish detailed specifications and design parameters for the power supply modules and microgrid systems to be used in the BlueBARGE project.

This document serves as a foundational guide for the development and integration of power supply solutions that will ensure high energy efficiency, reliability, and adaptability in marine environments. The specifications outlined herein aim to address the unique challenges of operating in harsh weather conditions and the marine environment, ensuring that the power-barge meets its energy demands effectively and sustainably.

Intended readership

This document, "D3.1: Power Supply Modules and Microgrid Specifications," is intended for a diverse audience involved in the BlueBARGE project and related fields. The primary readers include:

- **Project Engineers and Designers:** Professionals responsible for the technical design and implementation of power supply modules and microgrid systems. This report provides them with specifications and design parameters for developing reliable and efficient energy solutions tailored to marine environments.
- **Project Managers and Coordinators:** Individuals overseeing the progress and integration of Work Package 3 (WP3). The document helps them ensure that the development aligns with project goals and timelines, providing an understanding of the technical requirements.
- **Academic and Research Institutions:** Researchers and academics from institutions such as AAU, NTUA, VPF, NTNU, HYDRUS, ELKON, MMS, CORVUS, and ENEROX who are contributing to Task 3.1. The specifications detailed in this report will guide their research and development efforts, highlighting challenges for the development of the power system for the barge to gain coherence and collaboration across different teams.

1 Introduction

The delivery report "D3.1: Power Supply Modules and Microgrid Specifications" outlines the comprehensive specifications and design parameters necessary for the development of power supply modules and microgrid systems for the BlueBARGE project. This report is a crucial milestone in Work Package 3 (WP3), which focuses on defining and designing the power supply infrastructure to ensure energy efficiency, reliability, and integration with marine environments and maritime approvals.

WP3 aims to establish the specifications for power supply modules in accordance with the identified requirements and design alternatives for BlueBARGE. The power supply modules must be reliable, efficient, and capable of meeting the energy demands of a marine power barge, considering the challenges posed by harsh weather conditions and marine environments. This involves designing individual power supply modules at a desktop level and developing an integration module for the power bridge. The integration module will focus on achieving a high-efficiency microgrid.

Task 3.1, led by AAU with participation from NTUA, VPF, NTNU, HYDRUS, ELKON, MMS, CORVUS, and ENEROX, is dedicated to developing the specifications for these power supply modules and the microgrid. The main objective includes creating specifications for:

- Power supply modules capable of storing and supplying adequate energy.
- Power inverters, capable of delivering power according to the load profile from the ship or grid.
- Power Management System (PMS) to ensure reliable and safe operation of the power-barge power supply modules.
- Control and monitoring system providing real-time data on energy storage and consumption.
- Power connection with vessels, ports, and local grid to ensure adaptability and flexibility.

In summary, this report details the foundational specifications for the development of power supply modules and microgrid systems for the BlueBARGE. It serves as a guiding document for the design and integration of these systems, ensuring that they meet the project's goals of high energy efficiency and reliability in a challenging marine environment. The specifications outlined in this task contribute to several other tasks as follows:

- **T2.2:** The technical requirements derived in Task 2.2 are based on the specifications outlined in Task 3.1, including power demand and other use case specifications.
- **T3.2:** The specifications developed in Task 3.1 provide detailed guidelines on the type, capacity, and expected performance of the modules, ensuring they meet the project's technical and safety standards. These serve as the foundation for designing the individual power supply modules.
- **T3.3:** The power supply and microgrid specifications inform the design of the integration module, which manages and controls the energy stored onboard the power-barge.
- **T4.1:** The specifications from Task 3.1 provide essential data for setting up the assessment and design optimization framework.
- **T5.1:** The specifications guide the exploration and design of alternative configurations for the power-barge.
- **T5.2:** The detailed specifications for the barge power help analyse the compatibility of the power-barge interfaces with existing shore-to-ship power connection systems.
- **T5.3:** The detailed design of the power-barge incorporates the specifications and technical requirements defined in Task 3.1.

2 Specifications Development for Power Supply Modules

Developing specifications for power supply modules is a critical component of the BlueBARGE project, aimed at ensuring the reliable and efficient operation of the power barge in marine environments. This section first provides a brief introduction to key concepts for evaluating the power supply module's performance. Then a description of power supply module technologies and their performance with a focus on those with the most relevance for maritime applications. At last, a sizing of the most promising power supply module technologies is performed to meet the power demand of the use cases identified in T2.1.

According to the grant agreement **KPI1.4 states that** the minimum BlueBARGE should achieve at least 3MW discharge power and 35MWh power capacity.

An estimate of power consumption for vessels at a port stay can be seen in Table 1, based on calculations from [1]. This is for vessels at their whole port stay, where a large amount of the time will be spent at berth, where SSE can be provided for the ship. However, the vessels can also spend a lot of time at anchorage.

Table 1 Estimate of energy consumption for vessel types at port stay [1].

Energy consumption during port stay

Vessel type	Bulk	Bulk	Bulk	Bulk	Container	Container	Container	Ro-ro
Size	50k dwt	82k dwt	200k dwt	320k dwt	2,500 teu	14,000 teu	20,000 teu	5,000 lm
Duration [hours]	36	48	60	72	18	24	32	5
Power [kW]	230	280	340	400	1,200	5,600	8,000	1,300
Energy consumption [MWh]	8.2	13.4	20.4	28.8	21.6	134	256	6.5

Relevant Standard for PSM:

UL 9540 series provides standards for ESS and related equipment. It covers safety requirements, installation guidelines, and performance testing for ESS technologies, ensuring safe deployment and operation in various applications.

2.1 Terminology for power supply modules

This subsection serves as a brief introduction to fundamental concepts related to power supply modules specifications, with a focus on battery systems. Key terms include energy density, power density, Depth of Discharge (DoD), cycle life, and Round Trip Efficiency (RTE).

2.1.1 Energy density

Energy density refers to the amount of energy a technology can store per unit volume or mass, see horizontal axis in Figure 1 for volumetric energy density.

Batteries: Batteries store energy chemically, allowing for much higher energy densities compared to supercapacitors. This makes them suitable for applications requiring substantial energy storage, such as an hourly duration power supply.

Supercapacitors: Supercapacitors have the highest energy density among capacitor technologies but are significantly lower than batteries and fuel cells. They store energy electrostatically, which limits their energy capacity, making them suitable for short-duration applications that require rapid charge and discharge cycles.

Fuel Cells: Fuel cells have a high energy density and can continuously produce electricity as long as fuel is supplied. They are efficient for long-term energy supply and are suitable for applications needing sustained power over extended periods.

Green Fuel Generators: Generators powered by green fuels (such as biogas, biodiesel, and hydrogen) can provide high energy density, especially when using fuels with high energy content. They are capable of producing large amounts of energy, making them ideal for extensive and continuous power generation needs.

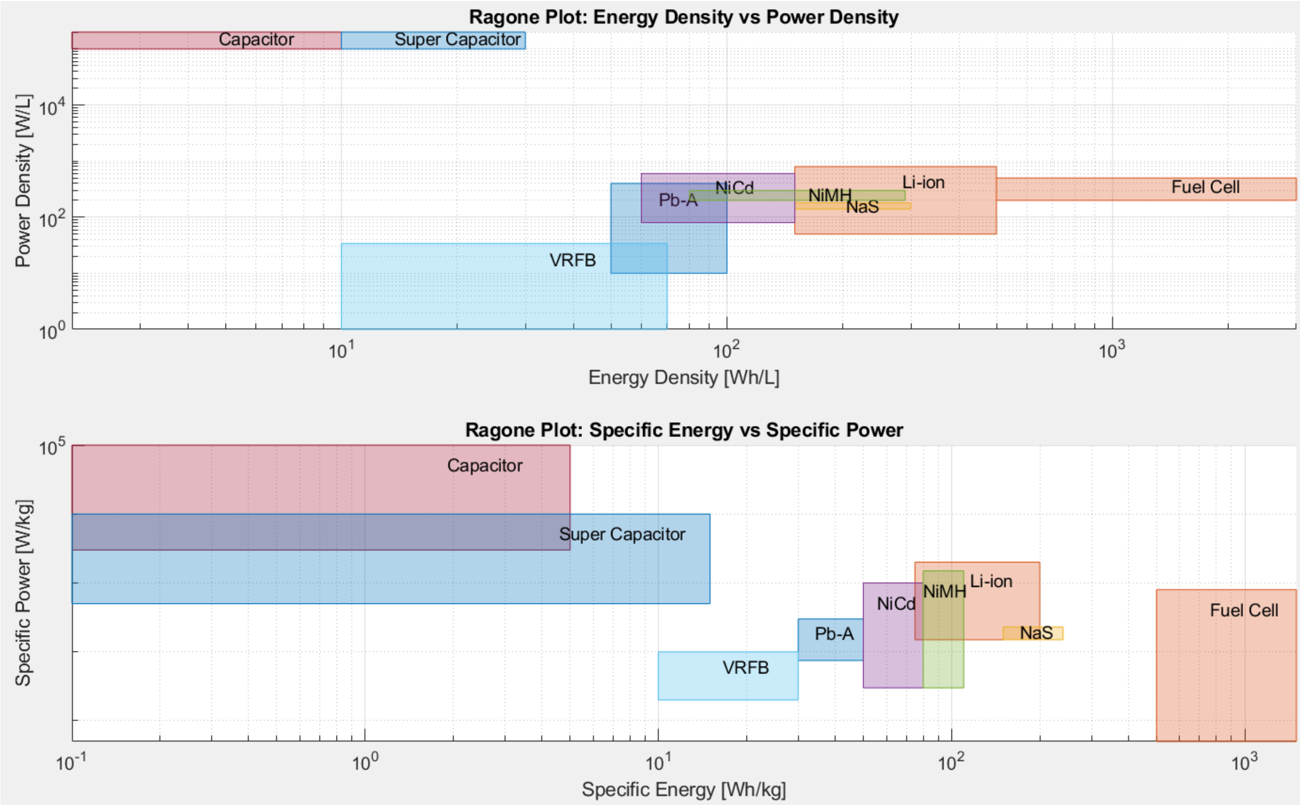

Figure 1 Ragone plot visualizing power and energy density of various non-containerized power supply module technologies, data from [2].

2.1.2 Power Density

Power density refers to the rate at which a technology can charge and discharge energy, see vertical axis in Figure 1 for volumetric power density.

Batteries: Batteries generally have lower power density than supercapacitors because chemical reactions involved in energy storage and release take longer. However, certain battery types like Lithium-Ion can achieve relatively high power densities.

Supercapacitors: Supercapacitors excel in power density, offering rapid charge and discharge rates due to their ability to store energy electrostatically. This makes them ideal for applications requiring quick bursts of energy, such as regenerative braking systems in vehicles and marine vessels.

Fuel Cells: Fuel cells typically have moderate power density, providing a continuous and steady output of power suitable for applications requiring consistent energy delivery over time.

Green Fuel Generators: These generators can offer variable power density depending on the design and fuel type. They can be engineered to provide both high power output for immediate needs and sustained power for continuous operation.

2.1.3 Depth of discharge

DoD refers to the percentage of the electrochemical energy storage device's capacity that has been used relative to its total capacity. It is a critical factor in determining the lifespan and performance of energy storage technologies.

Batteries: Batteries' lifespan is significantly affected by DoD. Higher DoD usually leads to fewer cycles. For instance, a Lithium-Ion battery that regularly discharges to 80% DoD will typically have a shorter lifespan than one that discharges to 50% DoD. Manufacturers often recommend operating within a specific DoD range to maximize cycle life. o An exception to this is flow batteries (such as the VRFB), where repeated 100% DoD cycling does not cause appreciable degradation[3].

Supercapacitors: Supercapacitors are less sensitive to DoD compared to batteries. They can endure deep discharges with minimal impact on cycle life, making them highly suitable for applications requiring frequent and full discharges.

2.1.4 Cycle life

In energy storage and generation technologies, the concepts of cycle life crucial in determining the long-term viability and performance of the energy storage devices, especially for batteries. Different technologies exhibit varying strengths and weaknesses in these aspects, which influence their suitability for specific applications.

Batteries: The cycle life of batteries is defined by how many complete charge-discharge cycles they can endure before their capacity drops to a specified level, usually around 80% of the original capacity. For instance, Lithium-Ion batteries, commonly used in consumer electronics and electric vehicles, typically offer several thousand cycles. In contrast, Lead-Acid batteries generally have a shorter cycle life, ranging from 500 to 1,500 cycles. The degradation in battery performance over cycles is primarily due to chemical and physical changes within the battery cells. However, VRFB does not suffer degradation as a result of cycling, because the electroactive components remain in solution at all times.

Supercapacitors: Supercapacitors are known for their exceptionally long cycle life compared to batteries. They can handle hundreds of thousands to millions of charge-discharge cycles with minimal performance degradation. This extended cycle life is attributed to their electrostatic energy storage mechanism, which avoids the chemical wear and tear that affects batteries. Supercapacitors are particularly well-suited for applications that require frequent and rapid bursts of energy, such as regenerative braking systems.

2.1.5 Round trip efficiency

RTE is a measure of how effectively an energy storage system converts and stores energy and then reverts it back into usable energy. It is a crucial metric for understanding the overall performance and practicality of energy storage technologies.

Definition: RTE is the percentage of energy that is retrieved from an energy storage system compared to the amount of energy initially put into it.

$$\text{RTE [\%]} = \left(\frac{\text{Energy Output}}{\text{Energy Input}}\right) \times 100$$

Batteries: Batteries typically have an RTE ranging from 70% to >90%. This efficiency reflects the energy lost due to chemical and electrical processes during charging and discharging. Advanced technologies, such as Lithium-Ion batteries, tend to have higher efficiencies, while older or less advanced battery types may show lower efficiencies.

Supercapacitors: Supercapacitors generally exhibit a high RTE, often above 90%. This is due to their electrostatic energy storage mechanism, which incurs lower losses compared to the chemical processes in batteries. Their high efficiency makes them ideal for applications that require rapid charge and discharge cycles.

2.2 Power Supply Module Technologies for Maritime Applications

This subsection explores the different commercially mature technologies for the power supply modules of the power barge.

2.2.1 Commercial Battery Technologies

Batteries represent a promising technology for maritime applications due to their potential for high efficiency, low emissions, and the ability to store and deliver energy effectively [4], [5]. In the maritime industry, batteries play a crucial role in propulsion, auxiliary power, and hybrid systems, helping to enhance operational efficiency and comply with stringent environmental regulations. As ships and marine vessels transition from conventional fossil fuels to cleaner energy sources, several established battery technologies have proven their reliability and effectiveness in the maritime environment

Lithium-Ion (Li-ion) Batteries:

Li-ion batteries are among the most advanced, but also widely used rechargeable battery technologies recently. Lithium-ion batteries encompass a diverse range of chemistries, all centered around the fundamental principle of charge and discharge reactions involving a lithiated metal oxide cathode and a graphite anode. Among the most prevalent lithium-ion variants are Nickel Manganese Cobalt (NMC) and Lithium Iron Phosphate (LFP). These chemistries are distinguished by their specific compositions and performance characteristics, each offering unique advantages and applications within the battery industry. However, LFP (Lithium Iron Phosphate) batteries prioritize safety and longevity over energy density, which contrasts with NMC (Nickel Manganese Cobalt) batteries that typically offer higher energy density but may pose greater thermal management challenges. Introduced in the early 1990s, they have revolutionized the portable electronics and electric vehicle markets due to their high energy density and long lifespan.

Applications: Consumer electronics, electric vehicles, grid storage, maritime propulsion systems, and auxiliary power units.

Advantages:	Disadvantages:
• High energy density • Long cycle life • Relatively low self-discharge	• High cost, • Flammable electrolyte • Potential scarcity of resources

Lead-Acid Batteries (Pb-A):

Lead-acid batteries are one of the oldest and most established battery technologies. Still, they remain widely used due to their reliability and low cost. These batteries consist of lead dioxide as the cathode, sponge lead as the anode, and sulfuric acid as the electrolyte.

Applications: Automotive starting, lighting, and ignition, uninterruptible power supplies, backup power, and maritime applications such as emergency power supplies and starting batteries for ship engines.

Advantages:	Disadvantages:
• Low cost • Reliable • High specific power	• Low specific energy • Low energy density • Low cycle life

Nickel-Cadmium (NiCd) Batteries:

NiCd batteries have been in use since the early 20th century and are known for their durability and reliability. They use nickel oxide hydroxide and metallic cadmium as electrodes. However, due to environmental concerns their use has declined, but they are still employed in specific applications where robust and long-lasting performance is critical.

Applications: Aviation, emergency lighting, medical equipment, and maritime applications require reliable backup power and emergency systems.

