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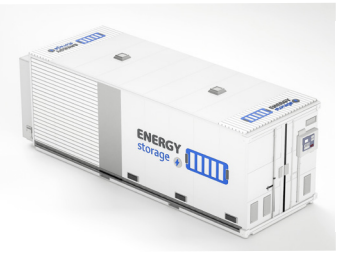
Scalable Onshore Power Supply Systems for Mid-Sized Ports



A pre-study carried out within the Swedish Transport Administration's industry program Sustainable Shipping, operated by Lighthouse, published July 2026

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HÅLLBAR SJÖFART

Scalable Onshore Power Supply Systems for Mid-Sized Ports

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Summary

This report presents the findings of the pre-study *Scalable Onshore Power Supply Systems for Mid-Sized Ports*, conducted within the Lighthouse/Swedish Transport Administration's industry programme Sustainable Shipping. The study responds to the growing need for Onshore Power Supply (OPS) in ports as a result of tighter climate regulations, increasing vessel electrification, and the implementation of the EU Alternative Fuels Infrastructure Regulation (AFIR). For many mid-sized ports, future power demand, vessel characteristics, and grid capacity remain uncertain, creating a need for OPS solutions that are flexible, scalable, and economically robust and resilient.

The objective of this pre-study was to provide decision support for planning and implementing OPS systems capable of adapting over time. The work combined a review of international standards and guidelines with stakeholder input from a shipping company and a port authority. Based on defined vessel power requirements, conceptual OPS solutions were developed for low-, medium-, and high-power scenarios, covering a range of different connection strategies, system architectures, and operational conditions.

The results indicate that considering scalability at an early stage is a key requirement for future-proofing OPS systems in mid-sized ports. Early design decisions related to grid connection level, system topology, and physical layout have a major influence on future expansion options and lifecycle costs. Modular OPS architectures were identified as particularly advantageous, as they support phased investments, improve efficiency at partial loads, and enable flexible operation for mixed- and changing-vessel traffic while maintaining compliance with power-quality requirements.

The study also finds that Battery Energy Storage Systems (BESS) can play an important supporting role when applied selectively and based on realistic vessel-power profiles. In such cases, BESS can help limit peak-power demand, mitigate grid constraints, reduce exposure to power-based tariffs, and improve dynamic system performance. However, BESS is not a universal requirement and should be evaluated based on local conditions and development pathways.

Consistent adoption of international standards, particularly the IEC/IEEE 80005 series, is essential to ensure safe and interoperable shore-to-ship connections. This report therefore emphasizes performance-based procurement, modular planning, and early coordination between ports, ship operators, and grid operators. Overall, this report offers practical guidance for mid-sized ports seeking to implement OPS in a way that supports gradual electrification, reduces investment risk, and facilitates long-term adaptability.

Sammanfattning

Denna rapport presenterar resultaten från förstudien *Scalable Onshore Power Supply Systems for Mid-Sized Ports*, genomförd inom Lighthouse/Trafikverkets branschprogram *Hållbar sjöfart*. Studien svarar mot det växande behovet av landströmslösningar (Onshore Power Supply – OPS) i hamnar, drivet av skärpta klimatregler, ökad fartygselektrifiering och implementeringen av EU:s förordning om infrastruktur för alternativa bränslen (AFIR). För många medelstora hamnar råder fortsatt osäkerhet kring framtida effektbehov, fartygskarakteristik och kapaciteten i elnätet, vilket skapar ett behov av OPS-lösningar som är flexibla, skalbara och både ekonomiskt robusta och resilienta.

Syftet med förstudien var att ge beslutsstöd för planering och implementering av OPS-system som kan anpassas över tid. Arbetet kombinerade en genomgång av internationella standarder och riktlinjer med insikter från en rederiaktör och en hamn. Utifrån definierade effektkrav utvecklades konceptuella OPS-lösningar för låg-, mellan- och högeffektsscenarier, som täckte olika anslutningsstrategier, systemarkitekturer och operativa förhållanden.

Resultaten visar att tidig hänsyn till skalbarhet är en central förutsättning för framtidssäkring av OPS-system i medelstora hamnar. Tidiga designbeslut kring anslutningsnivå mot elnätet, systemtopologi och fysisk layout har stort inflytande på framtida expansionsmöjligheter och livscykelkostnader. Modulära OPS-arkitekturer identifierades som särskilt fördelaktiga, eftersom de möjliggör stegvisa investeringar, bibehåller god effektivitet vid dellast och stödjer flexibel drift vid blandad och förändrad fartygstrafik, samtidigt som kraven på elkvalitet uppfylls.

Studien visar också att batterilagringssystem (BESS) kan spela en viktig stödjande roll när de används selektivt och baseras på realistiska effektprofiler för fartyg. I sådana fall kan BESS bidra till att begränsa effekttoppar, mildra nätbegränsningar, minska exponeringen för effektbaserade tariffer och förbättra systemets dynamiska prestanda. Dock är BESS inte ett universellt krav och bör utvärderas utifrån lokala förutsättningar och utvecklingsvägar.

Konsekvent tillämpning av internationella standarder, särskilt IEC/IEEE 80005-serien, är avgörande för att säkerställa säkra och interoperabla anslutningar mellan fartyg och land. Rapporten betonar därför funktionsbaserad upphandling, modulär planering och tidig samordning mellan hamnar, rederier och nätägare. Sammantaget erbjuder denna rapport praktisk vägledning för medelstora hamnar som vill implementera OPS på ett sätt som stödjer gradvis elektrifiering, minskar investeringsrisker och möjliggör långsiktig anpassningsförmåga.

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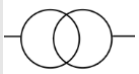
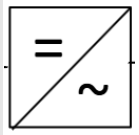
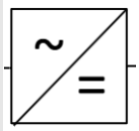
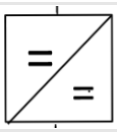
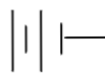
List of acronyms and units

Acronym/Unit/Icon	Full wording
AC	Alternating Current
AFE	Active Front End
AFIR	Alternative Fuels Infrastructure Regulation
ATEX	Atmosphères Explosibles (explosive atmospheres directive)
BESS	Battery Energy Storage System(s)
CMS	Cable Management System
DC	Direct Current
DNV	Det Norske Veritas
DSO	Distribution System Operator
EIFS	Energimarknadsinspektionens föreskrifter (Swedish energy markets inspectorate regulations)
EMSA	European Maritime Safety Agency
EU	European Union
HVAC	Heating, Ventilation, and Air Conditioning
HV	High Voltage
HVSC	High Voltage Shore Connection
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IMO	International Maritime Organization
kV	kilovolt
kVA	kilovolt-ampere
kVAr	kilovolt-ampere reactive
kW	kilowatt
kWh	kilowatt-hour
LV	Low Voltage
LVSC	Low Voltage Shore Connection
M€	million euros
MV	Medium Voltage
MW	megawatt
MVA	megavolt-ampere
MWh	megawatt-hour
NFPA	National Fire Protection Association
OCIMF	Oil Companies International Marine Forum

Acronym/Unit/Icon	Full wording
OPS	Onshore Power Supply
PCC	Point of Common Coupling
PCS	Power Conversion System
RISE	Research Institutes of Sweden
RVC	Rapid Voltage Changes
SFC	Static Frequency Converter
SSE	Shore-Side Electricity
TEN-T	Trans-European Transport Network
THD	Total Harmonic Distortion
TR06	Svenska kraftnät technical recommendation TR06
UPS	Uninterruptible Power Supply
WP	Work Package
Hz	hertz
V	volt
m	meter
m^2	square meter
ft	foot (feet)
C-rate	Charge/discharge rate of a battery
%	Percent
	Transformer
	Inverter
	Rectifier
	DC-DC converter
	Energy storage
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1 Introduction

1.1 Background and context

Onshore Power Supply (OPS), often referred to as shore power, shore-side electricity, or cold ironing [1, 2], is an umbrella term covering two main applications: the replacement of the use of a vessel's auxiliary engines with grid-supplied electricity while alongside (cold ironing), and the charging of onboard Battery Energy Storage Systems (BESS) (charging). By connecting to OPS, vessels can shut down their auxiliary engines during port calls, thereby cutting the vessel's fuel consumption as well as air and noise emissions [3-6]. This is increasingly relevant as a key measure for accelerating maritime decarbonization, including within Europe. The Alternative Fuels Infrastructure Regulation (AFIR) requires OPS availability for container and passenger ships in all TEN-T core ports by 2030, as well as TEN-T comprehensive ports if certain criteria are met, with similar requirements for inland ports on a shorter timetable [7-9].

Despite progress, OPS deployment and uptake across Europe remains uneven, with only about one-third of TEN-T core maritime ports currently equipped with OPS facilities and very limited coverage in TEN-T comprehensive ports [10]. Against this backdrop, ports and ship operators are now accelerating investments in OPS systems to meet regulatory expectations, improve local air quality, and support the transition towards hybrid and fully electric vessel operations. Yet, ports continue to face challenges and uncertainties related to future vessel requirements including increasing power demands for charging, simultaneous connections, and constraints in local and regional electricity grids. These uncertainties complicate decisions on how to design OPS systems that are both flexible and scalable under evolving operational and regulatory conditions.

In Sweden, OPS is also regarded as essential for achieving national and EU climate targets. Yet, many ports still lack clear tools or guidance on how OPS installations should be dimensioned to meet both current and anticipated power needs. The rapid development of vessel energy requirements, combined with limited grid capacity due to broader societal electrification, increases the risk of both over- and under-investment in OPS infrastructure. Because OPS infrastructure is complex and capital-intensive, and not all electrical components are inherently scalable, incorrect decisions during early planning stages can result in installations that either cannot be scaled up over time or are oversized and unnecessarily costly. There is currently no common guidance for designing OPS systems that can be scaled up stepwise as power demand grows.

1.2 Aims and delimitations

This pre-study addresses these challenges by providing guidance for designing OPS infrastructure that is flexible, scalable, and future-proof across diverse port contexts. It examines technical strategies for handling uncertainties – including rising demand and grid constraints – and clarifies which OPS components can be upgraded incrementally and which risk becoming bottlenecks. By mapping scalable design pathways and integration options such as BESS, the study seeks to reduce investment risks, support long-term operational and economic sustainability, and strengthen shared understanding

across industry, academia, public actors, and energy companies. More broadly, the work contributes to positioning ports as emerging multi-functional energy nodes.

The study builds on international standards (IEC/IEEE 80005) and EMSA guidelines [11], while also considering requirements from Stena and the Port of Gothenburg. To support practical decision-making, this report:

- presents three conceptual OPS design solutions (< 6 MW, 6–16 MW, > 16 MW);
- identifies which OPS components are scalable and which become obsolete as power levels increase;
- supports ports and shipping companies in transitioning from low to high power OPS or in designing scalable systems from the outset;
- clarifies when and how BESS can support future OPS demand;
- identifies areas of shared interest among ports, ship owners, grid operators, and energy producers relevant to ports' evolving roles as energy nodes.

The results are intended to support OPS planning, system configuration, component dimensioning, and procurement, ensuring installations that are technically robust and economically sustainable. Public actors – including municipalities, grid companies, and regulatory authorities – may apply the guidance in strategic electrification and infrastructure planning. More broadly, the study provides a foundation for OPS infrastructure development, demonstration projects, and national harmonization of OPS infrastructure.