Advantages:	Disadvantages:
• Robust • Long cycle life • Low cost	• Memory effect • Toxic material (cadmium) • Explosive hydrogen gas during charge • Low energy density

Nickel-Metal Hydride (NiMH) Batteries:

NiMH batteries emerged in the late 1980s as an improvement over NiCd batteries. They use a hydrogen-absorbing alloy for the negative electrode and nickel oxyhydroxide for the positive electrode. These batteries offer a balance between energy density and environmental impact, making them suitable for a range of applications.

Applications: Hybrid vehicles, consumer electronics (e.g., rechargeable AA batteries), and maritime applications such as auxiliary power units.

Advantages:	Disadvantages:
• Long cycle life • Low cost	• Memory effect • Explosive hydrogen gas during charge • Low energy density

Sodium-Sulfur (NaS) Batteries:

NaS batteries are high-temperature batteries that operate at around 300°C to 350°C. They are primarily used for large-scale energy storage due to their high energy density and efficiency. These batteries use molten sulfur as the cathode and molten sodium as the anode, separated by a solid ceramic electrolyte.

Applications: Grid storage, large-scale energy storage, and emerging maritime applications focused on large vessel energy management.

Advantages:	Disadvantages:
• High energy density • Low cost • Short cycle life	• High operation temperature • Safety concerts (Corrosive) • High maintenance

Vanadium Redox Flow Batteries (VRFB):

VRFB are an advanced type of rechargeable battery designed for efficient energy storage over long durations. They operate using vanadium ions in different oxidation states to store and release energy. VRFBs are characterized by their liquid electrolytes housed in separate tanks, which flow through the battery's cell stack during charging and discharging cycles. VRFB have several safety advantages, they are safe from short circuits and fire risks due to their non-flammable, water-based electrolytes and isolated electrolyte storage. including resistance to short-circuiting, immunity to reverse polarization, and a non-flammable nature

Applications: VRFBs are primarily utilized in grid energy storage systems due to their scalability and ability to store large amounts of energy. They are also gaining interest in maritime applications for managing energy on large vessels and in hybrid propulsion systems.

Advantages:	Disadvantages:
• 80% Reusable materials • Very safe • Long cycle life	• Low energy density • Complex system

In Table 2 important specifications for the battery power supply module technologies can be seen.

Table 2 Overview of considered battery technologies performance specifications for discharge over several hours [2], [6], [7].

Technology	Energy Density [Wh/L]	Power Density [W/L]	Specific Energy [Wh/kg]	Specific Power [W/kg]	RTE [%]
Pb-A	50–100	10–400	30–50	75–300	70–90
Li-ion	150–500	50 - 800	75–200	150–2000	85–97
NaS	150–300	140–180	150–240	150–230	80–90
NiCd	60–150	80–600	50–80	30–1000	60–90
NiMH	80-290	200–300	80-110	30–1500	50–80
VRFB	10–70	1–34	10–30	20–100	70–90

2.2.2 Commercial Supercapacitor Technologies

Supercapacitors, also known as ultracapacitors, are energy storage devices that bridge the gap between traditional capacitors and batteries. They store energy electrostatically rather than chemically, which allows them to charge and discharge rapidly and endure hundreds of thousands to millions of cycles. Supercapacitors represent a promising technology for maritime applications due to their potential for high power density, rapid charging and discharging capabilities, and long cycle life. In the maritime industry, supercapacitors play a crucial role in applications where quick bursts of energy are needed, enhancing operational efficiency. This makes them particularly suitable for applications such as load levelling, power smoothing, and energy recovery systems in maritime settings. Supercapacitors are known for their thermal stability, low risk of explosions, durability, and simple construction, although they require proper management of high current flow and voltage balancing to mitigate potential safety concerns.

Electrochemical Double-layer Capacitors (EDLCs):

EDLCs store energy through the electrostatic separation of charge at the electrode-electrolyte interface. They are known for their high power density and rapid charge-discharge capabilities, making them suitable for applications requiring frequent bursts of power. These are the most common types of supercapacitors.

Advantages:	Disadvantages:
• Mature technology • Low cost	• Low voltage range

Pseudocapacitors:

Pseudocapacitors store energy through fast faradaic reactions (redox reactions) occurring at the surface of the electrode. They offer a combination of battery-like energy storage with capacitor-like power delivery.

Advantages:	Disadvantages:
• Higher energy density • Improved voltage range	• Cost • Limited cycle life

Hybrid Supercapacitors:

Hybrid supercapacitors combine features of EDLCs and pseudocapacitors to achieve both high energy density and high power density. While they are gaining popularity due to their optimized energy storage and delivery efficiency, they are not as widely used as pure EDLCs. They find applications in areas requiring both rapid power delivery and substantial energy storage

Advantages:	Disadvantages:
• Balanced performance	• Higher complexity • Cost

2.2.3 Commercial Fuel Cell Technologies

Fuel cells represent a promising technology for maritime applications due to their potential for high efficiency, low emissions, and ability to utilize a variety of fuels, including hydrogen, natural gas, and methanol [8]. Fuel cells present safety concerns in maritime applications due to the storage and handling of hydrogen, a highly flammable and volatile gas. The potential for hydrogen leaks necessitates stringent safety protocols and robust containment systems to prevent explosions. Additionally, the high-pressure systems required for hydrogen storage pose risks, requiring specialized materials and designs to ensure safe operation.

The main capacity issue in maritime applications is storing large enough amounts of fuel to ensure extended operational capabilities without compromising vessel performance or safety. The fuel cells can utilize different types of fuels for electricity generation, an overview of the most common fuels (Marine Gas Oil (MGO), Liquefied Natural Gas (LNG)) and their key properties are shown in Table 3.

Table 3 Physical and Energy Properties of various fuels [9], [10].

Properties	Physical State	Lower Heating Value [MJ/kg]	Density at 15°C [kg/m³]	Volumetric Heating Value [MJ/L]
MGO	Liquid	43	Max. 900	38.7
Synthetic LNG	Cryogenic liquid	50	(-165°C, 1 bar) 448	(-165°C, 1 bar) 22.4
Methanol	Liquid	20	796	16
Ethanol	Liquid	28	792	21
Hydrogen	Cryogenic liquid	120	0.08 (Gas), 70.8 (Liquid)	0.01 (Gas), 5.6 (Comp. 70 MPa), 8.5 (Liquid)
Ammonia	Liquid	18.6	615	12.9

An overview of fuel cell technologies suitable for the maritime sector can be seen below:

Proton Exchange Membrane (PEM) Fuel Cells:

PEM fuel cells operate at relatively low temperatures (60-80°C) and use a solid polymer electrolyte. Their high power density, quick start-up times, and compact size make them suitable for maritime applications such as auxiliary power units and propulsion systems for smaller vessels. However, they require high-purity hydrogen, which can be a limitation in maritime environments where fuel logistics are complex. Additionally, the need for expensive platinum catalysts increases the overall system cost.

Advantages:	Disadvantages:
• High power density • Quick start-up • Compact size	• Requires high-purity hydrogen • High cost due to platinum catalysts

High-Temperature PEM (HT-PEM) Fuel Cells:

HT-PEM fuel cells, an advanced version of PEM fuel cells, operate at higher temperatures (up to 200°C). This allows them to be more tolerant of impurities in the hydrogen fuel, which is beneficial for maritime applications where fuel quality can vary. They also reduce the need for expensive platinum catalysts, thus potentially lowering costs. However, the higher operating temperature increases system complexity and the need for effective thermal management.

Advantages:	Disadvantages:
• Tolerant to fuel impurities • Reduced platinum catalyst requirement	• Increased system complexity • Higher operating temperatures

Molten Carbonate Fuel Cells (MCFCs):

MCFCs operate at high temperatures (600-700°C) and use a molten carbonate salt mixture as an electrolyte. Their ability to use a variety of fuels, including natural gas and biogas, makes them suitable for large-scale stationary power generation on ships. However, the high operating temperatures lead to material corrosion and degradation, which poses durability challenges. Their high efficiency and capability to generate both electricity and heat are advantageous for combined heat and power if heat is required on the barge.

Advantages:	Disadvantages:
• High efficiency • Fuel flexibility • Suitable for large-scale applications	• High operating temperatures cause material degradation • Durability issues

Solid Oxide Fuel Cells (SOFCs):

SOFCs operate at very high temperatures (500-1000°C) and use a ceramic electrolyte. They are highly efficient and can utilize a wide range of fuels, including hydrocarbons, which is beneficial for maritime applications where fuel flexibility is critical. However, their high operating temperatures lead to long start-up times, material degradation, and the need for robust thermal management systems. Their high efficiency and capability to generate both electricity and heat are advantageous for combined heat and power if heat is required on the barge.

Advantages:	Disadvantages:
• High efficiency • Fuel flexibility • Suitable for large-scale applications	• Long start-up times • High operating temperatures cause material degradation • Complex thermal management

The following table provides a comparative summary of various fuel cell types based on their operational characteristics and emissions.

Table 4 Key characteristics of fuel cells [11].

Fuel Cell Type	Fuel Compatibility	Emissions	Operating Temperature	Electrical Efficiency
MCFC	LNG, Methanol, H_2, Diesel	CO_2 and low levels of NO_x if carbon fuel is used.	High (600-700°C)	50%
SOFC	LNG, Methanol, H_2, Diesel, Ammonia	CO_2 and low levels of NO_x if carbon fuel is used.	High (600-800°C)	60%
PEMFC	H_2	None	Moderate (60-80°C)	50-60%
HT-PEMFC	LNG, Methanol, Diesel, H_2	CO_2 and low levels of NO_x if carbon fuel is used.	High (up to 200°C)	50-60%

2.2.4 Commercial Alternative Fuel Generator Technologies

To generate electrical power from sustainable fuel sources, two different technologies are considered. These two direct conversion technologies that efficiently utilize these renewable fuels to generate electricity.

Here are the primary methods for alternative fuel generator technologies:

Internal Combustion Engines (ICE):

Utilize ICEs specifically designed to burn biofuels such as biodiesel, hydrogen, methanol, bioethanol, or synthetic LNG. These engines directly convert the chemical energy of biofuels into mechanical energy, which is then used to drive electrical generators onboard ships. Typical electrical efficiency ranges from 35% to 45% [12].

Advantages:	Disadvantages:
• High efficiency at part load • Low cost • Established technology	• Maintenance-intensive • Emissions if carbon fuel is used. • Noise and Vibration

For usable fuels, see biodiesel properties in Table 5, for other fuels see Table 3.

Table 5 Properties of biofuels [10].

Properties	Physical State	Lower Heating Value [MJ/kg]	Density at 15°C [kg/m³]	Volumetric Heating Value [MJ/L]
Methyl ester (biodiesel)	Liquid	37.5	880	33.3
Oils vegetable (biodiesel)	Liquid	37.8	920	34.8

Gas Turbines:

Gas turbines can be adapted to burn e-fuels (electrofuels), which are synthetic fuels produced from renewable energy sources like hydrogen and captured carbon dioxide. E-fuel-powered turbines efficiently convert the energy from these fuels into mechanical energy to drive electrical generators, providing reliable power for marine applications. Typical renewable fuels are synthetic LNG and hydrogen, for properties see in Table 3. Typical electrical efficiency ranges from 25% to 35% [13].

Advantages:	Disadvantages:
• High power density • Rapid response time • Quick Start-Up	• Emissions if carbon fuel is used • Fuel availability and infrastructure • High initial costs

2.3 Overview of Current Implementation Power Supply Modules in Marine Applications

In this section, we explore various projects utilizing advanced power supply technologies for ship propulsion, backup power, load shaving, and auxiliary power. The focus is on projects leveraging batteries, fuel cells, and alternative generators to achieve significant reductions in emissions and operational costs. Below is a summary of key projects, their technologies, metrics, outcomes, and challenges.

Table 6 Overview of maritime projects using zero- or low-emission technologies.

Project Name	Power Supply Technologies (Manufacturer)	Key Metrics	Outcomes/Benefits	Challenges
E-Ferry Project (Car Ferry)	Li-ion G-NMC (leclanche)	Cap: 4.3 MWh Disc.: 1.4 MW Charge: 4 MW >30 % DoD	- Zero emissions - Reduced operational costs (Fuel)	- Battery weight - Initial high costs (Paid out after 5-8 years of operation)
Ampere (Car Ferry)	Li-ion NMC (Corvus)	Cap: 1 MWh DisC.: 0.9 MW Charge: 0.9 mW >75 % DoD	- 95% reduction in emissions - 60% lower fuel costs	- Limited range - Charging infra-structure 260 kWh battery at each dock to avoid blackout
HySeas III (Car Ferry, Not built)	PEMFC (H_2) + Li-ion batteries	600 kW (600 kg) 720 kWh	- Expect 89% reduction in emissions	- Hydrogen storage and infrastructure
Energy Observer (Boat)	Solar Panels Wind Turbines PEMFC (H_2) Li-ion	21 kW 2 x 1 kW 22kW (63 kg) 106 kWh	- Renewable energy utilization - Zero emissions	- Intermittent power generation - Complex system integration
Eidesvik Offshore's Viking Lady (Offshore support vessels)	ICE (LNG) (Wärtsilä) MCFC (LNG) (Tognum) Li-ion NMC (Corvus) 2024 SOFC (Amonnia) (Alma)	8 MW 330 kW Cap: 0.5 MWh 2 MW	- Reduced fuel consumption by 15%. - Emission reduces sulfur oxide by 100%, nitrogen oxide by 85% and carbon dioxide by 20%. - MCFC CHP efficiency near 90%	- Emissions
Yara Birkeland (Container Ship)	Li-ion G-NMC (leclanche)	6.7 MWh	- Autonomous - Annual operating cost savings in both fuel and crew, estimated at up to 90%,	- Regulations for autonomous shipping

These projects showcase the innovative use of renewable and low-emission technologies in marine power generation. Each project demonstrates significant benefits in terms of emissions reduction and operational efficiency, while also highlighting specific challenges such as system integration, fuel storage, and initial costs.

2.4 Overview of Commercial Available Containerized Power Supply Modules

In this section, an overview of the available 20-ft containerized power supply (TEU) modules for possible marine applications is presented. The Corus Special and Cellcube Special data can be found in WP5.1 "*Battery & Fuel Cells Modules Technical Requirements*".

Commercial Containerized Battery Modules

Table 7 Commercial containerized battery modules.

Product	Battery Tech-nology	Size TEU	Capacity	Power	Efficiency	DoD	Cycle life	Degra-dation	Marine Certificate
Corvus BOB[14]	Li-ion NMC	1	1.5 MWh ?	1C 1.5 MW 3C 4.5 MW	?	?	?	26.6 t	Yes (non-stackable)
Corvus Special*	Li-ion LFP	1	1.3 MWh	0.4C 0.5MW	>95%*	80%	10 k	21.7 t (14.6 t)	Yes* (non-stackable)
Cellcube Special*	VRFB	1	365 kWh 400 kWh	0.17C 50kW 0.08C 30kW	>85%*	100%	>20k	35 t	No*
CATL EnergyC [15]	Li-ion LFP	1	4 MWh	0.5C 2 MW	?	80% 70%	8 k 10 k	36 t	no
ABB Ability [16]	Li-ion ?	1	1.1 MWh	1.8C 2 MW	?	?	?	30 t	Yes (non-stackable)

* Under development.

2.5 Development of Specifications for Power Supply Modules

From **KPI 1.4** a set of power supply modules for marine environments for a minimum of 3MW discharge and 35MWh power capacity is required. The minimum for each commercial battery product is the lowest number of containers that fulfill both requirements.

Table 8 Specifications for the number of containers for each battery type.

product	Containers (Ideal)	Loss [%]	Containers (non-ideal)	Power rating (non-ideal)	Capacity (non-ideal)
Corvus Special	26 TEU	20% (DoD) 20% (Degradation) 5% (Conversion) 5% (Efficiency)	54 TEU	24 MW	35 MWh
Cellcube Special (0.08C)	100 TEU	10% (Degradation) 5% (Conversion) 15% (Efficiency)	125 TEU	3 MW	35 MWh
Cellcube Special (0.17C)	96 TEU	10% (Degradation) 5% (Conversion) 15% (Efficiency)	137 TEU	5.5 MW	35 MWh

The ideal case is without considering any losses for the system. The losses considered for the non-ideal case for the specific battery product are the DoD, the degradation occurred near the end of cycle times, and the efficiency associated with the discharge of the battery assumed to be half of the RTE. It should be noted that the power capacity is affected by all losses. Furthermore, the conversion loss is the guesstimate power loss associated with conversion in transformers and power electronics, such as DC/DC converters and inverters [17].

In contrast, the power rating capacity is only affected by conversion losses and discharge efficiency, reflecting the actual amount of energy that can be efficiently utilized during discharge.

Losses:

- DoD of batteries (80-100%)
- Degradation over lifetime (10-20%)
- Conversion loss of power electronics and transformers (5%)
- Efficiency of batteries (5-15%)

The Corvus Special offers a high power discharge, capacity, and efficiency compared to the Cellcube Special. However, the Cellcube Special has advantages over Li-ion LFP batteries such as those in the Corvus system. The Cellcube Special VRFB boasts a longer lifespan, often exceeding 10,000 cycles without significant degradation. It is also highly scalable and flexible, allowing capacity expansion by simply increasing the electrolyte volume, making it ideal for large-scale applications.

The BlueBARGE project aim to use a combination of the specially developed systems of Li-ion LFP batteries from Corvus and VRFBs from Cellcube to create a novel hybrid battery system, sized to fit the specifications developed in T2.1.

2.6 Future Trends for Power Supply Modules

This subsection serves as a brief introduction to fundamental concepts related to power supply modules, with a focus on battery systems. Key concepts include energy density, power density, depth of discharge, cycle life, and RTE. The future of power supply modules in marine environments, encompassing batteries, fuel cells, supercapacitors, and green fuel generators, is marked by rapid technological advancements and the potential for significant market transformations. All data and predictions in this subsection are derived from reference [18]. By 2050, these technologies will likely have evolved to meet the diverse and stringent energy needs of the maritime sector, driven by the dual imperatives of sustainability and efficiency. Each technology offers unique benefits and faces distinct challenges, but collectively, it will contribute to a more sustainable and resilient maritime industry.

Batteries

By 2050, battery technology is set to evolve significantly, influenced by ongoing technological advancements. Solid-state batteries, with improved safety and energy density (+400 Wh/kg), are likely to become commercially viable past 2030, offering substantial benefits over current lithium-ion technologies. The maritime industry will benefit from these advancements, as different applications—ranging from propulsion to auxiliary power—require tailored solutions. Cost reduction and enhanced performance will drive widespread adoption, with the possibility of metal-air batteries revolutionizing energy storage due to their high energy density (1000-3400 Wh/kg). These advancements will enable more efficient and sustainable maritime operations, although the exact trajectory remains uncertain due to the rapid pace of innovation.

Fuel Cells

Fuel cell technology is expected to advance considerably by 2050, driven by improvements in catalyst materials, membranes, and fuel processing. Hydrogen fuel cells, in particular, are set to become competitive with traditional power sources within the next decade. The maritime sector will benefit from fuel cells' high efficiency and low emissions, supporting both propulsion and auxiliary power needs. Regulatory pressures and the demand for sustainable solutions will propel the adoption of fuel cells, with significant investment from governments and private entities. Solid oxide fuel cells (SOFCs) may also emerge as a promising technology, offering high efficiency and fuel flexibility for maritime applications.

Supercapacitors

Supercapacitors will see significant advancements by 2050, particularly in energy density, power density, and efficiency. Innovations in materials science, such as the use of graphene and nanostructured materials, will enhance their performance and reduce costs. In the maritime industry, supercapacitors will be valuable for providing rapid bursts of power, peak shaving, load leveling, and regenerative braking. These capabilities are essential for hybrid and fully electric propulsion systems. The integration of supercapacitors with other energy storage and generation technologies will create hybrid systems that optimize efficiency and sustainability, addressing the diverse energy needs of maritime operations.

Green Fuel Generators

By 2050, green fuel generators powered by biofuels and e-fuels is expected to play a crucial role in the maritime sector. Advances in biofuel production, including second and third-generation biofuels from non-food biomass and algae, will enhance their availability and cost-effectiveness. E-fuels, synthesized from renewable electricity, will become more prevalent, offering a carbon-neutral alternative to traditional marine fuels. Improved engine designs and fuel processing technologies will increase efficiency and reduce emissions. The maritime industry will adopt green fuel generators for primary and auxiliary power, driven by the need to reduce greenhouse gas emissions and reliance on fossil fuels, supported by evolving regulatory frameworks.

2.7 Conclusion for Power Supply Modules

To meet the specifications for the barge energy systems, it is crucial to explore and evaluate alternatives to existing technologies investigated as Lithium-Ion LFP and Vanadium Redox Flow Batteries (VRFB). Each alternative presents unique benefits and challenges, impacting overall efficiency, cost, and operational feasibility.

1. **Alternative Fuel Generators are Not Suited:**

   While alternative fuel generators offer a range of options, they generally fall short of the efficiency levels achieved by advanced fuel cells. Biodiesel, for instance, emerges as a promising solution due to its renewable nature and compatibility with existing engines. However, it is accompanied by undesired emissions, which pose environmental and regulatory challenges that need to be addressed.

2. Stacking Ability of Containers for Barge Size Reduction:

The potential to stack energy storage systems could significantly reduce the size of marine barges, leading to cost savings and operational efficiencies. By optimizing the physical footprint of energy storage solutions, vessels can be designed with greater flexibility and reduced overall costs, making them more competitive and environmentally friendly.

3. Fuel Cells as a Promising Solution:

Fuel cells stand out as promising alternatives, potentially enhancing energy capacity and addressing storage issues. Their high efficiency and lower emissions offer significant advantages over traditional combustion-based systems. However, challenges related to fuel cell technology, such as cost and integration, and containerized fuel storage, must be overcome to fully realize their potential for the barge application.
One promising commercial solution could be the Corvus Pelican PEM fuel cell system.

4. Supercapacitors for Peak Shaving:

Supercapacitors, with their rapid charge and discharge capabilities, could become highly relevant for peak shaving applications. By efficiently managing power consumption during peak demand periods, supercapacitors can complement existing power supply modules, optimizing overall energy management and operational efficiency.

5. Future Battery Technologies are Promising:

The future of energy storage is promising with advancements in battery technologies. Solid-state batteries, which offer higher energy density and improved safety, are expected to become more cost-effective and widespread. Additionally, novel topologies such as metal-air batteries could revolutionize energy storage by providing even greater energy density and potentially lower costs.

In conclusion, while Li-Ion LFP and VRFB remain effective, exploring and integrating alternative energy storage and generation solutions, especially fuel cells, is crucial for advancing the barge energy storage systems. The ongoing development of new technologies and optimization of existing ones will play a pivotal role in shaping a more efficient, cost-effective, and environmentally sustainable future.

3 Specifications Development for Power Inverter

High-power inverters play a critical role in interfacing ships with the BlueBARGE energy storage system by converting direct current (DC) from the power supply modules into alternating current (AC) suitable for shipboard electrical systems. These inverter systems are designed to handle large power capacities, often ranging from several hundred kilowatts to several megawatts, depending on the ship's power demands and the size of the BlueBARGE system.

This project aims only to use **three-phase inverters** because both the port and vessels operate on three-phase AC power, which is standard for marine applications due to its efficiency and capacity to handle higher power loads. Three-phase inverters are crucial for these settings as they ensure compatibility and allow for seamless integration and efficient power transfer as described in IEC/IEEE 80005-1.

Furthermore, according to **IEC/IEEE 80005-1** and **80005-3**, a dedicated **isolation transformer** is assumed to be present on shore, as it is required to galvanically separate between both the port and the vessel to ensure safety and compatibility in the power connection, further details for the transforms in the power system can be found in 0.

Relevant standards:

IEEE 1662 provides essential guidelines for the design and application of power electronics in marine electrical power systems, covering equipment with power ratings of 100 kW and above, and voltages up to 52 kV (AC or DC). It ensures robust integration and reliable operation of components like inverters, rectifiers, and converters in maritime environments. Emphasizing safety, performance, and compatibility, the standard addresses the unique challenges of marine conditions, such as thermal management and electromagnetic compatibility. Adhering to IEEE 1662 helps enhance the reliability, safety, and efficiency of electrical systems on ships and other marine vessels.

IEEE 1250 standard provides guidelines for identifying and improving voltage quality in power systems. It outlines methodologies for measuring and addressing voltage fluctuations, interruptions, and harmonics. The standard helps utilities and operators maintain a high-quality power supply and resolve voltage-related issues. By following IEEE 1250, power systems can achieve better voltage stability and reliability, ensuring efficient and effective management of voltage quality across the grid.

IEEE 1547 standard provides guidelines for connecting DERs to the electric grid, including ESS through inverters. It specifies how inverters should operate to ensure grid reliability and safety. This includes requirements for voltage regulation, frequency response, and anti-islanding protection, which help maintain stable grid conditions. The standard also mandates communication capabilities for inverters, allowing for remote monitoring and integration into smart grid systems. By following IEEE 1547, inverters ensure ESS can be safely and effectively integrated into the power grid.

3.1 Inverter system configuration

The choice of type and topology of the inverters used is primarily dependent on the specific inverter system configurations. These configurations are crucial as they determine the direction and efficiency of power flow between the barge, the port grid, and the vessels. Figure 2. illustrates the inverter system configurations, highlighting how they enable bidirectional power flow between the barge and the port grid, and unidirectional power flow from the barge to the vessels.

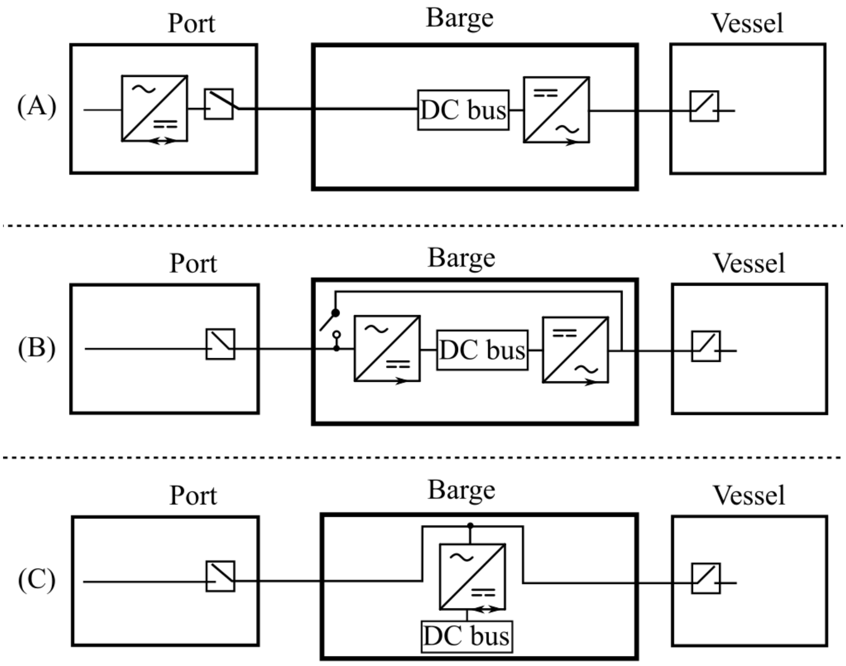

Figure 2 Inverter systems configurations facilitating bidirectional power flow between the barge and the port grid, and unidirectional power flow from the barge to the vessels. The arrows on the converters indicate the power flow direction.

In Figure 2 the three configurations of inverters for bidirectional power flow can be described:

(A) *DC-link*: Here a bidirectional power inverter system is placed at shore, this enables a DC-link from shore to barge and enables bidirectional power flow. To interface with the vessel, a unidirectional inverter setup onboard the barge can used.

(B) *Separate Charger and Inverter*: Here a rectifier system on the barge is utilized to enable charging of batteries from the SSE supply through an AC link. When at the shore, the unidirectional power inverter setup can be used to deliver power back to the grid. When the barge is at a vessel the same unidirectional inverter setup onboard the barge can used to deliver power to the vessel.

(C) *Grid-tied Battery Inverter*: Here a central bidirectional power inverter system is placed on the barge, this is utilized to enable the charging of batteries from the SSE supply through an AC link when at shore and also supply loads.

To choose the best configuration of the inverters, a short introduction is given to the unidirectional and bidirectional inverters and their pros/cons.

Unidirectional Inverters:

Unidirectional inverters convert power in a single direction, from DC to AC. They are simpler in design, offering high reliability and ease of maintenance. They are typically used in applications where dedicated conversion is required, such as in power supply systems that focus solely on energy discharge. However, an additional rectifier is required for charging at the port. The rectifier charging the batteries could be located at the shore, for less space requirements.

Advantages:	Disadvantages:
• Simpler inverter structure • Redundant • Specialized Functionality	• Requires more space

Bidirectional Inverters:

Bidirectional inverters are capable of converting power in both directions, handling both charging and discharging within a single unit. This flexibility simplifies system design and integration, making them ideal for dynamic applications like energy storage systems. They efficiently manage power flow, allowing seamless transitions between energy storage and supply modes, which is particularly beneficial for compact and space-constrained environments.

Advantages:	Disadvantages:
• Compact Design • Simplified System Design • Lower Cost	• Lower efficiency

3.2 Discussion for choice of inverter system configuration

In evaluating the DC-link for charging within inverter system configurations, the following conclusions can be made:

Configuration A is non-standard for OPS due to the onshore converter bidirectional converter, the shore-barge DC-link, and requires multiple inverters, making it expensive, complex, and thereby undesirable.

Configuration B proposes a switch to allow power flow from the barge to the grid if necessary, a setup typically used in Uninterruptible Power Supplies for commercial use. This configuration requires both separate rectifiers and unidirectional inverters, rendering it undesirable.

Configuration C employs a single bidirectional inverter system, simplifying the inverter system configuration. However, this might result in slightly lower efficiency compared to Configuration B, depending on the inverter topology and sizing. However, these configurations are widely seen in high-power commercial grid-tied battery energy storage systems, see Table 10.

Therefore, it is recommended to use the inverter system configuration in **Configuration C**, where a single bidirectional inverter system located on the barge is used to interface both the OPS and vessel.

3.3 Inverter Control Features

Inverters are vital components of electrical infrastructure and must be equipped with integrated control features to operate effectively. When an inverter is configured to deliver power back to the grid, it is crucial that it adheres to the specific grid code requirements of the country in which it is installed. These grid codes vary from country to country and are essential for ensuring that the inverter not only operates safely but also contributes to the overall stability and efficiency of the electrical grid. Compliance with these requirements helps in maintaining grid reliability, supporting voltage and frequency regulation, and managing power quality, thus ensuring that the inverter can seamlessly integrate and interact with the local grid.

The following features are significant for inverters, categorized into basic features, application-based features, and grid support features.

3.3.1 Basic features required

Automatic Output Synchronisation: When paralleled or connected to an AC bus with other generators, inverters benefit from automatic output synchronization, simplifying integration into live bus systems. The controller adjusts phase voltage and frequency to match the output profile before enabling the inverter modules, ensuring smooth transitions between power sources.

Dual-Frequency Operation: The inverter must support both 50 Hz and 60 Hz operation modes, allowing it to work seamlessly with ships that have different grid standards.

Power Flow Control: Advanced power flow control capabilities enable precise management of power transfer between AC grids. This feature is particularly valuable in microgrid and smart grid applications, facilitating bidirectional power flows and control of real and reactive power.

3.3.2 Application-based features

Remote Synchronisation: In addition to automatic output synchronization, inverters feature dedicated inputs for synchronizing output with external three-phase voltage references. This capability is useful for synchronizing separate buses before connecting them, such as closing bus tiebreakers on vessel switchboards.

Grid-Forming Capability: The inverter must establish and maintain stable voltage and frequency, creating a local grid. This allows other power sources and loads to synchronize and connect smoothly.

Power Module Redundancy: Modular designs often incorporate built-in redundancy, allowing the system to maintain operation by redistributing load to functional modules in the event of a fault with one module. This ensures continued operation with minimal impact on output capacity, as the inverter typically operates below full load. Effective control and power management units are essential for seamless redundancy.

Parallel Load Sharing: Inverters can operate in parallel with other voltage sources, facilitating load sharing through programmed frequency and voltage droop profiles. This enables multiple inverter units or generators to share power without requiring additional communication signals.

Output Short Circuit Protection: Inverters provide automatic current limiting in response to short circuits on their outputs, protecting downstream equipment. If a fault persists beyond a defined period, typically 2 seconds, the inverter will trip offline to prevent damage.

Environmental Ruggedness: The inverter should be designed to operate reliably under various environmental conditions, including extreme temperatures and humidity, ensuring consistent performance in island mode.

High Surge Capacity: The inverter must handle high surge currents needed to start large inductive loads, such as motors and pumps, which draw significantly higher currents upon startup.

3.3.3 Grid Support Features

Voltage and Frequency Compensation: Battery inverters must be capable of performing various grid support functions as mandated by grid codes. This includes voltage and frequency regulation to maintain grid stability. Inverters should be able to automatically adjust their output to help manage grid fluctuations and support voltage and frequency control.

Reactive Power Compensation: Many grid codes require inverters to provide reactive power compensation. This involves adjusting the inverter's output to support voltage levels and correct power factor issues, thereby enhancing grid reliability and efficiency.

Harmonic Compensation: Inverters must be designed to manage and mitigate harmonic distortions that can affect power quality. Compliance with harmonic limits ensures that the inverter does not contribute excessive harmonic currents to the grid, thereby preventing potential interference with other equipment.