The scope excludes supplier-specific results, civil works (e.g., buildings, ducts), cable management systems (CMS)), and single-port case studies. Fictional yet representative scenarios are used to ensure broad applicability across Swedish ports.

The pre-study was carried out in collaboration with Stena, Göteborgs Hamn AB, RISE, DNV, ABB, Actemium, and MantaMarine.

2 OPS standards and vessel compatibility requirements

The implementation of OPS systems requires adherence to a set of international standards and technical guidelines to ensure safety, interoperability, safety for personnel, efficiency across vessel types and port configurations, reduced costs for shipowners by avoiding custom setups, and scalability for future vessel sizes and power demands [12]. The most widely recognized framework is the IEC/IEEE 80005 series, which defines the requirements for both high and low-voltage shore connections (LVSC), as well as data communication interfaces. Of particular relevance for this pre-study is the IEC/IEEE 80005-1 for high-voltage shore connection (HVSC) requirements, with an explicit focus on 6.6 kV and 11 kV connections at 50/60 Hz and the implications for different ship segments.

In addition to the IEC/IEEE 80005 standards, the European Maritime Safety Agency (EMSA) provides comprehensive guidance on Shore-Side Electricity (SSE) to support ports and administrations in planning, designing, and operating OPS systems [11]. The EMSA guidance covers the full decision-making chain – from early feasibility studies and governance frameworks to power demand calculations, equipment selection, compatibility assessments, operational procedures, safety measures, and emergency response requirements. It outlines standardized practices for technology configuration, cable management, risk assessment, competencies and qualifications, and shore-to-ship data exchange, offering a structured reference to ensure safe and interoperable OPS deployment across Europe. These guidelines also emphasize the importance of harmonized operational procedures, robust safety controls, and systematic compatibility evaluation between ships and port infrastructure, thereby serving as a practical complement to the technical specifications defined in IEC/IEEE 80005.

Although existing EMSA guidelines and the IEC/IEEE 80005 standards provide essential foundations for safe and interoperable OPS deployment, they do not offer guidance on how OPS systems should be scaled, upgraded, or designed for different power levels. They also do not address component-level scalability, multi-installation port configurations, battery storage integration, or how ports can plan cost-effective, stepwise expansions as power demands grow. This pre-study aims to fill these gaps by providing practical, scalable design concepts and decision-support tools.

2.1 Ship types and compatibility

While individual vessels may exhibit specific OPS requirements, depending on onboard systems, operational profiles, and retrofit decisions, ships of similar type and size tend to display comparable power demand patterns when berthed. This is primarily due to similarities in auxiliary machinery operation, hotel loads, cargo-handling equipment, and safety systems. Consequently, OPS installations are generally designed to accommodate vessel-type-specific power ranges, rather than the exact requirements of individual ships. Table 1 therefore presents indicative ("generic") cold ironing power demand values for selected vessel categories, classified by vessel type and size. The values represent typical average and peak electrical loads for cold ironing. The table could be used for reference during initial planning of OPS systems but should always be complemented based on actual needs. Power frequency compatibility reflects the prevailing frequency distribution

within each vessel segment. Battery charging loads are excluded here but must be considered when planning for future installations and connections, as it is expected that more and more vessels will be hybrid and contain batteries onboard to support the vessels' propulsion and energy needs.

Table 1 Generic values for cold ironing based on vessels type and size (planning-level values, excluding battery charging) (QinetiQ [13], complemented by IEC/IEEE standard annex guidance and port OPS design practice)

Vessel type	Average power (MW)	Peak power (MW)	Typical OPS frequency (50/60 Hz)	Typical OPS voltage	OPS type	Key applicable standards
Container vessels (<140 m)	0.2	1.0	50 Hz	6.6 kV	HVSC	IEC/IEEE 80005-1; IEC 62613-2
Container vessels (>140 m)	1.2	8.0	60 Hz	6.6, (11 kV)	HVSC	IEC/IEEE 80005-1; IEC 80005-2; IEC 62613-2
RoRo / RoPax-Ro / Ro-Pax	1.5	2.0	60 Hz	11 kV, (6.6 kV)	HVSC	IEC/IEEE 80005-1 Annex B
Oil & product tankers*	-	-	60 Hz	6.6 kV	HVSC (ATEX-controlled)	IEC/IEEE 80005-1; IMO MSC.1/Circ.1675; OCIMF**
Cruise ships (<200 m)	4.1	7.3	60 Hz	11 kV	HVSC	IEC/IEEE 80005-1 Annex C
Cruise ships (>200 m)	7.5	11.0	60 Hz	11 kV	HVSC	IEC/IEEE 80005-1 Annex C
Inland waterway vessels	0.2	0.4	50 Hz	400 V	LVSC	IEC/IEEE 80005-3; IEC 60309-5

*OPS power requirements for tankers are heavily dependent on the design of the ship's cargo pumping system [14].
**Industry guidance specific to oil and product tankers and their terminals.

3 Methodology

The pre-study was carried out in four work packages (WP1–4) with the aim of producing guidance for scalable design of OPS installations:

- WP1 focused on developing three conceptual design solutions for the following power levels: <6 MW, 6–16 MW and >16 MW per OPS connection. One of the concepts should illustrate a scenario where shore-side battery storage supplies the vessel. The power levels should reflect common scenarios in Swedish ports and may therefore be adjusted so that they reflect relevant power levels based on the type of equipment.
- WP2 analyzed what technical differences exist between these power levels — for example regarding transformers, cabling, frequency converters, CMS, and safety functions.
- WP3 evaluated which of the components identified in WP2 are scalable between the power levels, and which instead need to be replaced if the power demand increases.
- WP4 compiled the results in a guidance document that clearly shows which components may be advantageous to oversize from the beginning — in order to reduce costs and the need for reconstruction during future upgrades — as well as which components will need to be replaced for higher power levels.

This pre-study began with a comprehensive literature review covering existing international technical standards and guidelines for OPS systems, vessel characteristics and operational profiles, and prevailing OPS configurations and technologies. This initial conceptual groundwork provided the basis for identifying relevant design pathways, technical uncertainties, and scalability considerations. The emerging findings were subsequently validated and refined through targeted meetings and interviews among the project partners and with the project's external contributors (see section *1.2 Aims and delimitations*, p.8). Their input ensured that the conceptual designs and analytical assumptions reflected practical operational conditions and industry experience.

3.1 Stakeholder input and regulatory framework

The work began with structured engagement of key stakeholders, primarily Stena and the Port of Gothenburg, to establish a shared understanding of operational needs, constraints, and long-term objectives for the charging solution. They presented the generic design criteria for charging points and power levels. The stakeholders were, throughout the project, involved in discussion regarding input on the impact of vessel characteristics, operational schedules, berth usage, and integration with existing port infrastructure on the project results. Furthermore, aspects like space availability, grid connection limitations, environmental exposure, and port safety requirements were also considered at this stage.

In parallel, relevant standards and relevant documentation were identified and reviewed. These include regulations related to electrical installations, high-power charging systems, maritime shore connections, and occupational safety. The purpose was to ensure that all

subsequent design work is compliant with applicable requirements and aligned with industry best practices.

3.2 Definition of charging requirements and design criteria

Based on stakeholder input and the regulatory framework, the functional and technical requirements for the charging system were defined. This includes the required charging power and voltage levels, energy transfer capacity, and charging time windows. Operational aspects such as system availability, built-in redundancy, and local environmental conditions were also considered to ensure that the OPS solution can function reliably and support daily port operations without unexpected disruptions.

To steer the development of suitable solutions, a set of design criteria was established. Safety and compliance are treated as fundamental principles, ensuring safe operation for personnel, vessels, and port infrastructure. Scalability and future-proofing are emphasized to allow for increased power demands, additional vessels, or future port development without major redesign. Reliability and maintainability were also key considerations, with the aim of achieving high system availability and straightforward operation and maintenance over the system's lifetime.

3.3 Conceptual design development and feasibility validation

Using the defined requirements and design criteria, one or more conceptual design alternatives were developed. These concepts describe the overall system architecture, key components, and interfaces at a high level, providing a basis for comparing different technical approaches. Layout considerations, equipment placement, and integration with existing infrastructure were addressed to ensure the concepts are realistic and implementable.

To validate the feasibility of the proposed concepts, technical discussions were held with relevant hardware manufacturers and technology suppliers. These discussions focused on confirming achievable power levels, component availability, compliance with standards, and practical considerations related to installation, operation, and maintenance. Feedback from manufacturers was used to refine the conceptual designs and reduce technical risks, resulting in a robust and credible basis for further detailed design and project planning.

4 Technical background

This chapter provides the technical foundation required to understand the conceptual OPS designs developed later in the report. It summarizes the key electrical components, system configurations, and operational considerations that influence scalability, power quality performance, and compliance with international standards. The intention is not to prescribe specific equipment or vendor solutions, but rather to clarify the technical principles, limitations, and interdependencies that shape OPS design choices for different power levels. By outlining how elements such as transformers, converters, grid connections, BESS integration, and cable systems function within an OPS installation, this chapter establishes the technical context needed to assess scalability across the low, medium, and high-power scenarios analyzed in the following sections.

4.1 Vessel requirements

The requirements forming the basis for the conceptual designs described in this report have been set out by Stena and Göteborgs Hamn AB. Three different specifications have been made, detailing a low-, medium- and high-power scenario, each connecting two different vessels simultaneously.

The low-power scenario reflects two vessels having BESS onboard enough to cover parts of the hotel load, operating thrusters during manoeuvring, enabling fewer auxiliary engines during normal operation, or as peak-shaving and power redundancy.

The medium-power scenario reflects two hybrid vessels designed to, at least, operate fully on BESS during manoeuvring.

The high-power scenario reflects one fully electric vessel requiring extensive BESS charging and one hybrid vessel designed to operate fully on BESS during manoeuvring. Table 2 shows three scenarios for low-, medium-, and high-power requirements for vessels and power grid.

Table 2 Power requirements for vessels and power grid

Scenario	Vessel A requirement			Vessel B requirement			Requirement from grid	
	Power (MVA)	Voltage (kV)	Freq. (Hz)	Power (MVA)	Voltage (kV)	Freq. (Hz)	Power (MVA)	Voltage (kV)
Low	5	11	50/60	3	11	50/60	8	11
Medium	13	11	50/60	7	11	50/60	20	11
High	50	11 or 15	50	7	11	50/60	57	130

4.2 Components

Before describing each component in detail, Figure 1 illustrates a simplified OPS system overview, showing a generic arrangement of the grid connection interface and medium-voltage (MV) switchgear, step-down transformer, rectifier, Direct-Current (DC) bus (with optional DC-connected BESS), inverter, step-up transformer, and the ship-side high-voltage (HV) interface.