Fault Ride-Through Capability: Inverters must have the ability to remain connected and operate during grid disturbances or faults. This feature, known as fault ride-through, ensures that the inverter can continue to support the grid even when there are temporary voltage dips or frequency variations. These features highlight the versatility and reliability of inverters, supporting efficient and resilient energy management in diverse operational environments for the barge operation requirements.

Black Start Capability: Some grid codes require inverters to have black start capability, allowing them to initiate and energize the system without an external power supply. This feature ensures that the inverter can help restore power in the event of a complete grid outage.

3.4 Inverter topologies

A literature review on converter topologies for battery ESS connected to MV grids was in [17]. The study examined the connection of battery ESS to MV grids through various converter topologies and categorized these into two main groups: those using transformers and those that are transformerless. For transformer-based converters, it focused on voltage source converters (VSCs), Z-source inverters (ZSIs), and quasi-Z-source inverters (qZSIs), with VSCs being preferred for their simplicity despite certain operational limitations.

The study also highlighted the use of parallel power blocks for high-power applications, the benefits of three-level neutral-point clamped (NPC) converters, and the emerging transformerless multilevel topologies, such as cascaded H-bridge (CHB) and MMCs. Each topology was assessed for efficiency, cost, and impact on battery life, providing a thorough overview of current practices and future directions in battery ESS integration with MV grids. Notably, there is a growing trend towards MMC topologies due to their lower losses and enhanced reliability.

Both transformer-based and transformerless inverters require filters to manage harmonic distortion and ensure compliance with grid standards. Transformer-based systems generally deal with filter complexities due to transformer impedance, while transformerless systems face challenges related to higher filtering requirements to compensate for the lack of galvanic isolation. Each approach has its own trade-offs between system size, complexity, and performance.

Table 9 Comparison of performance for inverters and rectifiers, taken from [19].

	Diode Rectifier*	Thyristor Rectifier / LCI	IGBT Rectifier*	MMC		NPC**	ANPC**
				Half-bridge	Full-bridge		
Output voltage levels	-	-	2	N+1		3	
Voltage stress	-	V_{dc}	-	V_{dc} /N		V_{dc} /2	
Filter inductor size	-	High	-	Low		Medium	
Capacitor number	-	1	-	6N		2	
Switching frequency	-	Several to tens of kHz		Hundreds of Hz		Hundreds to thousands of KHz	
Number of Switches	6 diodes	6 thyristors	6 IGBTs	12N IGBTs	24N IGBTs	12 IGBTs and 6 diodes	18 IGBTS
Control Complexity	None needed	Simple		Complex		Medium	
Fault tolerance	-	X	-	✓		X	
Fault ride-through capability	-	X	-	X	✓	X	

*** Represents only for rectifiers;**

**** Represents only for inverters; otherwise, the topologies are suitable for both rectifiers and inverters.**

3.5 Commercial large-scale inverter modules

This section presents various commercial inverter modules. To enhance the power rating of the inverter system, multiple modules can be connected in parallel, provided they offer this option together with the parallel load-sharing feature. The use of multiple inverters increases the redundancy of the system, however, it most likely comes with larger space and cost requirements.

Table 10 Commercial grid-tied battery inverter modules.

Technical Data	SMA - SCS 2630 UP-XT-US[1]	Huawei LUNA2000-200KTL-H0[2]
DC bus voltage	1003 V to 1500 V	1,180 V - 1,500 V
Nominal Grid-Feed AC power	3 MW (at 1200 Vdc and cos φ=1.0 and 25 °C)	0.2 MW (at 40 °C)
Charging mode	2.7 kVA (25 °C)	-
AC power frequency / range	50 & 60 Hz (±3 Hz)	50 & 60 Hz
Dimensions (W x H x D)	2815x2318x1588mm (~10.3m³)	875x820x365 mm (~0.26 m³)
Weight	>3400 kg	>99kg
Efficiency	Max. 98.6 %	Max. 99%
Certifications and approvals	UL 62109-1, UL 1741, NERC, UL 1741-SA + SB, IEEE 1547-2018, IEEE 1547 a-2020, IEEE 1547.1-2020, MIL-STD-810G, UL 1998, CAN/CSA C22.2 107.1 2016	RoHS, IEC 62477-1, IEC 61000-6-2, IEC 61683, VDE 4120, EN 50549, IEC / EN 61643-11, etc.
Units needed for 3MW	1	15

[1] https://www.sma.de/en/products/battery-inverters/sunny-central-storage-up-xt#c222

[2] https://solar.huawei.com/download?p=%2F-%2Fmedia%2FSolar%2Fdatasheet%2FSmart-PCS.pdf

3.6 Challenges

Adapting to Diverse National Standards: The inverter used to interface the barge power system with the grid must comply with the grid codes where it operates. Adhering to these diverse standards can be complex to implement, as it often requires the usage of advanced control features and careful integration to ensure proper functioning across different national regulations.

Challenges in Implementing Applications-Based Inverter Features: Adding advanced functionalities such as e.g. enhanced grid support to existing commercial inverters can be difficult due to limitations in firmware and hardware design from the manufacturer. Modifications may require significant engineering changes, proprietary constraints, and extended development time.

3.7 Conclusion

Optimal Inverter System Configuration for Commercial Viability and Scalability: A single bidirectional inverter configuration was identified as the most suitable option for the barge, offering a simplified system design and commercially available high-power inverters. This configuration also supports the parallel connection of suitable bidirectional converters, allowing for scalability and redundancy. Additionally, two commercially available inverters were identified as potential options for implementation.

Inverter Features are Essential for Optimal Operation and Integration: The bidirectional inverter for the barge has to have basic features such as automatic output synchronization, dual-frequency operation, and power flow control. Furthermore, application-based features like remote synchronization, grid-forming capability, power module redundancy, and output short circuit protection could be crucial for reliable and resilient operation for certain use cases.

4 Energy Infrastructure Specifications

This section covers the general systems architecture, detailing the primary infrastructure elements, examples of technological solutions, and various practical applications for Onshore Power Supply (OPS) and BMG (Barge Micro Grid).

Relevant standards:

IEC/IEEE 80005 series provides guidelines for connecting shore-side electrical power to ships, ensuring safe and efficient power transfer. Key components include **IEC/IEEE 80005-1**, which covers high voltage shore connection systems, addressing safety, system design, and operational procedures. **IEC/IEEE 80005-3** focuses on low voltage shore power connections, detailing system components, safety requirements, and protocols. **IEC/IEEE 80005-2** specifies the communication interface for shore-to-ship power connections, including data exchange and control protocols. These standards help reduce emissions by allowing ships to shut down engines while docked and ensure reliable power transfer, supporting environmental sustainability and operational efficiency.

IEC 60092 series provides guidelines for the design, construction, and installation of electrical systems on ships and offshore units, ensuring safety, reliability, and efficiency. Key components include IEC **60092-10**1, which covers general requirements for marine electrical systems, including system planning, material selection, and safety measures. **IEC 60092-202** have guidelines for designing marine electrical systems, addressing power generation, distribution, and fault protection. **IEC 60092-350** to **376** specify types and construction of cables used in marine environments and their testing procedures. **IEC 60092-401**-407 outline requirements for protecting and controlling electrical systems. **IEC 60092-501-507** provide standards for electrical equipment like generators and motors. These standards ensure safe operation, prevent electrical hazards, and support long-term reliability of marine electrical systems.

The IEEE 45 series offers essential guidelines for the installation and equipment of shipboard electrical systems, ensuring safety, reliability, and efficiency. IEEE Std 45.1-2023 focuses on the design of ship electrical systems, including system architecture and load management. IEEE Std 45.2-2023 provides standards for control systems and automation integration. IEEE Std 45.4-2018 addresses electrical installations for various marine sectors and mission-specific systems. IEEE Std 45.5-2014 emphasizes safety considerations to prevent electrical hazards. IEEE Std 45.6-2016 outlines procedures for electrical testing to verify system reliability. IEEE Std 45.7-2012 covers the design, installation, and maintenance of AC switchboards. IEEE Std 45.8-2016 details the selection, installation, and maintenance of shipboard cable systems. Collectively, these standards provide a robust framework for ensuring that shipboard electrical systems operate safely and efficiently.

In Figure 3 the primary component block typically found in shore-barge-ship energy infrastructure can be seen.

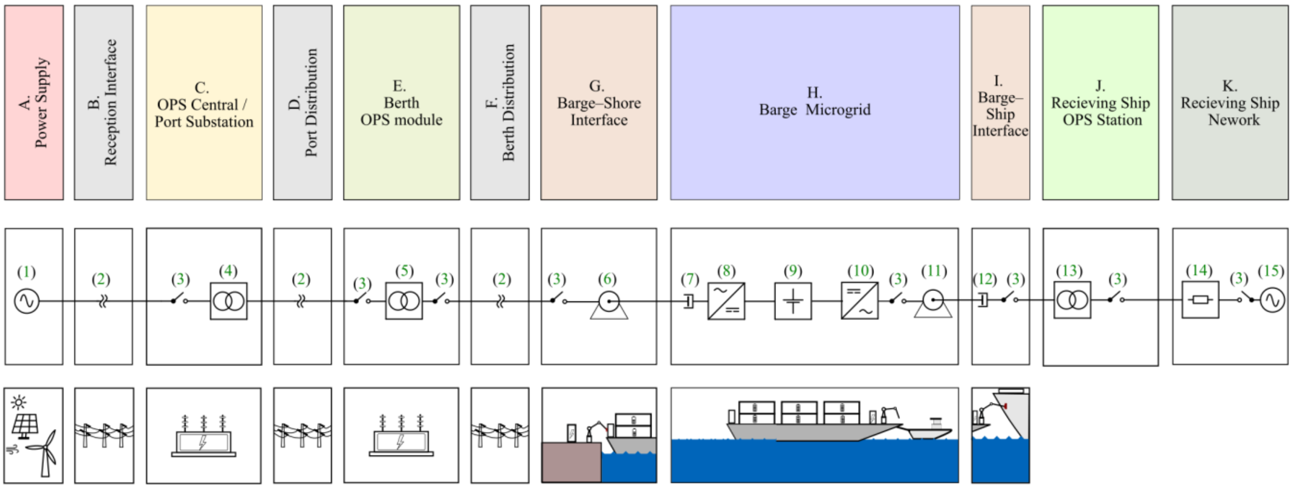

Figure 3 Representation of key components found in shore-barge-ship energy infrastructure.

The main components shown in the figure are identified by the corresponding green letters in the coloured blocks and reference numbers in parathesis.

A. **Main Voltage Supply:** The power source (1) where HV is sourced, which can be the national/local HV distribution grid with input voltages of 6.6-36 kV AC or other AC/DC voltages from local power production, including port shore/offshore power plants.
B. **Reception Interface:** The point where electricity is transferred into the port area (2), which may include cable routing, overhead, or underground HV. This provides the OPS central/port substation with electricity according to energy contract characteristics, where contractual electricity supply is verified.

C. **OPS central/port substation, including:**
   a. Circuit breakers and/or switchgears (3).
   b. Step-down, step-up or protection transformers (4), to bring HV to MV/LV for port/berth distribution voltage. Transformers are fundamental technological enables for OPS. They allow for voltage adjustment and provide for isolation.
D. **Port Distribution:** Distributes HV/LV lines from the OPS central/main substation to different berth OPS modules, usually underground. Distribution at HV/LV depends on the optimal assessment of cable routing distances and the efficiencies associated with various distribution concepts.
E. **Berth OPS Modules:** May contain step-down or isolation transformers (5). In decentralized systems, frequency conversion is performed at dedicated berth OPS modules, typically for high-power consumers/ships.
F. **Berth Distribution:** Distributes electrical energy at the berth level directly to OPS supply points.
G. **Barge-Shore Interface:** Includes infrastructure elements for cable handling (6), either HV/LV shore connection (See electrical specifications in Table 11). Systems may be manual, semi-automated, or fully automated. Connection cables can be provided by the shoreside as (6), but it is also possible to do it from the barge side. The cables are located on a cable reel for flexibility. The connection is established through appropriate connection through the plug (7), shown here on located on the barge.
H. **Barge Microgrid:** The BMG shown consists of an energy system (9), which includes various types of power supply modules and a PMS. The inverter system configurations (8, 10) can vary depending on the application as seen in 3.
I. **Barge-Ship Interface:** Includes infrastructure elements for cable handling (11) on the barge, for either HV/LV ship connection. Systems and connections may be manual, semi-automated, or fully

automated. Connection cables with the appropriate plug type (12) for the ship type will be provided by the barge, often with a cable reel for flexibility.

J. **Receiving Ship OPS Station (Ship-Side):** Houses the barge/OPS to ship interface transformer (13) to accommodate various voltage ratings on the ship consumer side, as well as the main ship-side circuit breaker and switchgear.

K. **Receiving Ship Network (Ship-Side):** Includes the main switchboard, onboard generators (15), and onboard consumers (14).

4.1 A) - Power Supply

The primary power supply on the grid side at the shore is crucial for interfacing the electrical energy to the Barge-to-Shore Electrical system. It is designed to meet specific parameters such as current, voltage amplitude, phase, and frequency requirements. The HV shore connections are standardized with nominal voltages of 6.6 kV AC and/or 11 kV AC, ensuring galvanic separation from the shore distribution system as per **IEC/IEEE 80005-1.**

The power sources can vary and include:

1. National electricity grid distribution, connected to substations near the port area, necessitating consideration of HV infrastructure routing, which may be aerial or underground depending on feasibility and safety.
2. Port generators, both floating and shore-based units, offer flexibility in electricity supply to manage costs or meet operational requirements.
3. Renewable energy plants such as wind, shore, or offshore facilities, and photovoltaic (PV) panels, integrated with electrical energy storage systems (battery modules).
4. ESS systems are used in conjunction with distributed networks to accommodate irregular green energy production from renewable sources.
5. Emergency backup power units provide additional energy security.

A combination of the above power sources can be advantageous both due to added robustness, cost reduction, and green energy utilization. However, it should be noted that the barge can help act as an ESS or even emergency backup power if the energy capacity on the barge is sufficiently high.

The connection of ports to the utility network should follow agreements between the port and network suppliers, addressing specific user needs related to:

- Supply size
- Installed power
- Substation location
- Metering requirements

For the interfacing inverter (8) to act as an energy resource for a grid, various considerations should be taken into account, these are mainly explained in the following sections.

The various rated characteristics standardized in the references for SSE electricity supply can be seen in Table 11.

Table 11 Electrical Characteristics for SSE (Values at the Supply Point) – This table exclusively presents the characteristics of AC supply.

Parameter	Reference(s)	High Voltage Shore Connection (HVSC)	Low Voltage Shore Connection (LVSC)
Voltage	IEC/IEEE 80005-1 IEC/IEEE 80005-3 IACS Unified Requirements Electrical	6.6 kV or 11 kV	400 V, 440, V 690 V. 230 V for consumption less than 50 kW
Voltage Tolerances		- No-Load Conditions: 6% of nominal Voltage increase - Load Conditions: 3.5% max voltage drop	- No-Load Conditions: 6% of nominal Voltage increase - Load Conditions: 5% max voltage drop
Frequency		50/60 Hz or DC for Fast DC Charging systems	
Frequency Tolerances	IEC/IEEE 80005-1 IEC/IEEE 80005-3 IACS Unified Requirements Electrical	Continuous tolerance: ±5%	
Transient Response		dV (voltage transient peak variation): -15% < dV < 20% (1.5 s) df (frequency transient variation): ±10% (5 s) Transient Response should be well known and documented for: 1. <u>Shore-side</u>, for the voltage and frequency response, when subject to an appropriate range of differing off load step changes. 2. <u>Barge-side</u> for the maximum step change in load expected for the charging of the batteries, but also external loads (This can be e.g Air Conditioning compressors or electrical pumps for cooling). The component of the system that experiences the largest voltage dip or peak during the connection or disconnection of the maximum step load shall be identified.	
Harmonic Distortion		For no-load conditions, voltage harmonic distortion limits: < 3 % (single harmonics) < 5 % (for total harmonic distortion)	
Voltage variations for DC supply	IACS Unified Requirements Electrical	Voltage tolerance (continuous): ±10% Voltage cyclic variation deviation: 5% Voltage ripple (RMS over steady DC voltage): 10%	
Voltage variations for battery systems		Components connected to the battery during charging: +30%, -25% Components not connected to the battery during charging: +20%, -25% Note: Different voltage variations as determined by the charging/discharging characteristics, including ripple voltage from the charging device, may be considered.	

It is crucial to implement comprehensive protections against rapid transient overvoltage surges for both HVSC and LVSC, such as those caused by lightning strikes or switching operations. The response characteristics of the shore connection are heavily influenced by variations in the barge-side load steps. Therefore, the plant operators should prioritize documenting and be able to control the load consumption profile for the barges. The shore supply installation must be robust enough to handle transient load fluctuations caused by the barge side while also ensuring adequate protection for SSE infrastructure and equipment.