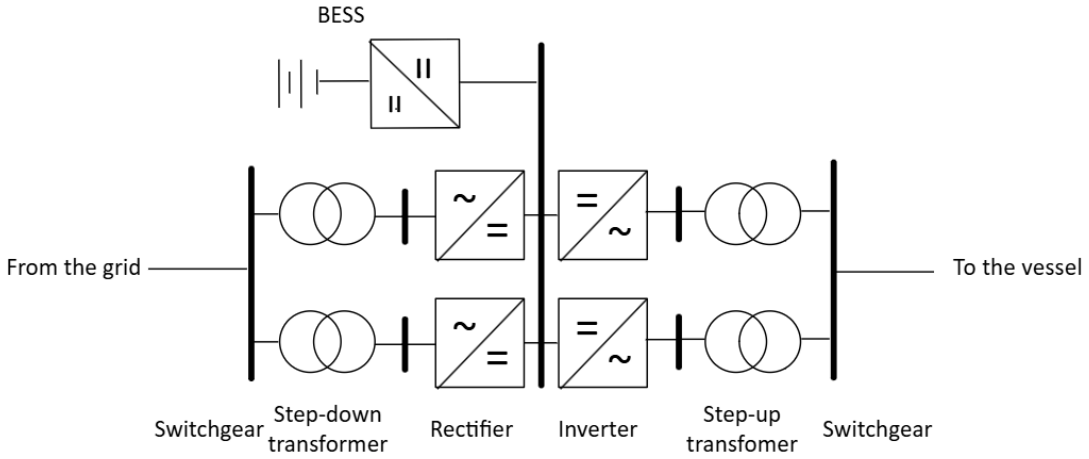


Figure 1 Simplified, generic OPS system and component overview

4.2.1 Power supply – grid connection

For this report, it is assumed that the power supply will come from the power grid supplied by a Distribution System Operator (DSO). Local and regional grids operate at different voltage levels depending on the responsible DSO, geographical location, and the existing electrical infrastructure in proximity to the port or connection point. Typical voltage levels for local and regional grids are 10 kV, 24 kV, 70 kV and 130 kV. While the voltage level largely determines the size of the load that can be connected, other factors – such as grid strength, available short-circuit capacity, and protection coordination – also influence which power levels are technically feasible to connect to what voltage level. Table 3 presents an overview of selected voltage levels and corresponding power intervals that can be connected at each voltage level. The voltage levels relevant for a specific connection can differ between and within countries. In Sweden, the most common voltage levels are 10 and 130 kV. The appropriate voltage level for each connection must be discussed with the relevant DSO.

Table 3 Voltage levels and sizes of loads that can be connected to each voltage level [15]

Voltage level	**Power range**
10 kV	1–20 MVA
24 kV	10–50 MVA
70 kV	20–200 MVA
130 kV	20–500 MVA

Where the option to connect to the grid is only 10 kV or 130 kV, for the 8 MVA, 20 MVA and 60 MVA there is a clear threshold between 10 kV and 130 kV. 10 kV can be suitable for both the 10 MVA and 20 MVA load scenario, but a 130 kV is necessary for 60 MVA. The 130 kV connection is also an option for the 20 MVA case (see Table 2 and Table 3). When standing between two feasible voltage levels, the choice of which could

be the most suitable often comes down to which is the most economical solution, which in turn can depend on the total energy consumption of the connection.

There are no clear thresholds for when connecting to a higher or lower voltage level is most favourable, since it depends on both technical and economic considerations.

A typical scenario is that the DSO owns the cables from their grid to the connection point, but it is the connecting party that owns the station to which the cables are connected. The principle is shown for a connection to the 130 kV-grid in Figure 2.

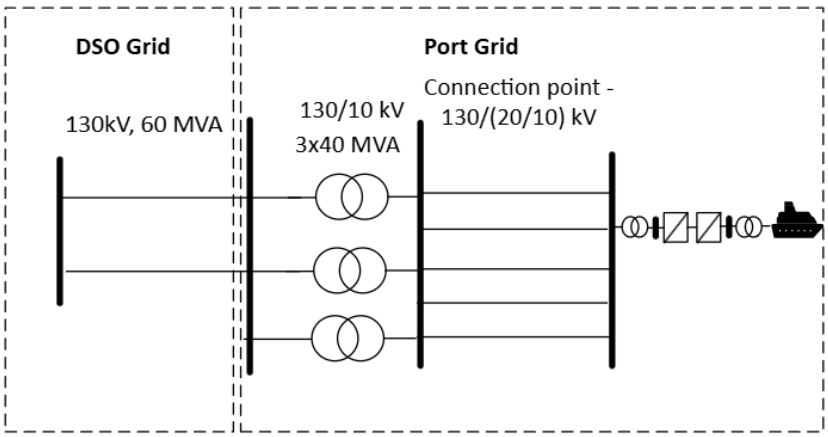


Figure 2 Typical ownership of connection equipment for 60 MVA 130 kV connection

4.2.2 Cables

Cabling forms the physical link between the OPS system and the vessel and must be dimensioned for the required load and installed in accordance with safety and environmental requirements. Cables should be adequately protected against mechanical damage, moisture, and UV exposure, and installed in ducts, trenches, or tunnels where feasible, while maintaining accessibility for inspection and maintenance.

In port environments, cable routing is often complex due to existing infrastructure, operational constraints, and exposure to heavy traffic. These factors increase civil works costs and require careful planning to ensure reliability and safe operation. Given the high cost and disruption associated with civil works, early planning for future capacity is essential. Designing cable routes and infrastructure to accommodate additional or larger cables from the outset reduces the need for costly retrofits.

For future load increases using parallel cables, equal cable length and identical cable types are required to ensure proper load sharing. In addition, all cables must be rated for the maximum prospective fault currents. More detailed guidance on cables can be found in the IEC/IEEE 80005 standards and in the EMSA [11] OPS guidelines.

4.2.3 Transformers

A transformer's purpose is to change the voltage, so it matches what ships or port equipment need, either increasing or decreasing it. When installing a transformer station, several important design choices must be made. One key decision is whether the station will be outdoors (in weatherproof enclosures or containers) or indoors (inside special

rooms or buildings), depending on what works best for the port's layout, available space, and safety requirements, ensuring safe operation and shielding the equipment from weather and damage.

Other critical aspects include sizing the transformer for the maximum expected load, with allowance for future expansion, ensuring proper ventilation or cooling to prevent overheating, and providing robust earthing and protection against electrical faults.

There are two common types of transformers, oil-cooled and dry transformers. Which kind of transformer is the most suitable for each installation depends on and comes down to a few different choices. The first aspect to consider is fire and environmental safety. Air-cooled, dry transformers offer more fire safety, and there is no risk for oil leakages. In areas where fire safety is important and leaks can lead to environmental implications, dry transformers are preferred. The drawbacks of dry transformers are that they need to be placed indoors or in a container, as they cannot stand directly outside due to lack of protection, as well as a shorter life expectancy compared to oil-cooled transformers. Dry transformers require less space than oil-cooled transformers; they are roughly 2/3s of the size of the oil-cooled transformer. Dry transformers are the preferred choice for OPS-purposes.

Switchboards are also typically located in the transformer station. Their role is to safely distribute and control the flow of power to different parts of the port or to ships, helping operators manage and protect the electrical system.

4.2.3.1 Galvanic isolation

According to IEC/IEEE 80005-1, galvanic isolation needs to be achieved between the shore-side electrical system and the vessels, and between vessels connected at different berths. Galvanic isolation is achieved in the step-up transformers. This means there is no direct electrical connection between the two sides, only magnetic coupling. Thus, no unwanted currents, like stray DC or earth currents, can flow from shore to ship or vice versa. This is especially important in OPS systems due to the high risk associated with corrosion from unwanted currents.

4.2.3.2 Transformers in parallel connection

Parallel operation of transformers presents technical challenges that must be carefully managed. Even small deviations in turns ratio or percentage impedance can lead to unequal load sharing, causing one transformer to overload while another remains underutilized, and mismatched voltages can create circulating currents that generate additional heating and losses. Differences in vector group or phase shift further risk improper current distribution or even fault-like conditions, making strict alignment of electrical characteristics essential. Despite these challenges, paralleling transformers can significantly increase system flexibility. Instead of relying on a single large transformer, multiple smaller units can be combined to achieve the required capacity, simplifying handling, transport, installation, and maintenance. To maintain the flexibility, it is recommended not to use transformers larger than 16 MVA, since these become very large, which makes them hard to handle and ship.

Adding transformers in parallel is common practice for OPS systems. The transformers connect to the switchgears and thus flexibility and redundancy can be achieved through multiple options on how to route the power.

4.2.3.3 *Special features of step-up transformers for OPS systems*

Aspects of step-up transformers used for OPS systems that make them different from standard distribution transformers include that they might need to be able to withstand both 50 Hz and 60 Hz frequencies, and in some cases also 6.6 kV and 11 kV output voltage. It is not within the scope of this report to facilitate 6.6 kV-power supply. However, this voltage level is standard for many vessels and, for a port to offer the possibility to charge with 6.6 kV, it adds flexibility for more ships to use the connection.

4.2.4 Switchgear

Switchgear in OPS systems is used to safely control, protect, and isolate the electrical equipment that delivers shore power to vessels. In OPS installations, switchgear forms part of the shore side distribution network both for the incoming power from the grid that distributes the power to the transformers connected, and on the ship-side where the power is distributed to the cables connecting the vessels.

What determines whether a switchgear installation is scalable is its modular design and expandability. This includes the number of available bays, whether additional bays can be added without major reconstruction or extended outages, and whether the busbar system is designed and rated for the maximum anticipated operational currents and short-circuit fault levels. Scalability also depends on the switchgear's thermal capacity, mechanical strength, and protection and control architecture, ensuring that future increases in connected load or additional vessels can be accommodated safely and reliably. The most commonly used size of switchgear is the 630 A rating and using these can be comparatively cheaper than other sizes. For this report, the assumptions for the sizes will however be the need for current rating.

4.2.5 Circuit breakers

Circuit breakers are safety devices in transformer stations and OPS installations. Their main purpose is to automatically disconnect power in case of faults such as overloads, short circuits, or earth faults to protect both equipment and people.

In OPS systems, circuit breakers are selected and installed according to strict standards to ensure they can handle the maximum expected fault currents. They must be coordinated with other protection devices so that only the affected part of the system is disconnected during a fault, keeping the rest of the port's power supply running safely. Circuit breakers can also be equipped with features for remote operation, monitoring, and backup power for critical protection functions.

Circuit breakers must be rated for the maximum load current and the maximum prospective short-circuit current at their point of installation. For HV shore connections, the breakers must be able to withstand and interrupt fault currents as specified by international standards, e.g. IEC/IEEE 80005-1.

4.2.6 Frequency converter

A frequency converter is an important component in OPS systems. It enables ports to supply ships with electrical power at the frequency they require, regardless of the local

grid standard. This is particularly important because many ships are designed to operate on 60 Hz power, while the local grid in many regions, such as Europe, supplies 50 Hz.

The conversion process consists of two main stages:

- Rectification: The incoming Alternating Current (AC) power from the grid, typically at 50 Hz, is first converted into DC by a rectifier.
- Inversion: The DC is then converted back into AC at the required frequency, either 50 or 60 Hz by an inverter.

The intermediate DC stage in a frequency converter is essential for precise control of output frequency and voltage, ensuring compatibility with ship requirements. Modern OPS systems mainly use static (solid-state) converters due to their efficiency, compactness, and flexibility.

All frequency converter installations must comply with international standards such as IEC/IEEE 80005 to guarantee safety, compatibility, and reliable performance for a wide range of vessels.

One important aspect to consider when choosing which converters to use is which voltage level the converters should operate at. For OPS purposes, the choices available are low-voltage (LV) and medium-voltage (MV) converters. Typically, the LV inverters are simpler and cheaper to make, however when the power levels increase so does the current, and for larger power levels MV converters become the preferred choice. Where this threshold falls will be further elaborated on in section *5 Findings: Conceptual design optio*ns (p.26). The frequency converters, in series with step-up and step-down transformers can be connected in parallel, however, it is preferable not to mix LV and MV frequency converters by connecting these in parallel.