<u>Relevant onshore power standards:</u>

IEC/IEEE 80005-1: Specifies general requirements for high voltage shore-side electricity connections in ports, accommodating up to 20 MVA per vessel (depending on the vessel). This standard ensures the safe and efficient transfer of electrical power from shore to ship.

IEC/IEEE 80005-2: Covers data communication requirements for monitoring and controlling high voltage shore-side connections (HVSC) in ports. This standard ensures reliable data exchange for the operational safety and performance monitoring of shore power systems.

IEC/IEEE 80005-3: Defines the general requirements for LV shore-side connections in ports, typically handling less than 1 MVA. This standard provides guidelines for the safe and efficient transfer of electrical power at lower voltages.

IEC 62613-2: Focuses on the dimensional compatibility and interchangeability requirements for plugs, socket outlets, and ship couplers used in HV shore connection systems (HVSC). This ensures that accessories used by different types of ships can be easily connected and used safely.

IEC 60309-5: Specifies the dimensional compatibility and interchangeability requirements for plugs, socket outlets, ship connectors, and ship inlets for low-voltage shore connection systems (LVSC). This standard ensures that low-voltage connection accessories are standardized for industrial purposes, facilitating safe and efficient connections between shore power systems and ships.

These standards ensure the interoperability, safety, and efficiency of shore-side power connections, facilitating reliable power supply to ships while docked in ports.

4.2 B, D, F) - Power Distribution Infrastructure

The primary functions of transmission HV cables are to transfer electrical power between designated locations while ensuring insulation of energized components from earthed structures at rated operating voltages and specified switching and lightning impulses. This section discusses the relevant aspects of fixed power cable installations within SSE infrastructure, including transmission line equipment.

Within the port area, HV electricity infrastructure depends significantly on the port layout, incoming transmission lines, SSE connection points at different berth locations, vessel types, sizes and other factors. The infrastructure includes various components such as the Reception Interface, where HV cables from the utility grid are received either by overhead or underground cables, the Port Grid distribution, and Berth distribution systems.

The distribution HV cabling within SSE infrastructure involves several considerations. The main aspects include the identification of the HV electrical distribution/transmission system, conductor sizing and protection, installation requirements, determination of the smallest allowable cross-sectional area, short circuit current, protective earthing conductor, neutral conductor, and equipotential conductor. Concluding, an important issue in terms of infrastructure is the size needed to house all the aforementioned components/equipment.

The major components of an HV distribution cable system include single or multi-core cables, connections, terminations at substations, cable link boxes, and monitoring system components. A typical HV XLPE insulated power cable used in underground distribution systems consists of several layers, each serving a specific function. The stranded compacted conductor transports electric current, while the semi-conductive conductor screen ensures a uniform electric field in the cable insulation. The XLPE insulator provides electrical separation between the high voltage cable conductor and the cable sheath at ground potential. The semi-conductive insulator screen contains the electric field, and the copper wire screen or tape offers structural stability and protection. Additional layers such as fillers, the lead sheath, bedding, armouring or metallic shield, PP wrapping tape, and the overall sheath contribute to the cable's structural integrity and protection against mechanical damage and environmental factors.

Conductor sizing and protection involve a detailed analysis of the power requirements of the entire SSE installation. This includes considering the expected range and size of ships and barges to be connected, both individually and simultaneously, at any given time. The cabling and its protection must meet several conditions to ensure a safe and reliable installation. These conditions include carrying the permanent full load current and normal short-time overcurrent, and not causing voltage drops that could result in inferior performance of certain connected loads. Protective devices, such as circuit breakers or fuses, must protect the cabling and busbars from overcurrent up to short-circuit currents and ensure protection against indirect contact hazards. The cross-sectional areas of conductors are determined by applying relevant standards, such as IEC 60364-5-52.

Several best practice requirements should be considered when defining the procurement, commissioning, and installation of electrical distribution cable systems. These requirements include ensuring that cables are suitable for demanding applications, rated and installed to support maximum input and output powers without overheating, and designed to allow for future expansion. Installation should follow manufacturer recommendations, with special attention to earthing, shielding, and connection of HV cables. Cables should be arranged in cable ducts for indoor routes or conduits for outdoor routes, and direct burial should be avoided unless specified. The installation must withstand any transverse loading, allow easy access for future replacement and repair, and provide adequate above-ground identification throughout the cable route. Additionally, all new cable support systems should be used to no more than 50 percent of their working capacity to allow for future expansion.

Technical Standards and References

Compliance with relevant standards is crucial for the safe and efficient installation of HV cabling systems. Key reference standards include **IEC 60826** for the design criteria of overhead transmission lines, European standard **EN50341-1** for overhead electrical lines exceeding AC 1 kV, **IEC 60364-5-52** for low-voltage electrical installations, and several others specific to HV cable systems. These standards provide comprehensive guidelines on the selection, erection, and maintenance of electrical equipment and wiring systems, ensuring the reliability and safety of HV cabling installations in the port area.

4.3 C, E) - Substations

Substations are vital for housing critical and sensitive equipment in the SSE port grid, making their layout, location, and protection crucial for ensuring an energy interface for the barges. The number of substations needed depends on the grid's architectural choices and topologies, including voltage step-down transformation. HV/LV substations can be located anywhere within the port area, with a preference for locations balancing protection and accessibility.

The substations can have different types depending on their application. Indoor substations are located within buildings, which may be purpose-built or adapted for their use. They handle the transformation and conditioning of electrical energy but are less preferred due to their limited flexibility, the need for specialized cooling systems, and potential difficulties in emergency access. Outdoor fixed substations are more commonly used in SSE setups. They offer flexible placement options and can be prefabricated for easier, modular installation. These substations often include dry transformers, providing a balance between protection and accessibility within the port area. Outdoor mobile substations offer high flexibility and are ideal when permanent installations are impractical. Typically modular and mounted on truck-trailers, they can be easily deployed and connected easily. Outdoor substations without housing are less common for SSE installations and are generally found in industrial settings. These substations do not have protective enclosures, requiring all equipment to be weatherproofed to withstand environmental conditions.

4.4 G) - Barge-Shore Interface

The barge-to-shore connection is an important system, composed of the following equipment:

- **Shore-to-barge OPS connection cable**: Ensures the transmission of electricity from shore to the barge at specified voltage and current ratings, designed to handle both electrical and mechanical requirements for the intended conditions of use.
- **Shore Cable Management System:** Designed to handle the SSE connection cable and connectors, ensuring that a mechanical shore-to-barge connection is viable under different conditions.
- **Barge Connectors:** Allows for mechanical plug-in electrical connection between shore and barge, connectors should be used according to **IEC 62613-1**.
- **Interlocking, Earthing Switches, and Safety Functions:** Ensures essential electrical safety functions in the shore-to-barge connection. Emergency shutdown functions are covered by this point.
- **Control and Monitoring Cable**: When automation is involved, this cable ensures control and monitoring within the shore-to-barge connection.
- **Data Communication:** Covers the exchange of relevant data, including power quality, operation logging data, and alarm notifications.

This equipment works together in the shore-to-barge interface to ensure a safe SSE connection. Ideally, all elements should be part of one assembled system, designed by one system integrator, ensuring that all elements are part of a single safety concept, working adequately together with minimal system barriers/interfaces. The shore connection equipment and installations shall be in accordance with **IEC 61936-1.**

4.5 I) - Barge-Vessel Interface

This setup is similar to the barge-vessel interface, with the notable difference that the cable management system is located on the barge, which should have various connectors for different vessel types.

Barge Cable Management System: Located on the barge, this system manages the electrical connection cable and connectors. It must account for the relative motion between the two floating units, ensuring a mechanical barge-to-vessel connection is viable under varying sea conditions. This design centralizes cable handling, making the system more robust and easier to manage.

Vessel Connectors: These allow for a secure mechanical plug-in electrical connection between the barge and the vessel, ensuring a reliable power transfer. Connectors should be carefully chosen to match the specifications and requirements of different vessels, ensuring compatibility and safety.

4.6 H) - Barge Microgrid

The BMG is an essential topic considered in this task. This section will detail the specifications for the interface options for the power supply modules, configurations of the DC bus, and the microgrid interface to HV and LV vessels as well as the MV grid.

In this context, the general structure of a BMG with only a PSM consisting of a battery ESS connected to the MV grid is shown in Figure 4. The system consists of the battery pack, a DC/DC conversion stage, and a DC/AC conversion stage. However, it should be noted that the DC/DC stage can be omitted for batteries, this is denoted as a direct integration of batteries to the DC bus.

Converter topologies in each stage can either include a transformer or be transformerless. For the DC/AC stage, when low voltage switches are employed in 2 or 3-level topologies, a step-up transformer is required to connect to the MV grid. A disadvantage of these topologies is the high current on the transformer's low voltage side, which can decrease efficiency [20]. As a result, transformerless DC/AC converter technologies, such as 2-level converters with serial switches and modular multilevel converters (MMC), are becoming increasingly attractive. To achieve galvanic isolation for the PSMs when utilizing transformerless DC/AC converters, the DC/DC stage can be isolated using high-frequency transformers. High-frequency transformers in the DC/DC stage help improve efficiency and reduce size compared to conventional transformers [21]. It should be noted that other PSM technologies, such as fuel cells and alternative generators, should be connected only through unidirectional DC/DC converters, which also come with and without transformers. There is also the possibility of direct integration of batteries directly into the DC bus this simplifies the DCMG architecture, and reduces conversion losses [22]. However, this approach suffers from practical problems such as unregulated battery charging, which needs to be coordinated by multiple parallel converters. These converters have inherent imperfections in bus voltage measurement, causing circulating current problems that lead to uneven loading and accelerated wear and tear of the batteries. Additionally, it poses challenges in voltage matching, stability, and effective load sharing between battery packs. Higher initial costs due to the need for specialized equipment further complicate this approach.

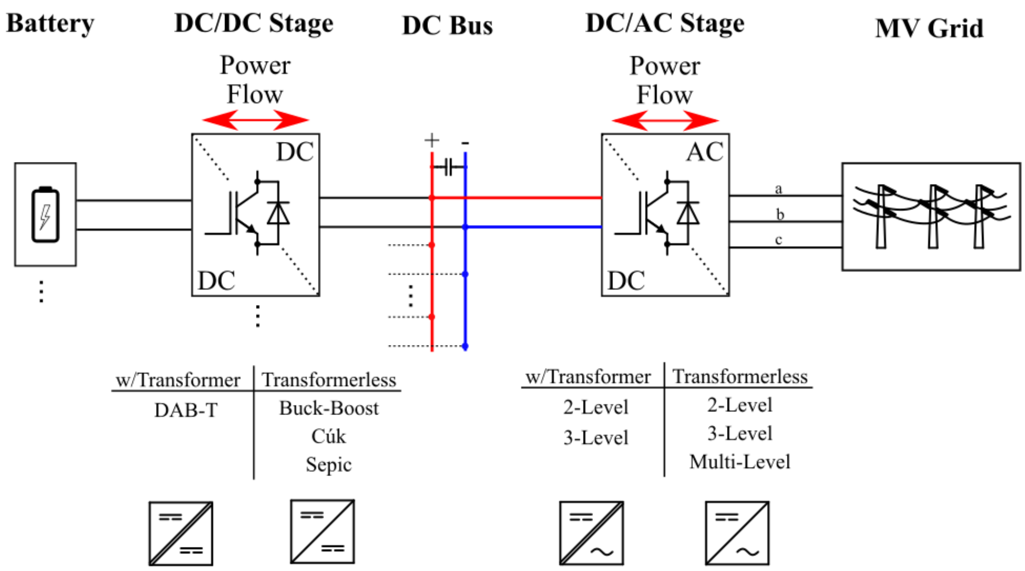

Figure 4 Visualization of microgrid structure of battery ESS connected to the medium voltage (MV) power grid.

4.6.1 DC Microgrid Architectures

The selection of a DC microgrid topology is pivotal for optimizing system performance in terms of flexibility, reliability, cost, and scalability. Each architecture exhibits distinct structural characteristics that influence its operational efficiency and suitability for specific applications.

Radial

The radial DC microgrid architecture is characterized by a single, centralized DC bus that distributes power to various branches connected to generation sources, energy storage, and loads. This configuration can be visualized as a linear or tree-like structure with one main conduit (the bus) extending outward to multiple end-points. The simplicity of this architecture makes it cost-effective and straightforward, particularly for low-voltage applications such as residential or small-scale systems. However, it offers limited fault isolation, as the failure of one branch can impact the entire system unless redundancy is incorporated.

Multi-Bus

In the multi-bus architecture, multiple DC buses are interconnected to form a network of nodes. This arrangement can be conceptualized as a grid-like structure with several parallel and intersecting lines. Each bus functions as a hub that connects to adjacent microgrid clusters, enabling power exchange between them. This design enhances system reliability and operational efficiency by allowing for redundant power paths and automatic isolation of faulty sections. It is particularly advantageous in applications where continuous power availability is critical, such as in naval and marine environments.

Zonal

The multi-terminal topology features a more complex structure akin to a high-voltage interconnected web. It consists of multiple input terminals connected to a central DC bus through various voltage source converters. This configuration supports numerous power transmission paths and facilitates integration with multiple AC grids. The arrangement resembles a network of interconnected terminals, allowing for dynamic power balancing and flexibility. Due to its complexity, this architecture is typically employed in large-scale systems, such as offshore wind farms, where diverse power sources and high-voltage operations are prevalent. More information for designing the zonal distribution system is accessible in **IEEE 1826**.

Ring

The ring bus architecture is visually represented as a closed-loop or circular arrangement where all components—generation units, storage systems, and loads—are connected in a continuous ring. Each component is connected to its neighbors on both sides, creating multiple pathways for power flow. This configuration improves fault tolerance and system reliability, as a fault in one segment can be isolated while maintaining power flow through the remaining loop. The ring architecture is suitable for systems requiring high resilience and redundancy, offering advantages in environments where continuous operation is essential.

Each DC microgrid architecture presents a unique structural configuration, influencing its effectiveness for different applications, including marine and large-scale energy systems. The choice of architecture affects the system's performance, fault management, and overall reliability.

Table 12 Comparison of DC microgrid architectures performance for MV DC ships [19] .

Bus Scheme	Radial	Zonal	Ring
Description	Two buses connected by one breaker.	One ring bus with 2n+2 breakers.	One ring bus with six breakers.
Reliability	Low	High	Medium
Survivability	Low	High	Medium
Reconfigurability	Low	High	Medium
Complexity	Low	High	Medium
Number of Applied Cases	Most	Medium	Least

In [19], a qualitative comparison of radial, zonal, and ring distribution architectures presented for DC ships MG in **IEEE 1709** and their key performance metrics is presented in Table 12. These metrics include bus schemes, reliability, survivability, reconfigurability, and complexity. The radial scheme requires the fewest breakers and has the simplest structure, but it has the lowest reliability, survivability, and reconfigurability. The zonal scheme provides the best performance in these areas but comes with high system complexity and a large number of breakers, especially for large ships. The ring scheme offers medium performance across these metrics. Based on this comparison, it can be concluded that the radial scheme is suitable for small ships with few components, such as short-distance ferries, where system reliability requirements are not very high. In contrast, for large ships with high requirements for system reliability and survivability, such as vessels, cruises, and cargo ships, zonal and ring schemes may be preferable for better safety of personnel and cargo. Currently, the radial scheme is the most widely used in practice, as many electric ships are refitted from older ships, maintaining the popularity of the radial scheme.

4.6.2 DC bus Architecture and Voltage Levels

In DC networks, there are two primary types of DC bus architectures unipolar and bipolar systems, see Figure 5.

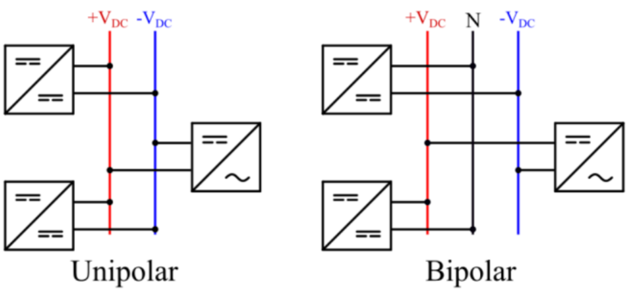

Figure 5 DC bus architectures.

In a **unipolar** DC system, all components are connected to a two-wire DC bus, consisting of positive and negative lines through converters. The system operates at a single voltage level, making the selection of the DC bus voltage a critical factor. Although the unipolar design is straightforward and simplifies implementation, it lacks redundancy and is vulnerable to single-point failures [23][24]. Higher voltage levels increase the system's power transmission capability but necessitate additional DC-DC converters to ensure compatibility across different components.