4.2.6.1 Single-drive vs. multi-drive configuration

In frequency converter systems, the choice between a single-drive or a multi-drive configuration depends largely on how many consumers are supplied and how tightly integrated the installation is. A single-drive solution uses one converter per consumer, with each unit having its own rectifier, DC link, and inverter. This creates electrically independent systems but requires separate feeders, protection devices, and cabling for each drive, resulting in a larger installation footprint.

A multi-drive system, on the other hand, is built around a shared DC bus, where a common supply unit feeds multiple inverter modules. The multi-drive principle enables a single power entry point and common DC bus resources for all connected drives. This reduces the amount of cabling and switchgear needed, simplifies installation, and allows for a more compact and efficient system layout.

The shared DC bus in a multi-drive configuration also provides a straightforward interface for connecting additional DC equipment. For example, a BESS can be tied into the common DC link via a dedicated DC/DC converter. This integration is possible because all inverters in a multi-drive arrangement already operate from the same stabilized DC bus, making it a natural connection point for DC equipment without modifying the AC infrastructure.

Furthermore, the multi-drive topology supports a range of supply-side rectifier configurations. The supply unit can be a simple diode rectifier or a more advanced active IGBT rectifier. Multiple rectifier units can be paralleled when higher power ratings or redundancy are required. This modularity is one of the core advantages of the multi-drive approach compared to single-drive systems, where each consumer requires its own independent rectifier stage. However, multi-drive systems are generally more expensive.

4.2.6.2 Rectifier

The supply unit of a frequency converter can be implemented either as a simple diode rectifier or as an Active Front End (AFE), each offering different performance characteristics. A diode rectifier is passive and highly efficient, providing a robust and cost-effective solution with minimal component count and very little control complexity. Its simplicity does, however, mean that it produces characteristic harmonic distortion, cannot control the power factor, and only supports one-way power flow.

An AFE uses an actively controlled IGBT converter to shape the grid current and regulate the DC bus voltage. This allows it to operate with low harmonics, maintain near unity power factor, and support bidirectional power flow, including regeneration. These capabilities make AFEs attractive in applications with demanding power quality requirements or where stable DC-bus control is important. The trade-offs are higher cost, somewhat higher losses, and increased control complexity compared with a diode bridge.

In practice, the choice depends on system priorities: diode rectifiers are preferred where efficiency, cost, and simplicity dominate, while AFEs are selected when controllability, power quality, or regeneration are critical.

4.2.7 Buildings

Containerized electrical units offer a fast, compact, and mobile solution for housing equipment such as switchgear, converters, and transformers. Their structural strength and ability to be transported as complete modules are clear advantages, particularly where space is constrained or installations must be relocated. However, they also come with some drawbacks, some of which are the risk of containers rusting, and the limited space for maintenance and repairs on the equipment within the containers.

Purpose-built electrical buildings, by contrast, offer greater flexibility in layout, improved ventilation, and more stable environmental control. Buildings also generally allow easier access for maintenance and equipment upgrades. However, they demand higher upfront civil works investment, require more space, and have longer construction timelines compared to prefabricated containerized systems. Containerized OPS systems are often chosen for their speed of deployment and modularity, whereas buildings are preferred when durability, expandability, and long-term operating conditions take priority.

One aspect to consider is if the waste heat that comes from the transformer and converter losses can be recovered and reused. If this should be done, buildings provide far better practical conditions for effective heat-reuse systems. Their larger internal volume, better insulation control, and easier integration of ducting and heat-exchange equipment make them more suitable for engineered heat-recovery solutions.

Containerized units can technically support heat reuse, but they are more constrained. Containers rely on compact Heating, Ventilation, and Air Conditioning (HVAC) systems designed primarily for equipment cooling rather than heat capture. Space limitations, ventilation requirements, and the need to prevent overheating of sensitive components make heat recovery integration more challenging.

4.2.8 Battery energy storage systems (BESS)

Battery energy storage systems (BESS) can be implemented by ports as an optional complement to OPS infrastructure. These systems can serve several purposes, such as providing backup power during outages, supporting grid stability and improving the power quality, limiting the contracted peak-power capacity with the DSO, or enabling the integration of renewable energy sources like solar or wind.

Depending on the needs of the port, batteries can be installed to help manage peak loads, ensure uninterrupted power supply for critical operations, or smooth out fluctuations in renewable energy production. The size and capacity of the battery system can be tailored to the expected load and the desired duration of backup or support.

How valuable a BESS system can be for an installation largely depends on the operational profile of the loads, especially if the battery should be used for reducing the size of the grid connection. The kind of load profiles that have the most to gain by introducing BESS are high peak, short duration profiles that are predictable in time, or that can be time-shifted to match the energy price and/or power tariffs ("*effekttariffer*").

For OPS-system purposes, vessels operating on fixed routes and timetables, such as passenger ferries, often have highly predictable power demand and load profiles. This predictability makes it easier for the port to size and operate a BESS efficiently. For other vessel types, the power demand as well as the load profile are typically less predictable from the port's perspective, making both grid connection sizing and BESS optimization more complex. The sizing of the BESS and the potential cost saving are further explored in section *5.6 Possibility of BESS integration* (p.32).

4.2.8.1 Key considerations for BESS in OPS systems

The following points are aspects to consider when determining if BESS should be included in the OPS system:

- Reducing peak power demand from the grid (both for cost reasons and for grid stabilization reasons)
- Adding to the available grid capacity (if a larger connection is not possible due to grid congestion or available power)
- Resilience and redundancy
- Power quality improvements
- Enabling faster ramping-up and ramping-down of power, e.g. for higher utilization of the time in port for charging of onboard batteries
- Storage of renewable energy produced in or close to the port
- Providing ancillary services such as frequency restoration services, or energy trading

For the purpose of this report, the BESS system will be evaluated for its ability to reduce the peak power demand from the grid. This means that the connection capacity from the grid can be reduced.

4.2.9 Cable management system

The cable management system (CMS) is out of scope for this project, as its design and implementation are highly vessel-specific and depend on the unique requirements of each ship and port interface. However, the CMS plays a crucial role in OPS installations by ensuring the safe, efficient, and reliable handling of shore power cables during connection and disconnection between ship and shore.

A CMS is responsible for supporting, guiding, and protecting the heavy and often bulky power cables used in OPS. It helps manage cable tension, accommodates vessel movement due to tides or loading, and prevents excessive bending or mechanical damage that could lead to electrical faults or safety hazards. By organizing and supporting the cables, the CMS also speeds up connection and disconnection procedures, reduces operational risks, and extends the service life of the cables.

Depending on the operational context, a CMS may include cable reels, articulated arms, cranes, or other mechanical aids, and is typically installed ashore, except for container vessels, where it is typically installed onboard (see vessel-specific annexures of IEC80005-1). Its design must be tailored to the specific vessel and berth, but its function is generally considered essential for safe and effective OPS operations, especially for HV or high-power connections. More detailed guidance on cable management can be found in the IEC/IEEE 80005 standards and in the EMSA [11] OPS guidelines.

4.3 Power quality and harmonics

OPS systems must deliver electricity to vessels in a way that is stable, safe, and predictable. This means the power supplied at the ship's connection point must stay within certain limits for voltage, frequency, and electrical "cleanliness" (harmonics). These limits come from both national grid rules and the international standards.

4.3.1 OPS power quality requirements

OPS installations must comply with applicable port grid-code requirements and IEC/IEEE 80005-x power-quality objectives, including limits for harmonic distortion, flicker, rapid voltage changes (RVC), voltage transients and unbalance. Since OPS represents a large, fast-changing load (typically 8–57 MVA per connection), maintaining acceptable power-quality at the Point of Common Coupling (PCC) on both 10 kV (MV) and 130 kV (HV) DSO networks is essential.

In addition to national grid-code requirements, IEC/IEEE 80005-1 specifies the allowable shore-side supply quality and the ship-side compatibility criteria, which must both be satisfied for a compliant OPS installation.

4.3.2 Regulatory power quality limits (DSO connection, Sweden)

OPS connections must meet the legally binding EIFS 2023:3 limits for voltage quality ("*spänningskvalitet*"), see Table 4 and Table 5 of the applicable power quality limit for OPS connections on DSO networks at 10 kV and 130 kV. The methodological principles for planning margins and emission allocation follow the framework in *Svenska kraftnät*'s TR06 (good practice, although formally applicable to the transmission grid).

Table 4 Total harmonic distortion (THD)

	10 kV (MV)	130 kV (HV)
Voltage THD (all 10-min values)	≤ 7.3 %	≤ 6.5 %

Table 5 Individual voltage harmonics (odd and even)

	Harmonic order (n)	MV (10 kV) Max %	HV (130 kV) Max %
Odd	3	4.0	3.0
	5	5.5	5.0
	7	4.5	4.0
	9	1.3	1.3
	11	3.3	3.0
	13	2.8	2.5
	15	0.5	0.5
	17	2.0	2.0
	19	1.5	1.5
	21	0.5	0.5
	23	1.5	1.5
	25	1.5	1.5
Even	2	1.9	1.9
	4	1.0	1.0
	6...24	0.5	0.5

Higher voltage levels impose slightly stricter limits but typically have much higher short-circuit capacity, making compliance easier.

Comment on IEC vs. EIFS THD limits:

While EIFS 2023:3 defines the legally binding harmonic limits at the DSO PCC, it is important to note that IEC/IEEE 80005-1 specifies stricter THD requirements at the shore-to-ship interface. IEC/IEEE 80005-1 limits THD to ≤ 5 % (and individual harmonics to ≤ 3 % under no-load conditions), which is tighter than the corresponding EIFS limits at 10 kV and 130 kV. The difference arises because IEC/IEEE 80005-1 aims to protect shipboard electrical equipment, whereas EIFS governs grid-level voltage quality. As a result, the OPS installation must ensure that harmonic mitigation measures (filters, converter topology, control strategies) produce a waveform that simultaneously complies with EIFS at the PCC and the stricter IEC limits at the ship connection point.

4.3.3 Technical implications and vendor practices

Large OPS installations place significant demands on the grid. High-power converters can create voltage fluctuations and electrical distortion, so the design must include

suitable filtering and control strategies to keep power quality within required limits. Systems that serve several berths or operate in weaker parts of the grid may need more advanced filtering or active compensation. Connecting ships smoothly requires careful control of how load is increased, especially at lower voltage levels where the grid may be more sensitive. Short-circuit levels must be planned early to ensure protection systems work correctly and to avoid overstressing the equipment.

Before an OPS system can be approved, it must demonstrate, through studies and onsite measurements, that it meets all power quality requirements. Vendors differ in how explicitly they document their performance, which means port authorities and project owners must clearly define the acceptance criteria for voltage quality, harmonics, flicker, and behaviour during connection and load changes.

A modern and increasingly preferred solution is to design OPS systems as modular, meaning several smaller converter units work together instead of one large unit. This improves efficiency, especially at partial load, and increases reliability and flexibility for ports serving different ship types. Another benefit is improved power quality: by giving different modules small phase angle shifts, their harmonic currents can cancel each other out, resulting in much cleaner power. This approach also integrates well with battery-based support systems, which help reduce grid impact and operational costs. In procurement, it is important to require that vendors describe how their modular systems achieve these harmonic and operational benefits, and how they ensure the ship-side power meets the IEC/IEEE 80005-1 limits under real operating conditions.

5 Findings: Conceptual design options

The design and configuration of the OPS system are dependent on what the connection to the grid looks like, as well as the connection to the vessels. In Figure 3, the different scenarios that will be evaluated in this report are presented. These are based on the vessel requirements specified in section *4.1 Vessel requirements* (p.14).

What the vessel requirements are will determine the need for capacity at the point of connection and through the OPS system. This chapter describes the different configurations that can be used, both at the connection point and for the OPS system. The shore-to-ship interface, consisting of a cable management system will not be described or evaluated further.

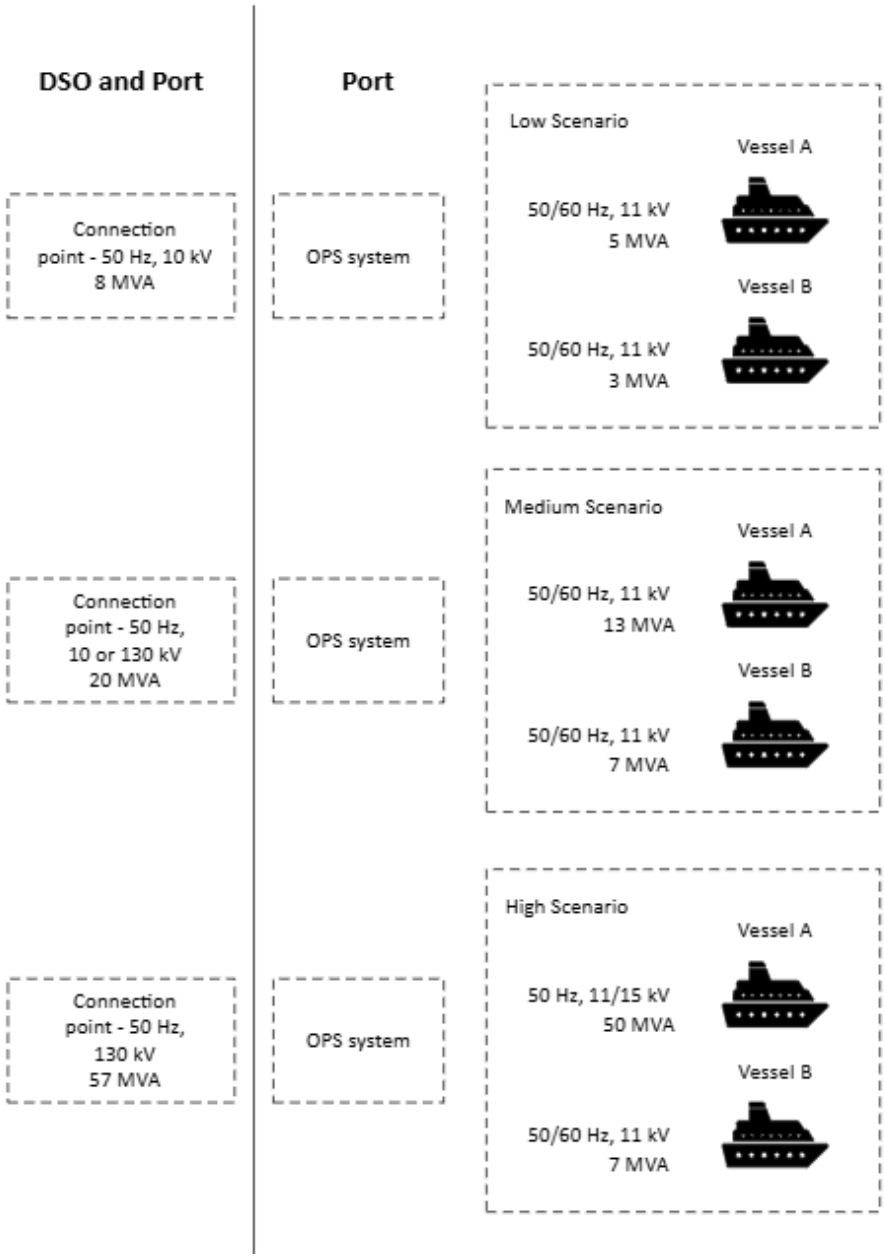


Figure 3 Visualization of requirements for grid connection and vessel charging for the low, medium and high scenarios and the line of responsibility between DSO and Port

5.1 Connection point

The design of a connection point is strongly influenced by the required power level, as it determines the appropriate voltage level and infrastructure needed. These considerations are based on one DSO's assessment of its own network structure and operating conditions. Other DSOs may have different voltage levels, standard materials, or network configurations, which could require alternative technical solutions and infrastructure. In general, the DSO owns the power cables from the grid up to the circuit breaker at the point of connection within the port substation.

The options offered for grid connection in the scenarios presented in this report are either a connection to the 10 kV or 130 kV grid. For loads below 20 MVA, the connection is typically made to the 10 kV grid. For loads larger than 20 MVA, the connection would typically be made to the 130 kV grid. The cost to connect is lower at lower voltages and the availability for a connection is typically higher, but reliability and long-term efficiency can improve when connecting to higher voltages. Thus, although the initial installation cost increases with voltage level, connecting at higher voltages can improve reliability and reduce total lifecycle costs for large power demands.

From this, a required connection capacity of 20 MVA can be considered a breaking point when the choice stands between a 10 kV or 130 kV connection. At other geographical locations, where other voltage levels can be available, other capacities could be the critical limits per voltage level.

The input voltage for the transformers connected to the frequency converters is 10–20 kV. When the voltage exceeds the 20 kV, the voltage transformation from grid connection to converter terminal needs to be done in two steps. In the case of the 130 kV connection, this means connecting 130 kV/10 kV transformers and then 10 kV/3.6 kV before connection to the converters. The typical owner limits are shown in Figure 4.

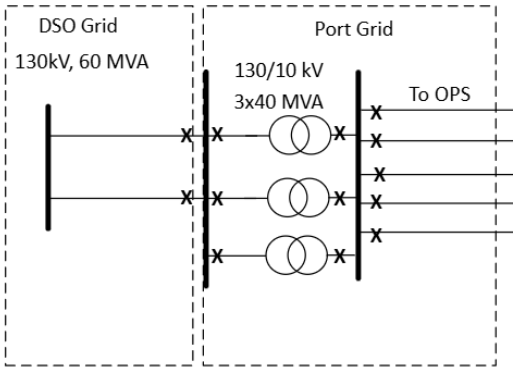


Figure 4 130 kV, 60 MVA connection from DSO grid to port grid showing typical owner limits

5.2 From connection point to shoreside

For both vessels in the low and medium scenarios, and one of the vessels in the high scenarios there is a requirement that the vessels should be able to be fed with both 50 Hz and 60 Hz, this requires frequency conversion. In addition to this the BESS system

should be included and the power quality for the grid and to the vessels needs to be in accordance with given requirements.

5.2.1 Transformer and converter packages

The most common way of designing and building an OPS system that requires voltage and frequency conversion is to add a step-down transformer in series with a rectifier and an inverter and lastly a step-up transformer, as shown in Figure 5. This is the most common and most recommended solution. These packages could then be connected in parallel to achieve the desired power level.

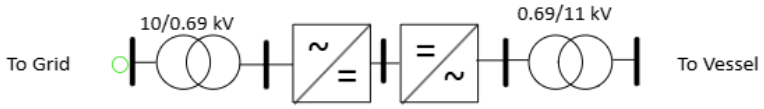


Figure 5 Connection of one "package" of step-down transformer, rectifier, inverter and step-up transformer

5.2.2 Placement of BESS

Where BESS is considered, one of the more important decisions is where to connect it. There are two main options. The first option is to connect the BESS directly to the 10 kV busbar on the grid side of the frequency conversion. This offers great flexibility in how the power is routed from the BESS to the grid or the vessels and is a good option when the BESS should provide services to the grid. The drawback with this placement is that it requires additional frequency converters and transformers that only charge the BESS, and for this reason, this option will not be evaluated further in this report. The second option that will be used in this report is to place the battery at the DC stage, between the rectifier and the inverter. Since BESS charges using DC, it utilizes the converters needed for the power supply and still offers great flexibility due to the switching opportunities before the power is routed to the vessels, as illustrated in Figure 6.

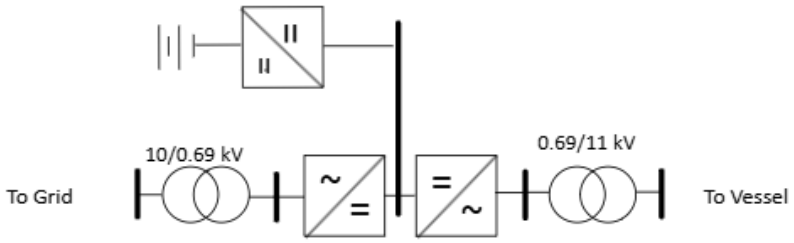


Figure 6 Illustration of BESS connection between rectifier and inverter, LV converters

5.3 Low-power scenario

In the low-power scenario, the system must supply one 5 MVA vessel and one 3 MVA vessel at either 50 or 60 Hz and at a voltage level of 11 kV. This corresponds to a total peak demand of 8 MVA. In this scenario, 50 percent of the required power is assumed to be delivered by a BESS, reducing the amount of power that must be drawn from the grid

and therefore lowering the required rectifier capacity. The inverter capacity, however, remains dimensioned for the full 8 MVA output to the vessels.

For this power range, LV converters operating at 690 V are the recommended choice. ABB's LV diode-supply rectifiers cover a power range of approximately 50–5500 kVA, matching the available inverter modules and allowing the same converter platform to be used on both the grid side and the BESS interface. A step-up transformer is then used to deliver the final 11 kV shore-connection voltage. Each rectifier and inverter connect to one transformer. The proposed layout is presented in Figure 7.

To supply the two loads, the needed components are:

- 2 x MV-switchgear
- 2 x step-down transformers
- 1 x DC-switchgear
- 2 x LV rectifiers
- 2 x LV inverters
- 2 x step-up transformers

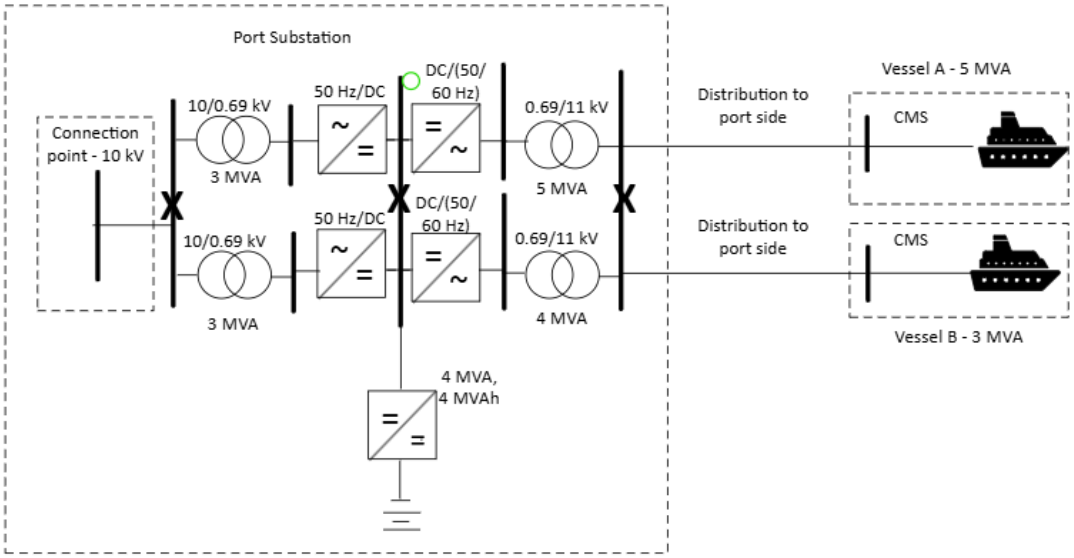


Figure 7 Layout of Low-power scenario

5.4 Medium-power scenario

In the medium-power scenario, the system must supply one 13 MVA vessel and one 7 MVA vessel, giving a combined peak demand of 20 MVA at 50 or 60 Hz and a shore-side voltage of 11 kV. For this scenario, the grid connection can be both 10 kV and 130 kV. If a 130 kV connection is used, this would require two 15 MVA 130/10 kV transformers before the connection to the switchgears that connect to the step-down transformers of the rectifiers. Two transformers are needed for redundancy.