In contrast, **bipolar** systems use a three-wire configuration: positive ($+V_{dc}$), negative ($-V_{dc}$), and neutral (N). Bipolar systems provide three distinct voltage levels: $+V_{dc}$, $-V_{dc}$, and $2V_{dc}$. This arrangement enhances reliability and power quality, as it allows continued power supply even if one DC pole fails, leveraging the other two wires and an auxiliary converter. Bipolar systems also offer greater flexibility in connecting loads and distributed generation sources, thanks to their ability to support multiple voltage levels [25]. However, this flexibility can lead to voltage imbalances due to unequal load distribution, requiring voltage balancer circuits or advanced control systems to stabilize the DC bus voltage [19].

Both unipolar and bipolar topologies are foundational for future DC microgrid architectures and grounding schemes. Bipolar systems are often preferred for their improved reliability and flexibility, addressing many limitations of unipolar designs. Current standards do not specifically define DC voltage levels for DC shipboard microgrids (DC-SMGs) [19]; instead, voltage levels are determined by factors such as cost, generator and propulsion motor drive voltages, converter design, load requirements, cable and bus-bar ratings, and fault energy considerations. Generally, low voltage DC (LVDC) systems operate below 1 kV with power capacities ranging from 1-20 MW, whereas medium voltage DC (MVDC) systems operate above 1 kV with capacities from 20-100 MW [19].

Relevant standards

IEEE 2030 provides guidelines for smart grid technologies, which can be useful for developing a smart grid system for the barge. It guides the integration of various technologies and ensures they work well together. This standard covers communication protocols for data exchange, which are essential for monitoring and controlling the barge's power system in real time. It also promotes interoperability, allowing different energy sources and storage systems to work together effectively. Additionally, IEEE 2030 includes frameworks for data management, security, and reliability, which can help make the barge's smart grid more efficient and secure.

4.6.3 Grounding

Grounding in DC BMG systems presents significant challenges due to the absence of a dedicated ground when at sea. Typically, the grounding on a ship is achieved by connecting the hull to the water, which acts as the grounding medium. For non-metallic vessels, a grounding plate is installed along the keel below the waterline to ensure it always remains in contact with the water. Therefore the **IEEE 1709** standard provides guidelines for grounding of MVDC Power systems on vessels. An ungrounded DC BMG system may exhibit low leakage and line-to-ground fault currents, complicating fault detection and location. The minimal leakage current leads to high common-mode voltages, necessitating stringent insulation levels and posing risks to personnel [26]. In some cases, the hull may serve as a grounding reference. Effective mitigation involves constructing the system with low impedance and isolating it from other ground references.

- **Bipolar Arrangement Without Grounding:** In this configuration, both poles of the MVDC bus are isolated from the ground, with grounding limited to metal bodies (e.g., cable sheaths and cabinets) for safety. While this minimizes corrosion issues and insulation requirements, it results in higher cable costs, increased space, and weight. Moreover, the absence of a grounding reference can cause drift of either pole with respect to ground due to leakage currents, making this approach less practical.
- **High Resistance Grounding:** This approach allows the system to continue operating even with a single line-to-ground fault. The system neutral is not solidly grounded, so each pole must withstand the full bipolar DC voltage during unbalanced conditions. This method is preferred for maritime

applications as it accommodates operational continuity during fault conditions, provided the system is well-designed for fault detection, localization, and reconfiguration.

- **Solidly Grounded Neutral Point:** In this setup, the system operates at half power with one pole out of service and provides insulation at half the voltage to ground. A neutral cable is necessary to return unbalanced and fault currents to the ground. This option allows operation under fault conditions but is generally less favoured due to the additional requirements for neutral cables and the potential impact on system balance.

These grounding strategies are essential for maintaining operational reliability and safety in DC BMG system.

4.6.4 Isolation and Disconnection Requirements

A set of requirements for MV DC shipboard systems for isolation of the DC bus is given in **IEEE 1709**. All loads and power sources connected to the MVDC bus must be equipped with a disconnect means, such as a switch, circuit breaker, or bus link. This disconnect device must be capable of isolating the load from the MVDC bus for safety and maintenance purposes. It should interrupt all power connections and be rated to handle operating and overload currents, but not for interrupting currents. To ensure safe disconnection, power electronics should be employed to bring the current to zero before the disconnect means is opened. Power sources must be secured before their respective disconnects are opened. Power electronics equipment must have internal or external isolation means. These isolating devices should:

- Provide a visible status indication.
- Include a locking mechanism with a padlock.
- Feature interlock circuits to prevent operation while power is applied.

Interlock circuits must ensure that the isolating means cannot operate until all power-down and circuit discharge functions have been completed and verified. The isolating means should be operable only when the converter is not loaded, ensuring physical separation from the rest of the power system. They should not be used to interrupt loaded converters. While separate devices for isolation and interruption are possible, a single device like a circuit breaker can serve both purposes if it is rated to handle the extreme conditions associated with both functions.

4.7 Control and Monitoring System

As per **IEEE 1709**, the control and monitoring system must be capable of real-time monitoring of PSM and loads and be able to:

- Advise operators on critical conditions and recommended actions to prevent instability and system collapse.
- Incorporate human factor engineering to help operators maintain situational awareness and respond appropriately during normal and emergencies.

4.8 Installation and Equipment

The equipment visualized in Figure 3 is explained in this subsection to provide clarity on the function and necessity of each component within the system. This includes the switchboards, protective devices, and various control and measurement instruments essential for ensuring safe and efficient operation. By understanding these components, we can better appreciate their roles in maintaining system integrity, preventing faults, and facilitating seamless load transfers between the shore, barge, and ship power supplies.

4.8.1 Switchboards

A switchboard is an assembly of panels with switches that redirect electricity, and are critical components in the power supply system. Typically housed in metal sheet-covered units containing modular components, switchboards direct electricity from one or more sources to various consumers or other switchboards. They are typically located at distribution points or interface stages in the power system and are not directly shown in Figure 3. The number and configuration of switchboards depend on the overall system architecture, including interfaces, substations, Converters, transformers, and energy storage elements, among other factors. Switchboards may also include controls for regulating the supply of electricity, as well as gauges that display frequency, current intensity, and other relevant metrics. The power entering a switchboard should generally equal the power exiting the loads, accounting for losses in internal conductors and consumption by internal devices like pilot lamps and space heaters.

The three main switchboards considered in this report are located at the shore, barge, and ship side. To ensure that the switchboard installation complies with **IEC/IEEE 80005-1** and achieves a test certificate, the switchboard installation must undergo verification tests. These tests are listed in **IEC/IEEE 80005-1** and should be conducted after installation is complete and carried out as witness tests in collaboration with the relevant authorities.

The considered switchboard's purpose, instrumentation, and protection measures are briefly described below.

4.8.1.1 Shore connection switchboard

The shore connection switchboard must be installed as close as possible to the receiving point and adhere to **IEC 62271-200,** and the shore connection equipment and installations shall be in accordance with **IEC 61936-1**.

The circuit breaker, disconnector, and earthing switch must be interlocked to ensure proper isolation before earthing, as specified by **IEC 62271-200**. It must include a circuit breaker to protect the barge's electrical equipment downstream; omitting this protection is not permitted by **IEC/IEEE 80005-1**.

The circuit-breaker and earthing switch must have a rated making capacity that meets or exceeds the prospective peak short-circuit current and a rated short-circuit breaking capacity that meets or exceeds the maximum prospective symmetrical short-circuit current, both calculated according **to IEC 61363-1**. An automatically operated circuit breaker is required.

According to **IEC/IEEE 80005-1**, the shore connection switchboard must be equipped with:

a. Voltmeter: For all three phases.
b. Short-Circuit Protection Devices: With tripping and alarm functions.
c. Overcurrent Protection Devices: With tripping and alarm functions.
d. Earth-Fault Indicator: With an alarm function.
e. Unbalanced Protection for systems with multiple ship inlets.

The protection and safety system must have continuous power. A standby power supply with automatic change-over, providing at least 30 minutes of operation, must be installed as per **IEC 60092-504**, 9.7.2.6.

If the battery charging fails or the backup system activates, an alarm must alert the relevant duty personnel.

Protection shore side

According to **IEC/IEEE 80005-1,** the HV circuit breaker on the secondary side of the transformer on shore should open all insulated poles under the following conditions:

a. Overcurrent, including short-circuit
b. Over-voltage/under-voltage
c. Reverse power (During charging of PSM)
d. Earth fault
e. Unbalanced cable protection

To meet these requirements, at least the following protective devices or equivalent measures shall be provided:

a. Synchrocheck (25)
b. Undervoltage (27)
c. Reverse power (32)
d. Negative phase sequence overcurrent (46)
e. Instantaneous overcurrent (50)
f. AC inverse time overcurrent (51)
g. Earth fault overcurrent (51G or 51N)
h. Overvoltage (59)
i. AC directional overcurrent (67)

It should be noted that further explanation of these can be found in **IEEE Std C37.2**, with the index number listed in brackets with a red number.

4.8.1.2 Onboard connection switchboards

The onboard connection switchboards are positioned on both the barge and the ship to enable the following parallel connections:

1. HV Shore Supply to the Barge's Power Supply System: This connection allows the barge to receive power from the shore supply, but also allows for the barge to send power to the grid through the shore supply.
2. HV Barge Power Supply System to the Ship: This connection facilitates the transfer of electrical power from the barge to the ship.

For these parallel connections, the interfacing inverter must have the feature to ensure proper load transfer and stable operation.

The circuit-breaker's rated short-circuit breaking capacity must be at least equal to the maximum prospective symmetrical short-circuit current as calculated per **IEC 61363-1.** The system must include an automatic circuit breaker. Additionally, if the main switchboard's rated voltage exceeds 1,000 V AC, an earthing switch must be installed.

According to **IEC/IEEE 80005-1**, the barge and ship switchboards must be equipped with the following instrumentation for parallel load sharing using **automatic synchronization**.

a. Two voltmeters
b. Two frequency meters
c. Either one ammeter with a switch to read current in each phase or a separate ammeter for each phase
d. A phase sequence indicator
e. A synchronizing device

One voltmeter and one frequency meter should be connected to the switchboard's busbars, while the other voltmeter and frequency meter should measure the voltage and frequency of the shore connection.

Protection onboard vessel side

The protection of the power supply systems using the circuit breaker must meet the following tripping and alarm criteria from **IEC/IEEE 80005-1:**

a. Short-Circuit: Tripping with an alarm.
b. Overcurrent: Initial alarm, followed by tripping with an alarm.
c. Earth Fault: Tripping with an alarm, if required by the isolation system used.
d. Over/Under-Voltage: Initial alarm, followed by tripping with an alarm.
e. Over/Under-Frequency: Initial alarm, followed by tripping with an alarm.
f. Reverse Power: Tripping with an alarm (Only for shipboard switchboard).
g. Phase Sequence Protection: Includes an alarm and interlock.

To ensure compliance, at least the following protective devices or equivalent protective measures shall be provided:

a. Synchrocheck (25)
b. Undervoltage (27)
c. Reverse power (32)
d. Phase sequence voltage (47)
e. Overload (49)
f. Instantaneous overcurrent (50)
g. Overcurrent (51)
h. Earth fault (51G) or (59N)
i. Overvoltage (59)
j. Frequency (81) (under and over)

It should be noted that further explanation of these can be found in **IEEE Std C37.2**, with the index number listed in brackets with a red number.

4.8.2 Circuit Breakers

The main placement of circuit breakers (3), but not limited to, is shown in the power system in Figure 3. These circuit breakers are crucial for protecting the system from overcurrent, short circuits, and other electrical faults by automatically interrupting the flow of electricity when such issues are detected. In some cases, fuses could also be utilized. This section details the specific locations and functions of these circuit breakers within the overall system.

The standards for HV and LV circuit breakers applicable to SSE systems vary. For HV shore connections, the relevant standard is **IEC 62271-200**, which covers high-voltage switchgear and control gear for rated voltages above 1 kV and up to and including 52 kV. For LV shore connections, the applicable standard is **IEC 60947-2**, which pertains to low-voltage switchgear and control gear, specifically circuit breakers.

The primary difference between HV and LV circuit breakers is the level of protection against arcing. HV circuit breakers utilize vacuum or sulfur hexafluoride arc quenching enclosures, which are designed to handle higher voltages. Other notable differences include the voltage rating and the specific design requirements for HV and LV applications.

There are various types of circuit breakers, each with different features and capabilities. Electromechanical or thermal control and tripping units are common and are commanded by dedicated relays. Many modern LV and HV circuit breakers also integrate microprocessor units, which provide optimized control over the tripping response based on circuit conditions and end-user requirements.

In high-power DC applications, the absence of a zero-crossing point in DC fault currents poses a significant challenge for circuit breakers. This lack of zero-crossing means that the circuit breaker faces difficulties in interrupting the fault current, leading to the potential for arc flash within the breaker. Therefore, either special circuit breakers or/and converters with fault isolation capability has to be employed for DC systems [26].

4.8.3 Transformers

Transformers play a crucial role in for the power barge and SSE installations, facilitating various applications by converting electrical energy in the AC network to different voltage levels. It should be noted that **all transformers provide galvanic isolation except autotransformers**.

Transformers can be used in parallel operation to handle loads exceeding the capacity of a single transformer. Furthermore, using parallel operation of transformers ensures a more efficient and scalable power supply system, enhancing reliability and reducing the need for costly larger units or spare parts [27].

4.8.3.1 Transformer types

Voltage Transformers

Voltage step-up or step-down of three-phase AC voltage is achieved using 3-phase transformers with various configurations eg. A three-phase transformer with star/delta connection. For a three-phase transformer, the three primary windings are connected together, and the three secondary windings are connected together.

Three-Winding Transformers

Three-winding transformers are voltage transformers capable of transforming the primary voltage into two different output voltages, determined by the number of wire turns on each winding. They are an economic and efficient way to step down high voltage into two separate values, particularly relevant after frequency conversion if two different supply voltages are needed.

Isolation Transformers

Isolation transformers link two circuits magnetically but provide no metallic conductive path between them. This is essential for preventing direct electrical connection between circuits while allowing voltage transfer.

Galvanic isolation is mandatory for high voltage shore connection (HVSC) and low voltage shore connection (LVSC) in accordance with **IEC/IEEE 80005-1** and **IEC/IEEE 80005-3**.

Auto Transformers

An autotransformer consists of a single winding tapped at a certain point. Voltage is applied across terminals of the winding, and a different voltage is produced across another portion of the same winding. They are a cost-effective option for incoming stations receiving utility grid power but cannot provide isolation. Autotransformers are cheaper, lighter, smaller, and more efficient for voltage ratios not exceeding about 3:1 compared to isolating (two-winding) transformers of the same rating. They are used in electric power distribution systems to interconnect different high voltage levels.

Solid-State Transformers

Solid-state transformers, or power converters, perform the same function as traditional transformers but with potential advantages in projects integrating DC and AC grids. They offer improved efficiency and adaptability for modern electrical distribution systems.

Grounding Transformers

Grounding transformers, also known as earthing transformers, provide a ground path in three-phase electric power systems, maintaining the system neutral at or near ground potential. These transformers are essential for integrating renewables with power quality management, offering high-frequency isolation, and eliminating higher-frequency harmonics. They are also used in shore power earthing systems to provide a low-impedance path to ground. Grounding transformers are a part of the earthing system of the network, allowing three-phase (delta-connected) systems to accommodate phase-to-neutral loads by providing a return path for current to a neutral.

4.8.3.2 Transformer Construction Types

Transformers are classified based on their dielectric insulation material, either oil-filled or dry-type.

Dry-type transformers are preferred in marine and SSE applications, this is due to their good safety, reduced maintenance requirements, and suitability for indoor installations[27]. They are constructed without a tank, with windings insulated typically with cast resin. These transformers are not designed for outdoor use because they lack sufficient IP ratings to withstand environmental conditions. Therefore, they should be installed in indoor substations where they are shielded from weather and other external factors. These types also require approx. 1/3 less space requirements.

Oil-filled transformers come in two types: with an expansion tank (conservator) and sealed. These transformers use oil for insulation and cooling, suitable for outdoor installations due to the protective tank. They are mainly used in distribution networks and can handle higher voltages and power capacities.

The **energy efficiency** of oil-filled transformers is typically slightly higher, but often by less than 0.5%, compared to dry-type transformers. Both types of transformers, however, can achieve energy efficiencies exceeding 98.5%, depending on the load and specific operational conditions [28].