Both LV and MV converters can be suitable for this scenario. Thus, both options will be shown in this case. With a total power demand of 20 MVA, roughly half of this capacity should be covered by the BESS. This makes the total capacity needed for the rectifiers lower than the inverters. The inverters will need to have a total capacity of 20 MVA, but

the total capacity needed for the rectifiers is roughly 13 MVA. It is not recommended to use transformers larger than 16 MVA for step-up and step-down the voltage before and after the converters. The proposed layout using LV converters, option 1, is presented in Figure 8 and the proposed layout using MV inverters, option 2, is presented in Figure 9.

To supply the two loads using LV converters, the components needed for option 1 are:

- 2 x MV-switchgear
- 3 x step-down transformers
- 1 x DC-switchgear
- 3 x LV rectifiers
- 4–5 x LV inverters
- 4–5 x step-up transformers

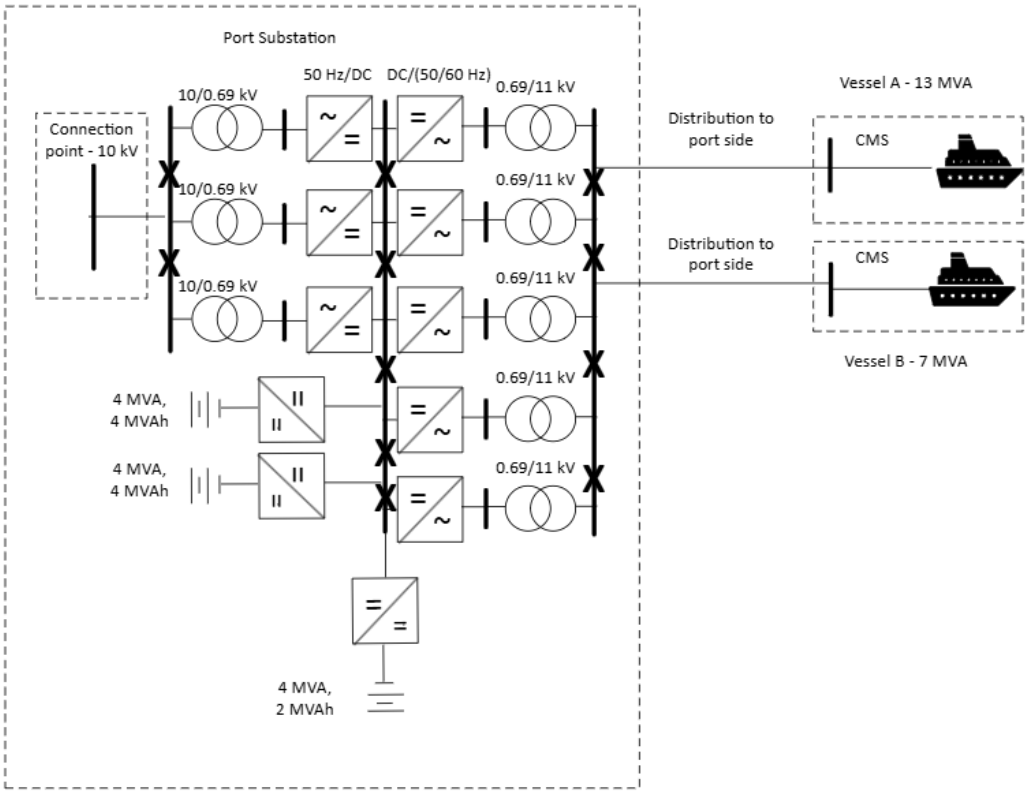


Figure 8 Layout of Medium power scenario, option 1, LV converters

To supply the two loads using MV converters, the components needed for option 2 are:

- 2 x MV-switchgear
- 2 x step-down transformers
- 1 x DC-switchgear
- 2 x MV rectifiers
- 2 x MV inverters
- 2 x step-up transformers

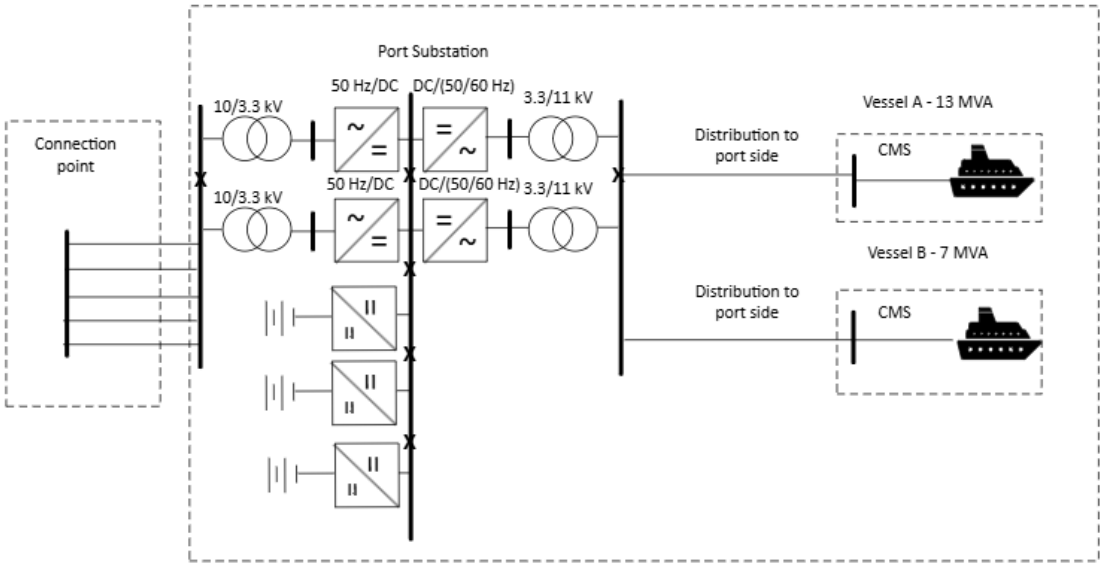


Figure 9 Layout of Medium power scenario, option 2, MV converters

Both LV and MV converters are feasible options in this scenario, and therefore both configurations are presented. The same is true for the voltage levels that are options for the grid connection, the medium power scenario can be suitable for both.

5.5 High-power scenario

In the high-power scenario, the system must supply one 7 MVA vessel and one 50 MVA vessel, giving a combined peak demand of 57 MVA. The 7 MVA vessel should be able to be supplied with 50 or 60 Hz and a voltage of 11 kV. For the 50 MVA vessel, the requirement is only having 50 Hz charging, but either 11 kV or 15 kV voltage. For a combined load of 57 MVA, the grid voltage is 130 kV, and the connection point shall be supplied by three 40 MVA transformers.

As the aim of the report is to compare scalability, option one for the high-power scenario is based on a similar design to the low and medium power scenario. This means all power will go through the frequency converters, even for the 50 MVA vessel that does not require 60 Hz output. Furthermore, the output voltage is assumed to be 11 kV for both vessels. The recommended layout is presented in Figure 10.

To supply the two loads using option 1, the components needed are:

- 2 x MV-switchgear
- 3 x step-down transformers
- 1 x DC-switchgear
- 3 x MV rectifiers
- 4 x MV inverters
- 4 x step-up transformers

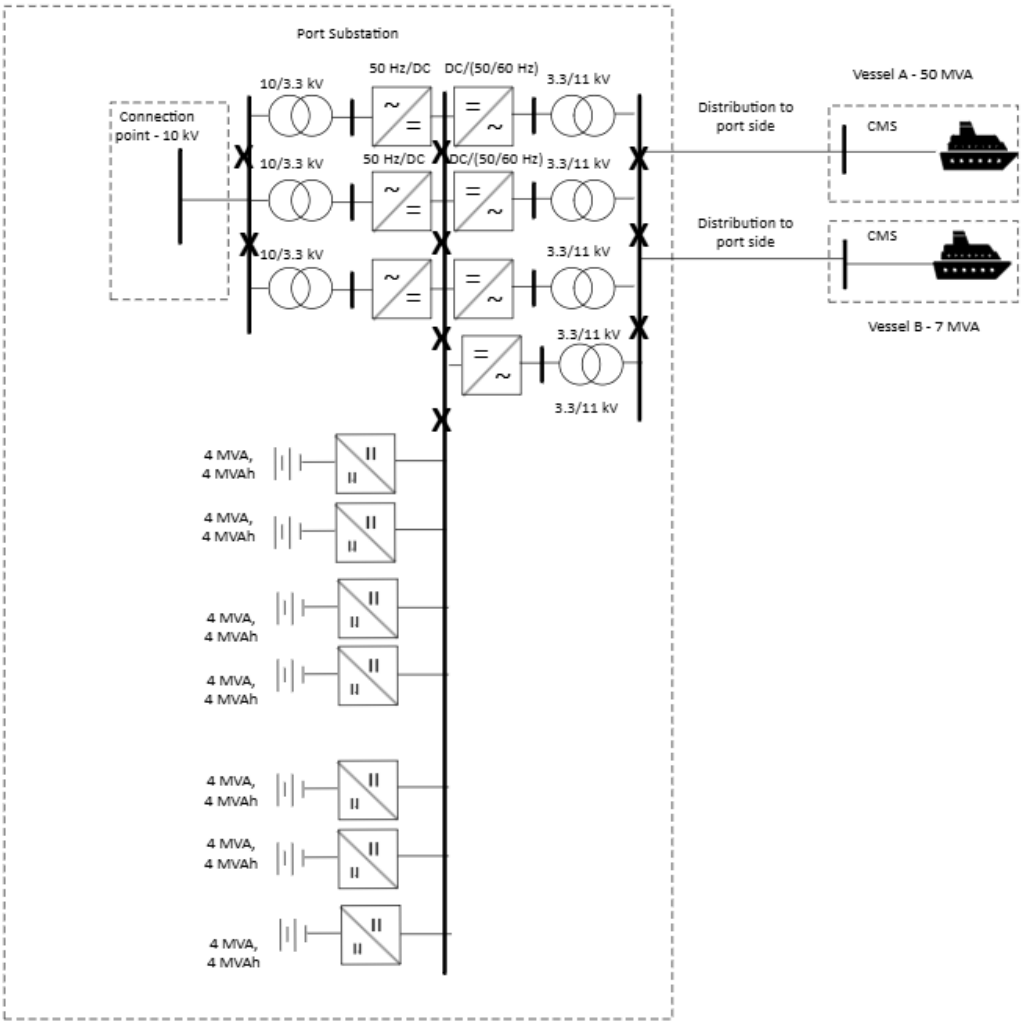


Figure 10 Option 1, High power scenario, MV converters

For option 2, the power to the 50 MVA vessel will not go through any frequency converters, and it is assumed that the vessel should be connected at 15 kV voltage level. This is the preferred configuration if an installation is made from the start according to ABB, as keeping the voltage higher reduces the current, and less equipment is needed if the vessel has the same frequency as the grid. The recommended layout is presented in Figure 11.

To supply the two loads using option 2, the components needed are:

- 2 x MV-switchgear
- 1 x step-down transformers
- 4 x step-down isolation transformers
- 1 x DC-switchgear
- 1 x MV rectifiers
- 2 x MV inverters
- 2 x step-up transformers

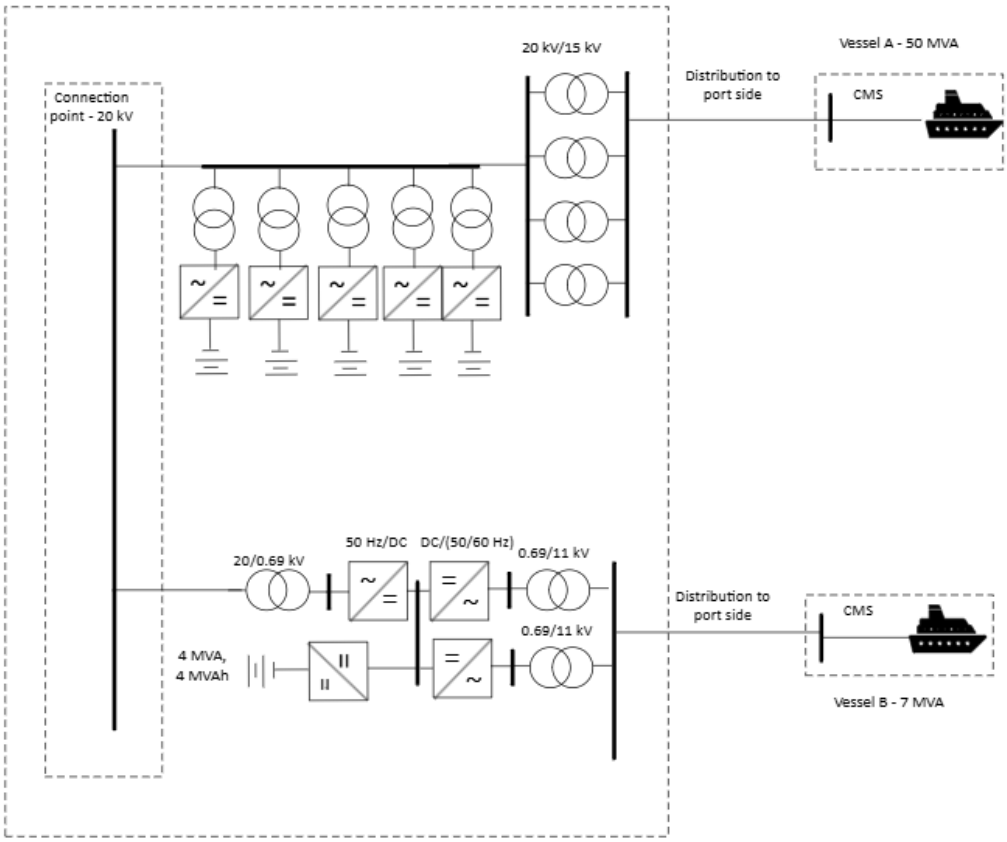


Figure 11 Option 2, High power scenario, no frequency conversion for vessel A, 50 MVA

5.6 Possibility of BESS integration

Typically, a grid network tariff consists of multiple components: a fixed subscription fee, an energy-volume (kWh) fee, and a capacity/demand (peak-power) fee, based on a consumer's maximum power draw during a defined billing period. Potentially, there may also be a reactive-power (kVAr) fee if reactive demand exceeds certain thresholds, meaning non-active power demand may also be penalized.

According to *Energimarknadsinspektionens föreskrifter och allmänna råd*/The Swedish Energy Markets Inspectorate's regulations and general guidelines (EIFS 2022:1), Swedish network tariffs must be structured to promote efficient long-term utilization of the grid. The regulation mandates that tariffs include four distinct components: a fixed fee (*"fast avgift"*), an energy fee (*"energiavgift"*), a customer-specific fee (*"kundspecifik avgift"*), and a power capacity/demand fee (*"effektavgift"*).

In this regulatory context, integrating BESS in an OPS system becomes a highly relevant tool for ports and vessel operators. A BESS can significantly reduce the required peak power demand during vessel port stay, since the system can be continuously charged at a lower power level while still delivering high instantaneous power to the vessel. This reduces the recorded monthly power peak, and thus lowers the power capacity/demand fee, which can represent a substantial share of total OPEX, particularly in high-power OPS systems (multi-MW). By reducing both peak demand and the need for increased subscribed capacity, BESS aligns directly with the cost-reflectivity principles mandated in EIFS 2022:1.

To emphasize the potential effect of BESS integration in OPS systems, Figure 12 below could serve as an illustrative example. The blue bars illustrate the medium-power scenario where a peak power demand of 20 MVA occurs when two vessels are connected to OPS simultaneously. The orange bars serve as an illustrative example of the same amount of energy (MWh) being taken from the grid continuously by charging shore-side BESS, rather than during peak periods only. In turn, the vessels are charged through both the grid and the BESS, reducing the peak power demand to 6 MVA.

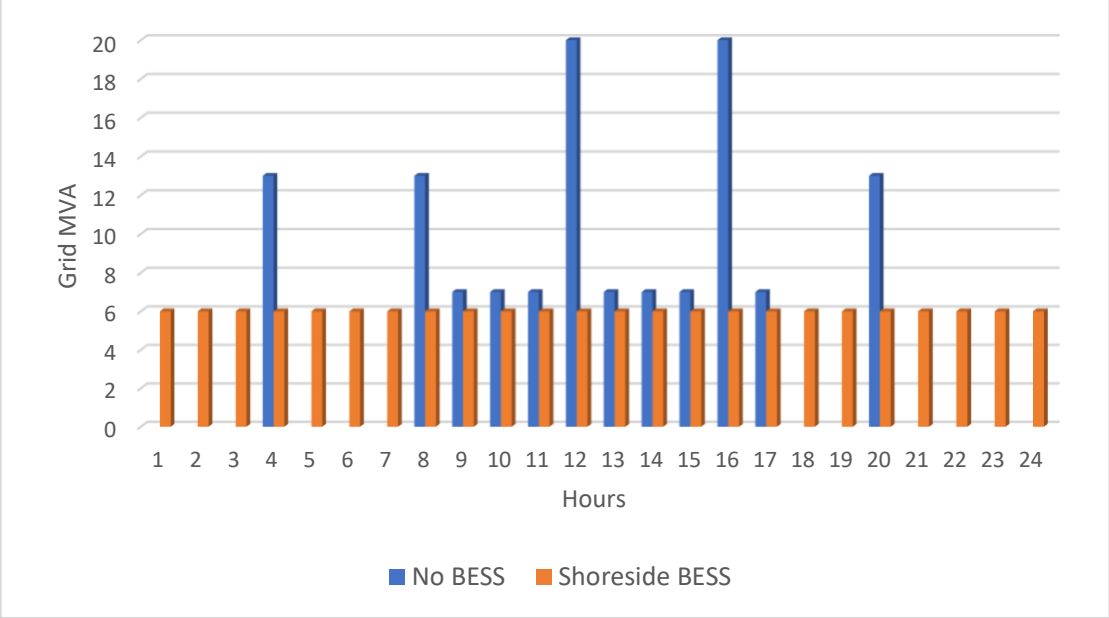


Figure 12 Example of the potential effect of BESS integration in OPS systems

Some considerations:

- High-power demand at the "wrong" time of day will become more expensive, while a more even load profile will be rewarded.
- Flexibility, batteries, and load management will become increasingly important tools for reducing network charges for consumers.
- Transparency and predictability of tariffs may increase, although customers should be prepared for a possible stronger focus on power (kW) and time-of-use.
- The tariff system of the future is designed to reward customers who reduce their impact on the grid's peak load.
- The BESS must be sized appropriately: storage capacity, power electronics, and discharge (C) rate must match the vessel´s load profile.
- Charging needs to happen during low-tariff periods and during periods where port power requirements are low.

In all three OPS scenarios (low-power, medium-power, and high-power configurations) shown in Figure 7–Figure 11, the BESS is integrated within the port substation and directly interfaced to DC distribution bus. Instead of using a 690 V AC power conversion stage and a step-up transformer (e.g., 0.69/11kV), the updated architecture

employs an LV battery system (typically 800–1000 V DC) connected to the MV-level DC bus through bidirectional DC/DC converters.

This DC-coupled configuration reduces the number of power-conversion stages, improves efficiency and dynamic response, and allows the BESS to support all OPS connections without modifying the ship-side CMS or the existing MV transformer interface. The BESS can therefore provide peak shaving, grid-support functions, contingency backup, and enhanced operational flexibility across the entire port electrical system. In addition, different integration levels (e.g., fixed import-power limitation, partial battery assistance, or full battery-only OPS supply) can be evaluated based on operational and commercial requirements.

1) BESS power rating for different OPS scenarios

The BESS rating is selected based on the total installed OPS capacity and the expected operational objectives. A practical engineering rule from some industrial partners is to size the BESS at 50% of the total OPS capacity: Some design specifications can be found in Table 6.

Table 6 Design specifications for BESS

Scenario	OPS capacity (MVA)	BESS power (MW)	BESS energy (MWh)	Estimated footprint with single layer (35–50m²/MWh)	Approx. No. of 40 ft containers (3 MWh per unit with single layer)
Low power	3+5 = 8	4	4	140–200 m²	1–2 units
Medium power	13+7 = 20	10	10	350–500 m²	3–4 units
High power	>30–50	15–25	15–25	525–1250 m²	5–9 units

Notes:
- Footprint calculations are based on

$$A_{\text{BESS}} = 35\text{–}50\ \text{m}^2/\text{MWh} \times E_{\text{BESS}}$$

including fire spacing, access lanes, and Power Conversion System (PCS)/DC/DC auxiliary equipment.

- Container count assumes modern LFP energy density: ~5 MWh per 20-ft container.

- Actual layout depends on fire zoning (NFPA 855, IEC 62933, grid codes), local port regulations, and equipment arrangement.

This sizing provides a good balance between technical performance and economic feasibility while ensuring compatibility with typical LV PCS and transformer-based MV interconnection.

2) C-rate and battery lifetime considerations

The BESS C-rate is defined as:

$$C\text{-rate} = \frac{P_{\text{ESS}}}{E_{\text{ESS}}}$$

Where P_{ESS} is the charging or discharging power of the energy storage system, and E_{ESS} is the rated energy capacity of the energy storage system. With the above sizing guideline (1–2 hours of rated discharge capability), the resulting operating C-rate typically lies between 0.5C and 1C, which is suitable for lithium-ion batteries used in stationary applications.