4.8.3.3 Standards for transformers

IEC 80005 series outlines specific requirements for transformers used in SSE systems. Key points include:

- **Automatic Voltage Adjustment:** Transformers must have automatic controls to maintain the HV or LV supply voltage within specified tolerances under load conditions.
- **Separate Windings**: Transformers must have separate primary and secondary windings to ensure proper isolation. The secondary side should be in a star configuration with neutral bushings.
- **Temperature Monitoring:** Transformer winding temperatures must be monitored. If over-temperature occurs, an alarm signal must be sent to the ship using the data-communication link, if available, to alert relevant personnel.
- **Short-Circuit and Overload Protection:** Each transformer must be equipped with short-circuit protection via circuit breakers or fuses on the primary side, and a circuit breaker on the secondary side. Overload protection is required for both primary and secondary circuits.
- **Neutral Earthing Resistor:** The neutral point of the transformer must be earthed through a neutral earthing resistor or, if frequency conversion is needed, through an earthing transformer with a resistor on either the primary or secondary side. The neutral earthing resistor must handle at least 1.25 times the prospective system charging current, with a minimum rating of 25 A for 5 seconds. Continuity must be continuously monitored, and any loss of continuity must trigger the shore-side circuit breaker.
- **Earthing and Bonding:** The system earthing conductor must connect the neutral earthing resistor to a nearby system earthing electrode. An additional bonding conductor should connect the neutral earthing resistor to the primary shore power switchboard's earthing bus, ensuring equipotential bonding between the shore and barge.

This standard series can also be extended to transformers needed to interface the power barge and loads.

IEC 60076 series encompasses a range of standards for power transformers, covering aspects from general requirements and insulation levels to energy efficiency. It ensures comprehensive guidelines for the design, testing, and performance of transformers, including their construction, dielectric properties, and operational efficiency. This series aims to enhance reliability, safety, and energy performance across different types of power transformers.

4.9 Electrical Start-Up Procedure

The data communication system between the vessel and barge should be done according to **IEC/IEEE 80005-1** using a fiber optic connection. The communication should be done through the Modbus TCP/IP protocol according to **IEC/IEEE 80005-2**.

The connection between the vessel(ship) and the barge(shore) can be adapted as per **IEC/IEEE 80005-2** involves a structured start-up procedure to safely initialize the power connection. This process includes several key steps:

1. **Initialize Start-up:**

- Ensure the communication link is active and both barge and vessel systems are in standby mode with no alarms.
- Confirm that pilot loops are closed, all circuit breakers are open, and earthing switches are closed.
- The vessel initiates the start-up procedure by switching to Start-Up Mode, with the barge responding by entering its corresponding Start-Up Mode.

2. **Droop Value Selection:**

- If droop adaptation is necessary, the vessel and barge exchange droop values. The vessel can accept, reject, or skip the droop adjustment. Once accepted, the procedure continues.

3. Power and Synchronization Mode Selection:
- The barge ensures its power capacity matches the vessel's requirements. The vessel selects a synchronization mode, and both sides confirm their capability to proceed.

4. Start of Power:
- Both vessel and barge signal readiness for power transfer. The vessel starts the power procedure by commanding the barge to open its earthing switch, followed by the vessel opening its own earthing switch.

5. Optional Cable Test:
- The vessel may choose to perform a cable test to verify cable integrity before synchronization. If successful, the synchronization procedure is activated; if not, the process is halted.

6. Synchronization:
- Depending on the selected mode, either the vessel or the barge will synchronize with the other, leading to the final power transfer and operation mode activation.

This systematic approach ensures safe and efficient power transfer between the vessel and the barge.

4.9.1 Synchronization and Load-Transferring Techniques

When either the barge connects to the shore or to vessels at anchorage a load transfer has to occur. This load transfer can occur either through blackout or automatic synchronization according to **IEC/IEEE 80005-1 and IEC/IEEE 80005-3** for HV and LV connections. Before transferring the load, to ensure the installation is isolated before earthing, the circuit breaker, disconnector, and earthing switch must be interlocked in accordance with **IEC 62271-200.**

For load transfer via **blackout**, interlocking mechanisms must ensure that the shore-barge or barge-vessel connects only to a dead switchboard, preventing simultaneous connection with an active switchboard. Protection systems must also guard against faults in the blackout monitoring circuit.

When transferring load via **automatic synchronization**, the external connected supplier must be automatically synchronized and connected in parallel to the onboard supply. The load transfer should be completed as quickly as possible without causing damage to machinery or triggering protective devices. Synchronization systems must not affect the ship's electrical system when no shore connection is present. The transfer time limit should be defined and communicated to responsible personnel, and adjustable limits documented in operating instructions. During the transfer, only the required ship power sources should be operated to ensure safety. Following to **IEC/IEEE 80005-2** three modes can be used for shore-ship synchronization, these could be adapted for barge-vessel synchronization also:

1. **Alternative 1 (A1)**: The vessel synchronizes with the barge. After a successful cable test, the barge side closes its circuit breaker and ramps up to nominal values. The vessel then synchronizes with the barge and closes its circuit breaker, transitioning both sides to their respective running modes.

2. **Alternative 2 (A2)**: The vessel commands the barge to adjust voltage and frequency. After the barge closes its circuit breaker and reaches nominal values, the vessel sends adjustment commands to synchronize the barge to the vessel. The vessel then closes its circuit breaker, completing synchronization.

3. **Alternative 3 (A3)**: The barge synchronizes to the vessel. The vessel closes its circuit breakers, then the barge synchronizes to the vessel. Once synchronization is successful, the barge closes its circuit breaker, and both sides transition to running mode.

In the case of the barge connecting to the SSE for charging, no special load transfer technique has to occur, as the OPS connects to the barge through a rectifier. However, in the case that the power system on the barge has to deliver power to an online grid the inverter must synchronize with the grid. In the case of connection to an offline grid, a blackout operation load transfer must occur.

Protection measures must be in place so that if the transfer time exceeds the limit, one power source is automatically disconnected, and an alarm is activated to alert personnel.

4.10 Challenges

This section will highlight some of the key topics related to the energy infrastructure specifications for the power-barge.

- **Barge-Vessel Interface Standardization:** While the shore-barge interface is widely adaptable from shore-ship interfaces, the barge-vessel interface is unexplored in terms of guidelines and standards both electrically and maneuverability. This involves aspects such as connection, connection plugs, and grounding, as well as the relative motion between the two vessels. Therefore, further investigation and standardization of this would benefit the use of power barges.
- **Galvanic isolation of Two Vessels at Sea:** The barge and vessels should be galvanically isolated from each other during connection, but as they are very close to each other in conductive sea water several issues could potentially arise with a common ground. The physical contact between the hulls might also create direct points of electrical connection, undermining the effectiveness of galvanic isolation.
- **DC Circuit Breaker Complexity:** DC circuit breakers by far more complex than AC breakers because they lack a natural current zero-crossing point, which makes extinguishing electrical arcs challenging. This absence requires advanced, expensive technology to manage the higher risk of arc flash and ensures effective operation in high-power applications, due to the fast short-circuit current rise in DC systems.

4.11 Conclusion

The conclusion for this chapter is divided into the respective main topics discussed:

- **Safe Electrical Interconnections**: To manage the electrical HV and LV interconnections, these must adhere to international standards such as the **IEC/IEEE 80005** series, and ensure robust power distribution. Furthermore, for proper connections, the **IEC 60309-5** for LV plugs and the **IEC 62613** for HV connection plugs should be followed. Proper integration and compliance with these specifications enhance the reliability, safety, and efficiency of maritime and port operations, ultimately supporting modern practices and fostering sustainability. This should be applied both for barge-shore connection, and also taken into careful consideration for barge-vessel connection.

- **Barge Micro Grid Specifications:** The design and operation of BMGs require careful consideration of various technical aspects, including PSM configurations, DC bus architectures, and grounding strategies according to the recommendations from **IEEE 1709**. The choice of DC microgrid architecture significantly influences system performance, reliability, and scalability. Additionally, the decision between unipolar and bipolar DC bus systems impacts the system's flexibility and fault tolerance. Furthermore, effective grounding methods and isolation requirements are important for ensuring safety and operational continuity, particularly in maritime environments. However, the optimal configuration will depend on the specific requirements and constraints of the use case.
- **Installation and Equipment Necessary:** The key components, including switchboards, protective devices, and transformers, have been detailed to emphasize their roles in ensuring system integrity and operational safety. Adherence to relevant international standards, such as the IEC/IEEE 80005 series and **IEC 60092** series, is essential for achieving reliable power transfer, preventing electrical faults, and facilitating seamless load transfers between the shore, barge, and ship power systems.

4.12 Example #1

The straightforward solution for the barge-shore-vessel system can be seen in Figure 6, where a set of transformers ensures appropriate HV AC connections between the shore-barge and barge-vessel at a two HV voltage level (Additional transformers/windings can be added for other voltage levels). The inverter system is in a *grid-tied battery inverter* configuration, where a single bidirectional inverter charges (rectifier) the batteries from the SSE, while it can act as an inverter to supply either the grid or vessels. The circuit breakers are placed on each side of the transformers for protection, and for each PSM to ensure appropriate disconnection (isolation) of the MV DC-bus. The DC-bus is chosen as a unipolar topology in a radial architecture.

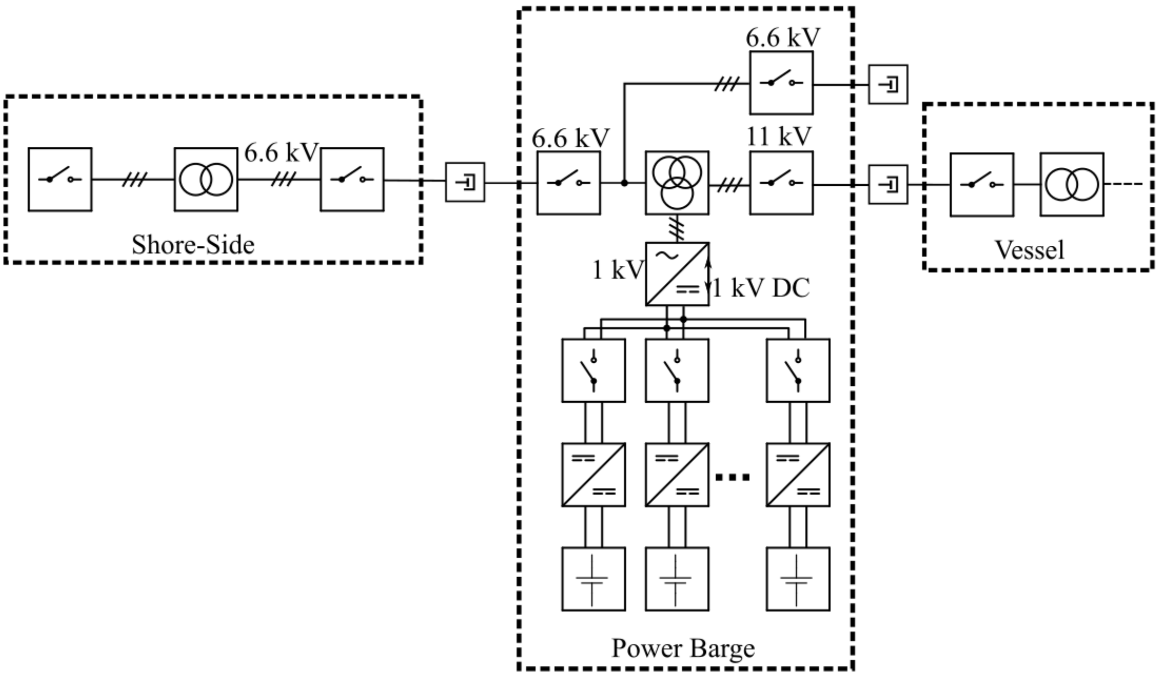

Figure 6 Demo#1: Example of a shore-barge-vessel power electronic Interface.

4.13 Example #2

The less simple solution for the barge-shore-vessel system can be seen in Figure 7, where only an LF transformer is placed at shore to ensure appropriate voltage levels for the barge-shore interface. The inverter system is again a *grid-tied battery* inverter configuration, where a CHB or MMC bidirectional inverter charges (rectifier) the batteries from the SSE, while it can act as an inverter to supply either the grid or vessels at various voltage levels. A central bidirectional isolated DC/DC converter topology is used to potentially step up the voltage required at the DC input for the bidirectional inverter and provide galvanic isolation using an HF transformer. The isolated DC/DC converter topology utilized is of an NPC type, which makes a bipolar DC bus topology, capable of proving a neutral point for grounding the DC BMG. The circuit breakers are placed on each side of the transformers and connection points for protection, and for each PSM to ensure appropriate disconnection (isolation) of the MV DC-bus. The DC microgrid is again in a radial architecture.

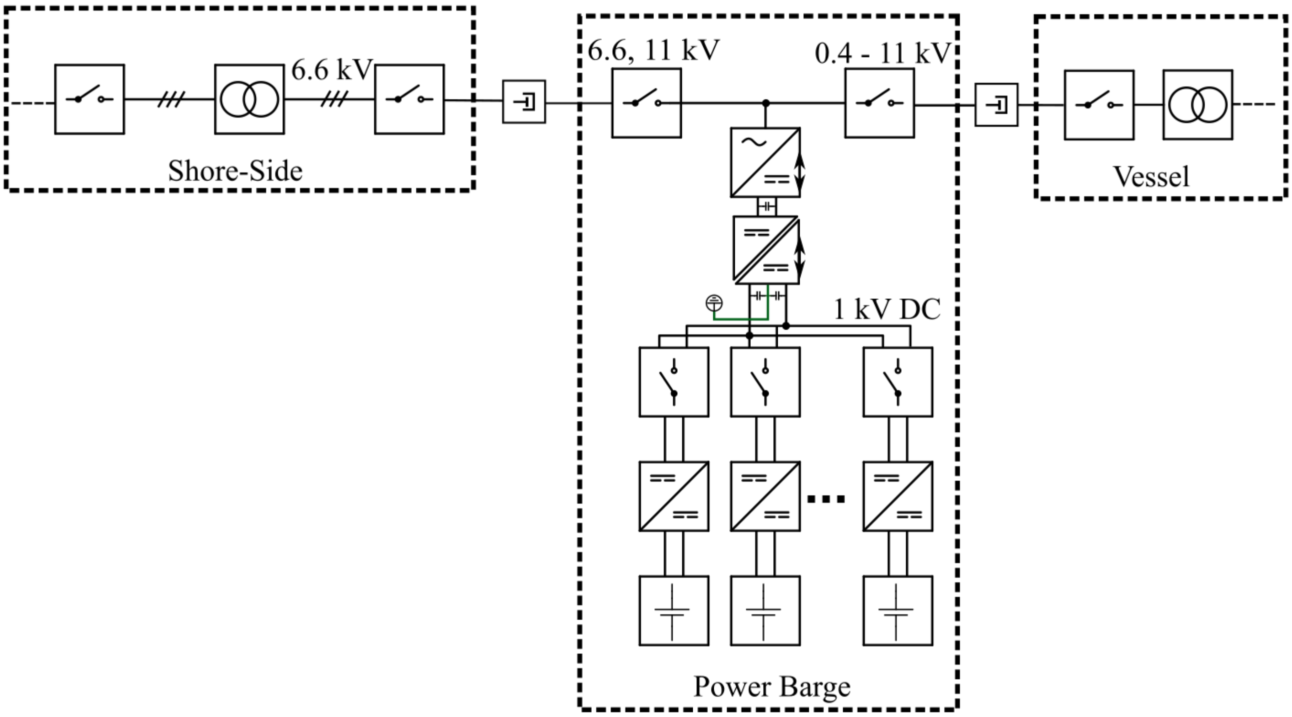

Figure 7 Demo #2: Example of a shore-barge-vessel power electronic Interface.

5 Power Management System Specifications

The PMS for an MVDC power barge should be designed to ensure stable and efficient power distribution under various operating conditions, while the Energy Management System (EMS) aims to optimize the operation according to various objectives, such as e.g. price. According to the **IEEE 1709** standard, the PMS should manage power, maintain quality of service (QoS), and maximize survivability during both normal and emergency conditions. The

The **IEEE 1709** standard outlines several key functions that the PMS should fulfill for MVDC ships:

- **Manage Power Under Normal Conditions**: Ensure sufficient power supply to all loads while accommodating load changes.
- **Maintain Quality of Service (QoS):** Balance the energy usage and generation, and provide dynamic load sharing among power sources.
- **Maximize Survivability:** Implement load shedding and restoration protocols to maintain critical operations during system disruptions.

Under normal conditions, the PMS performs several important functions to ensure efficient and stable operation of the MVDC power barge with e.g. batteries or fuel cells:

- **System Configuration**: Configure the MVDC system to ensure that all loads receive adequate power. The system should be responsive to potential large load changes.
- **Energy Balancing:** Balance the energy consumption of loads with the energy from batteries or fuel cells. This includes dynamic load sharing among power sources to maintain a steady state of operation.
- **Voltage and Current Control:** When batteries or fuel cells are connected to the MVDC bus through power electronics converters, one effective approach is to have one source converter regulate the DC bus voltage, while the other converters control the DC current. Another more advanced approach is droop control [29], which can be used for dynamic and adaptive power sharing among the sources, ensuring balanced and efficient power distribution across the system.

<u>Quality of Service (QoS) Management</u>

QoS issues can be managed at the load level. According to the **IEEE 1709**, it is important to:

- **Classify Loads**: Distinguish between loads that can tolerate short-term interruptions (a few seconds) and those that can handle longer interruptions (minutes or more).
- **Restore Power:** For short-term interrupt loads, the PMS should quickly reconfigure the electrical distribution system. For long-term interrupt loads, additional power generation capacity must be brought online before restoring power.

<u>Survivability Response</u>

When the power system on the barge is not able to serve all loads due to sudden damage or equipment failure, the **IEEE 1709** standard recommends:

- **Load Shedding:** Implement load shedding based on priority to maintain critical operations.
- **Restoring Power:** Restore power to shed loads when sufficient capacity and connectivity are available, ensuring minimal safety risks.
- **Mission Critical Coordination:** Coordinate load shedding with mission system controllers to ensure critical loads remain connected during mission-critical operations.

According to the **IEEE 1709** standard, a comprehensive PMS for an MVDC power barge is important for maintaining operational robustness, stability, and survivability. By incorporating real-time monitoring, dynamic balancing, and strategic energy storage and disposal, the PMS should effectively manage power distribution during irregular operating scenarios.

5.1 Example of Management Systems for a Power Barge

To manage complex energy systems like a DCMG a hierarchical control structure is often employed as seen in Figure 8. This control strategy organizes the system's management across multiple levels, each with specific objectives and responsibilities. Communication between these levels allows for the exchange of control signals and information, ensuring the system operates efficiently. In hierarchical control, each level operates on different time scales, ranging from minutes to hours, and is tasked with different objectives. For example, in a DCMG system, the upper-level controllers might focus on high-level tasks such as optimizing energy exchange across the entire system, managing demand, and responding to energy prices. In contrast, lower-level controllers handle more localized tasks, such as controlling power production, balancing supply and demand, and minimizing operational costs within individual microgrids.

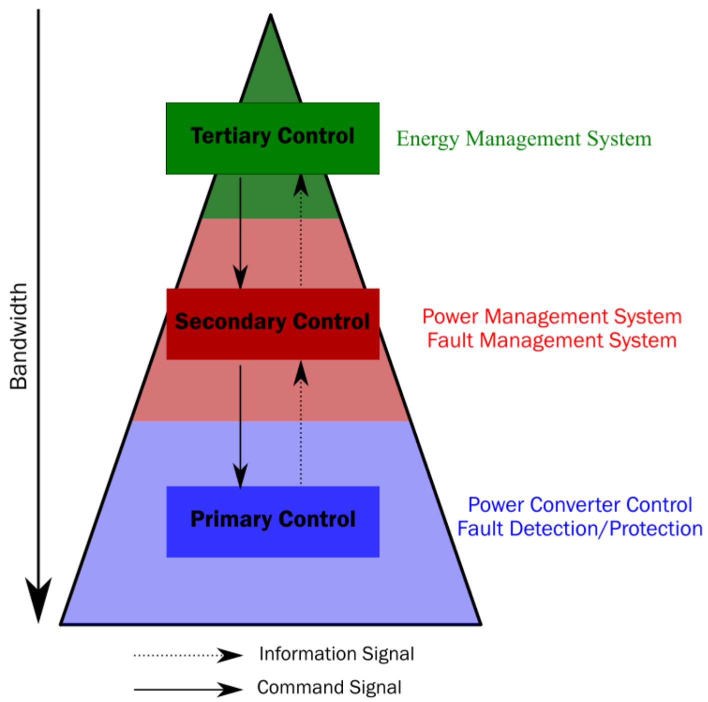

Figure 8 Visualization of a hierarchical control architecture.

To ensure proper communication between the barge and vessel, the **IEC/IEEE 80005-2** standard should be used, a visualization of the communication and control levels can be seen in Figure 9.

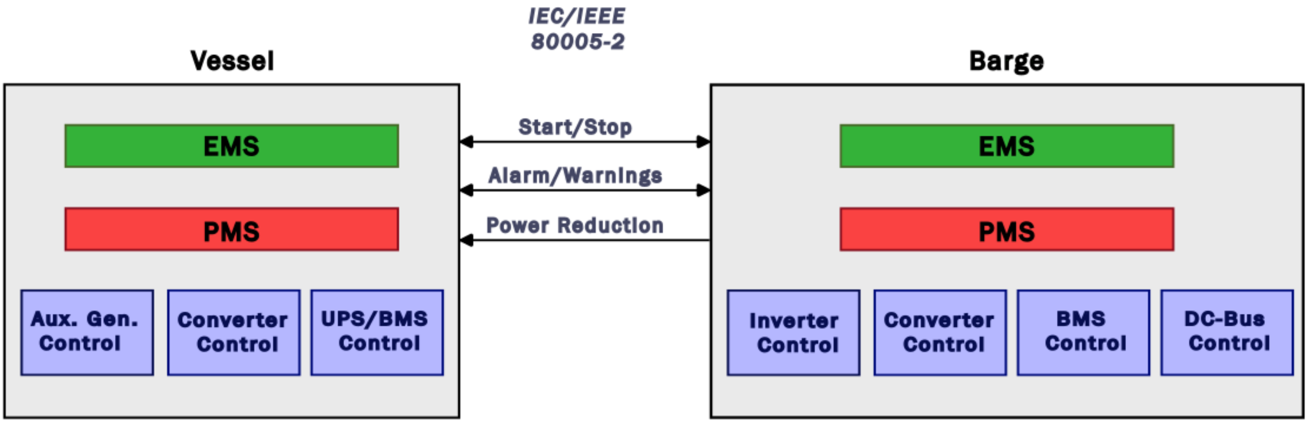

Figure 9 Control hierarchy and required communication parameters.

In Figure 10 an example of a PMS is shown for a *grid-tied battery inverter* configuration, where a single bidirectional inverter interconnects with the shore and vessels. Here an EMS optimizes the energy flow according to cost, and the PMS coordinates the instantaneous power flow. For the battery, a BMS is implemented for fault detection, balancing, and SoC estimation. For the fuel-cell a Fuel-Cell Management System (FCMS) is implemented for fault detection, flow regulation, and State of Storage (SoS) estimation.

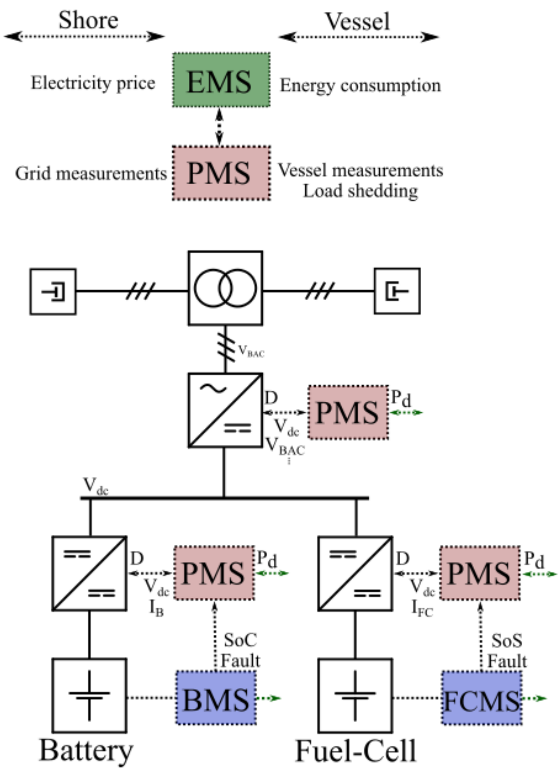

Figure 10 Example of a PMS and EMS for batteries and fuel cells for the shore-barge and barge-vessel operation.

Energy Management System

The EMS handles the planning of the power barge at large time scales, from several minutes to hours. In this example, the EMS controls the amount of charging for the batteries when it is connected to the SSE to optimize the battery ESS operations based on electricity prices focusing on enhancing economic efficiency by strategically scheduling charging and discharging activities.

- **Buying Low, Selling High**: The EMS charges the battery when electricity prices are low and discharges when prices are high. This price-based arbitrage allows for profit generation from the price differential, enhancing revenue from market participation.
- **Market Forecasting:** The EMS uses electricity price forecasts to schedule future charging and discharging activities, ensuring optimal timing to take advantage of expected price fluctuations before expected deployment at sea.
- **Renewable Energy Utilization**: The EMS can also align battery charging with periods of high renewable energy generation (Typically lower prices) and discharge during times when renewables are less available (higher prices). This not only decreases operation costs but would also support more renewable energy into the grid.

When the barge is supplying a vessel or load, the EMS plays an important role in coordinating the different PSM sources to ensure efficient, reliable, and cost-effective power delivery. With energy consumption data available, the EMS can optimize the operation of both the battery storage and fuel cells to meet the vessel's power demands.

- **Predictive Load Forecasting:** The EMS analyses power usage, ship logs, and current conditions to forecast future energy demands. During forecasted low-demand periods, the system can prioritize the use of the cheapest energy solution.
- **Optimized Fuel Cell and VRFB Operation**: Forecasting allows the EMS to run fuel cells and VRFBs at optimal efficiency levels. By aligning their output with predicted energy needs, the system reduces hydrogen consumption in fuel cells and maximizes the efficient use of VRFBs, leading to lower operational costs.
- **Strategic Battery Usage:** Based on forecasts, the EMS manages the Li-Ion batteries SoC to ensure they remain available for rapid responses. During forecasted periods of high demand or potential emergencies, the system avoids depleting the Li-Ion battery excessively.

Power Management System

The PMS handles the power flow control of the power barge at small time scales, from microseconds to milliseconds. The PMS should at all times ensure:

- **DC Bus Voltage Stabilization**: The PMS ensures the DC bus voltage remains stable by coordinating the power flow control strategy from various supply modules connected to the DCMG during discharge to the grid, preventing voltage fluctuations.
- **Fault Handling**: When a fault is reported to the PMS for a PSM e.g. the BMS reports over-temperature on a battery pack. Then it should handle it by either limiting or shutting down the power draw, depending on the severity of the fault. Furthermore, it should coordinate with the other PSM to still ensure stable power flow control.

In this example when the barge is connected to the SSE, the PMS monitors the grid and handles the overall power flow control for the converters, especially when it comes to fast operations for grid support if there is sufficient available capacity in PSM.

- **Rapid Frequency Response:** The PMS utilizes the fast-reacting capabilities of the bidirectional inverter to provide immediate grid support in the form of frequency support. When the grid frequency deviates from its nominal value, the PMS quickly commands the inverter to, typically inject power into the grid (for under-frequency events) or absorb power (for over-frequency events). This fast frequency response (FFR) is typically within seconds or even milliseconds, helping to stabilize the grid and prevent further deviations.
- **Dynamic Voltage Support:** Voltage regulation is another grid support function managed by the PMS. Using the bidirectional inverter, the PMS can control the reactive power output from the PSMs, providing dynamic voltage support. When grid voltage levels deviate, the PMS adjusts the reactive power flow to either absorb or inject reactive power, thereby stabilizing the voltage at the point of connection.

5.2 Challenges

Communication Protocols: Coordination e.g. load shedding between the barge and connected vessel can be complex without standardized communication protocols and consistent data availability. However, using the **IEC/IEEE 80005-2** communication protocol, there is the possibility for load shedding via and sending a "*shore power warning: reduce power*" to the connected vessel.

Custom Development Required: Several of the smart features for the EMS and PMS systems are not commercially available and would need to be developed, leading to increased development time and costs.

5.3 Conclusions

Hierarchical Control Structure: The overall control system for a DC BMG is of a hierarchical structure where the EMS handles strategic optimization, the PMS ensures real-time power stability and local controllers manage specific components, collectively ensuring efficient, reliable, and adaptive power barge operations.

Comprehensive Power Management: The PMS for an MVDC power barge, as outlined in **IEEE 1709**, ensures comprehensive power management by stabilizing DC bus voltage, managing energy distribution, and responding swiftly to load changes, which is essential for maintaining operational efficiency and stability.

Economic Optimization through EMS: EMS optimizes energy flow to the power barge by leveraging data available for e.g. electricity price forecasts, enabling strategic charging and discharging of batteries, reducing operating costs, and increasing revenue through market participation such as grid support.

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7 Standards, Guidelines, and Recommendations

American Bureau of Shipping (ABS)

- ABS Rules for Building and Classing Marine Vessels (Marine Vessel Rules)
- ABS Rules for Building and Classing Mobile Offshore Units (MOU Rules)
- ABS Rules for Building and Classing Facilities on Offshore Installation (Facilities Rules)
- ABS Requirements for Use of Lithium-ion Batteries in the Marine and Offshore Industries
- ABS Requirements for Methanol and Ethanol Fueled Vessels
- ABS Requirements for Hydrogen Fueled Vessels
- ABS Requirements for Ammonia Fueled Vessels

Det Norske Veritas (DNV)

- DNV 0043 - Recommended practice for Safety, operation, and performance of grid-connected energy storage system
- Technical Reference for Li-ion Battery Explosion Risk and Fire Suppression
- DNV GL Handbook for Maritime and Offshore Battery Systems
- DNV GL 0418 - Class programme for Electrical Energy Storage

International Electrotechnical Commission (IEC)

- IEC 1662 - IEEE Recommended Practice for the Design and Application of Power Electronics in Electrical Power Systems
- IEC 60076 - Power transformers
  - Part 1: General
  - Part 5: Ability to withstand short-circuit
  - Part 7: Loading guide for mineral-oil-immersed power transformers
  - Part 11: Dry-type transformers
  - Part 20: Energy Efficiency
- IEC 60092 - Electrical Installations in Ships
  - 101: General Requirements
  - 202: System Design
  - 350 to 376: Cables Construction and Testing
  - 401 to 407: Protection and Control Systems
  - 501 to 507: Electrical Equipment
- IEC 60309 - Plugs, socket-outlets, and couplers for industrial purposes
  - Part 5: Dimensional compatibility and interchangeability requirements for plugs, socket-outlets, ship connectors, and ship inlets for low-voltage shore connection systems (LVSC)
- IEC 60947 - Low-voltage switchgear and controlgear
  - Part 1: General rules
  - Part 2: Circuit-breakers
  - Part 3: Switches, disconnectors, switch-disconnectors, and fuse-combination units

- IEC 61557 - Electrical safety in low voltage distribution systems up to 1 000 V a.c. and 1 500 V d.c. – Equipment for testing, measuring, or monitoring of protective measures
- IEC 61558 - Safety of power transformers, power supplies, reactors, and similar products
- IEC 61936 - Power installations exceeding 1 kV AC and 1,5 kV DC
- IEC 62271 - High-voltage switchgear and controlgear
  - Part 1: Common specifications for alternating current switchgear and controlgear
  - Part 5: Common specifications for direct current switchgear and controlgear
  - Part 100: Alternating-current circuit-breakers
  - Part 200: AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV
- IEC 62613 - Plugs, Socket-Outlets, and Ship Connectors for High-Voltage Shore Connection (HVSC) Systems
  - Part 1: General Requirements
  - Part 2: Dimensional Compatibility and Interchangeability Requirements for Accessories
- IEC 62932 - Flow battery energy systems for stationary applications
  - Part 1: Terminology and general aspects
  - Part 2-1: Performance general requirements and test methods
  - Part 2-2: Safety requirements
- IEC 62933 - Electrical energy storage (EES) systems
- IEC/IEEE 80005 - Utility connections in port
  - Part 1: High Voltage Shore Connection (HVSC) Systems — General requirements
  - Part 2: High and low voltage shore connection systems – Data communication for monitoring and control
  - Part 3: Low Voltage Shore Connection (LVSC) Systems – General requirements

<u>Electrical and Electronics Engineers (IEEE)</u>

- IEEE 45 - IEEE Recommended Practice for Electrical Installations on Shipboard
  - 45.1 - Design
  - 45.2 - Controls and Automation
  - 45.3 - Systems Engineering
  - 45.4 - Marine Sectors and Mission Systems
  - 45.5 - Safety Considerations
  - 45.6 - Electrical Testing
  - 45.7 - AC Switchboards
  - 45.8 - Cable Systems

- IEEE 519 - IEEE Standard for Harmonic Control in Electric Power System
- IEEE 1250 - IEEE Guide for Identifying and Improving Voltage Quality in Power Systems
- IEEE 1547 - IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces
- IEEE 1709 - IEEE Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Power Systems on Ships
- IEEE 2030 - Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads

<u>European Maritime Safety Agency (EMSA)</u>

- Guidance on the Safety of on-board Battery Energy Storage Systems (BESS)
- Shore-Side Electricity Guidance to Port Authorities and Administrations
    - Part 1 – Equipment and Technology
    - Part 2 - Planning, Operations and Safety
- Study on the use of Fuel Cells in Shipping