Typical lifetime characteristics are:

- 0.25–0.5C continuous operation: 6000–8000 cycles [16], corresponding to 8–11 years at equivalent to 2 cycles/day and 2–3 years at 8 cycles/day.
- Around 1C operation [17]: 3000–5000 cycles, corresponding to 4–7 years at 2 cycles/day and 1–2 cycles/day.
- >2C high-power cycling: Rapid degradation; typically, 1500–2500 cycles, corresponding to 2–3 years at 2 cycles/day and 1 year at 8 cycles/day, suited mainly for short-duration buffering rather than daily cycling.

The lifetime can be extended if the daily cycling is less than one full equivalent cycle, for example 0.3 cycles/day. This means that the calendar life can still align this typical port-infrastructure lifetimes even at higher C-rates.

By sizing the BESS to operate in the 0.5–1C range during peak OPS loads, the system achieves a practical trade-off between power capability, lifecycle cost and operational reliability.

3) BESS size optimization

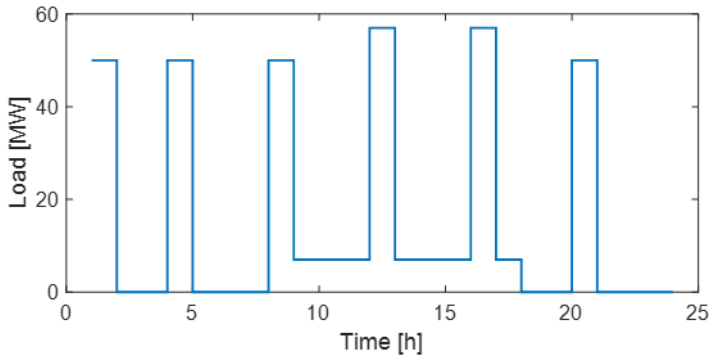
Below is an example showing the BESS size optimization using the typical daily charging profiles presented in Figure 13. The objective is to minimize the overall cost of the system while satisfying operational constraints such as power balance, battery limits, and grid constraints. The system considered in this study consists of OPS charging loads connected to the power grid and supported by a BESS. The BESS is used to manage the power flow between the load and the grid.

The main objective of the system is to determine the optimal BESS capacity and operation strategy that minimizes the total cost of the system. The system must satisfy several operational constraints, including power balance between supply and demand, battery power limits during charging and discharging, battery energy capacity limits, energy balance over the operating period. At every time step, the total power supplied by the grid and the BESS must match the system load demand. These constraints ensure the feasibility and reliability of the system operation. The BESS model is adopted from Xun, Tang [18] and a numerical example is shown in *9.1 Annex A* (p.47).

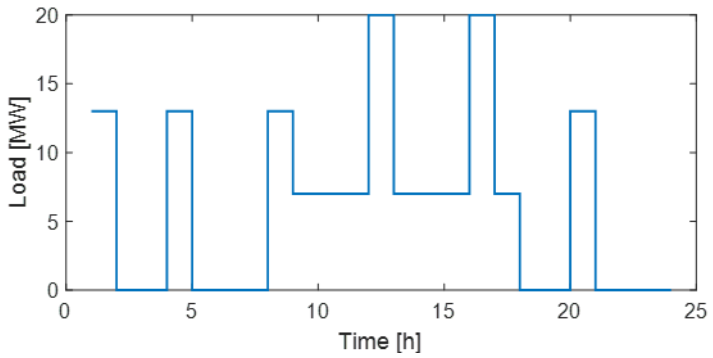
The objective of the optimization problem is to minimize the total system cost. The total cost consists of three main components: battery investment cost, grid cost, and electricity purchase cost. The objective function can be expressed as:

$$C_{total}=C_{bat}+C_{grid}+C_{el}$$

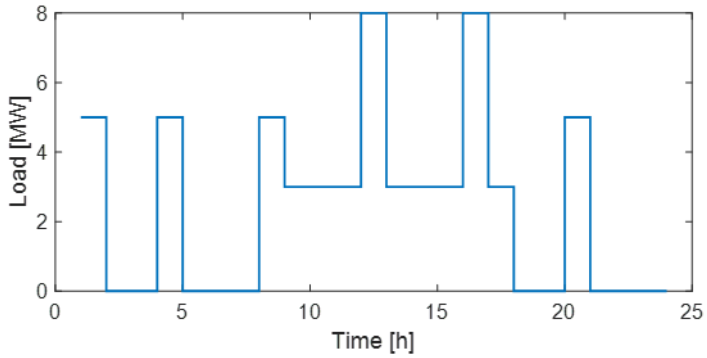
where C_{bat} represents the battery investment cost, C_{grid} represents the grid-related cost, and C_{el} represents the electricity purchase cost. The optimization variables include battery energy capacity, battery charging/discharging power, electricity purchased from the grid. monthly peak grid power demand. The state variable of the system is the battery energy level. Several constraints are included in the model: battery sizing limits, charging and discharging power limits, and daily energy balance. In addition, the total power supplied must equal the power consumed in the system. Accordingly, the typical daily charging profiles for OPS at different scenarios are illustrated in Figure 13.



(a) High charging power demand.



(b) Medium charging power demand.



(c) Low charging power demand.

Figure 13 Typical charging profile for OPS

The total cost considered in the example optimization consists of electricity purchase costs and grid costs. Electricity purchase cost is the cost paid to the electricity supplier for energy consumed from the grid. Grid cost is paid to the DSO and consists of three components: A monthly fixed charge is required to maintain the connection to the grid, regardless of the electricity consumption. This fee is proportional to the amount of electricity transported through the grid and is calculated based on energy consumption. This charge is based on the customer's peak power demand during a billing period. By incorporating battery storage, the system can reduce peak demand and therefore lower the peak power capacity/demand fee.

Indicative modelling done in MATLAB suggests that integrating BESS can reduce total daily operating costs by approximately 5–7%, primarily through reductions in peak power demand charges. See *9.1 Annex A* (p.47) for example assumptions.

5.7 Assessment of scalability

OPS systems are typically designed to be adaptable and modular to fit the different needs of the connections. Because OPS systems are modular and adaptable, they offer strong potential for scalable installations. However, there are some choices that are more and less suitable for the different scenarios, these are presented in Table 7.

For the components discussed in this report, the two main dividers between higher and lower power are the grid connection voltage and the voltage at which the converters operate. In both cases, the lower voltage is suitable for the low-power scenario, and the higher voltage is suitable for the high-power scenario. The medium power scenario can be a feasible option for both voltage levels, both regarding converters and grid connection.

The main factors limiting switchgear scalability are the total current rating and the number of available bays. Some switchgear solutions suitable for OPS applications allow additional bays to be added later. However, true scalability depends on whether the busbar and overall switchgear assembly are rated for the higher operational and fault currents associated with future load increases. If the initial installation is selected based on a low-power scenario, upgrading to medium or high power levels may not be possible without replacing the switchgear.

For cabling, the most costly and disruptive aspect is typically the civil works associated with cable trenches. Like switchgear, cables have a defined maximum current rating. If system load increases beyond this rating, the installed cables may not be adequate. Preparing trenches during the initial installation to accommodate additional or larger cables can significantly reduce future upgrade costs and operational disruption, as it avoids extensive new excavation and reconstruction work.

Circuit breakers are scalable only within predefined rating steps. Voltage and short-circuit capacity cannot be upgraded later, so future system growth must be considered at the initial design stage. Replacing a breaker with a higher-rated unit may be technically straightforward in modular switchgear, but it comes with extra costs due to equipment price, installation labour, and potential downtime. In fixed or compact designs, upgrades can be more difficult.

Table 7 Assessment of scalability of the relevant components

Component	Suitable for Low power	Scalable to Medium power	Scalable to High power	Notes
Grid connection 10 kV	Yes	Yes	No	Suitable up to around 20 MW power requirement
Grid connection 130kV	No	Yes	Yes	Suitable from around 20 MW power requirement
Step-down transformer 130/10 kV	Not applicable	Yes, suitable for HV connection	Yes	Additional transformers can be added
Frequency converters LV + step-down/up transformers	Yes	Partly	No	Can be built modular
Frequency converters MV + step-down/up transformers	Yes	Yes	Yes	Can be built modular
BESS	Yes	Yes	Yes	Can be built modular
Switchgear 450 A rating	Yes	No	No	Can be built modular if this choice is made from the start. Requires higher current rating for scalability.
Switchgear 1100 A rating	Yes	Yes	No	Can be built modular if this choice is made from the start. Requires higher current rating for scalability.
Switchgear 3100 A rating	Yes	Yes	Yes	Can be built modular if this choice is made from the start.
Switchgear 630 A rating				The most commonly used size of switchgear. Can be more advantageous due to price.
Cabling	Yes	Yes, if civil work was prepared in the first stage	Yes, if civil work was prepared in the first stage	Recommended to do civil work and trenching for any upgrades from the start. If the load at one berth increases, cables may need to be replaced to ensure equal loading across all parallel cables.
Circuit breakers 450 A rating	Yes	No	No	If higher load and short circuit current are expected than what the breaker is rated for, it will need to be exchanged.
Circuit breakers 1100 A rating	Yes	Yes	No	If higher load and short circuit current are expected than what the breaker is rated for, it will need to be exchanged.
Circuit breakers 3100 A rating	Yes	Yes	Yes	If a higher load and shorter circuit current are expected compared to what the breaker is rated for, it will need to be exchanged.

5.8 Footprint

The following section assumes the installations are put in containers. Buildings require more space but offer more robust installations.

5.8.1 Low-power scenario (5 + 3 MVA) – LV converters

In the low-power range, the physical footprint is dominated by compact containerized solutions. The 4 MVA diode-front end, combined air- and water-cooling system requires three 20-foot containers. The 5.3 MVA air-cooled configuration expands to six 20-foot containers, representing a noticeable increase in footprint but still well within the container-based modular format suitable for LV-converter applications. Together, the combined 5 MVA and 3 MVA can fit into six 20-foot containers if diode-front converters are used and they use a combined air- and water-cooling system.

5.8.2 Medium-power scenario (8 + 12 MVA)

Option 1 – LV Converters
For LV-based solutions in the medium-power range, the footprint continues to scale with output rating while remaining fully containerized. The 8 MVA unit requires six 20-foot containers while the 12-MVA solution expands to seven 20-foot containers. Both assume that diode-front end converters are used.

Option 2 – MV Converters
When selecting MV converters in this power class, the system architecture shifts toward building-based installations rather than containers. MV-based solutions at these power levels typically mirror the footprint behaviour of the 16 MVA converter configurations, meaning containers that are built together to what is called an e-house rather than multiple separate containers. This results in a more consolidated but building-dependent installation. A single 16 MVA system using MV converters occupy two 40-foot containers, for a 20 MVA scenario three 40-foot containers are necessary.

5.8.3 High-power scenario (7 MVA + 50 MVA)

At the highest power levels, the system transitions from smaller modular container solutions to largescale MV-converter installations. If a single 16-MVA system using MV converters occupies two 40-foot containers, this provides a basis for estimating the footprint of larger combined power configurations.

A 16-MVA MV-converter unit therefore requires 2 × 40-foot containers. To reach a combined rating of 57 MVA (7 MVA + 50 MVA), the installation would scale proportionally. Rounded up, this corresponds to 4 MV-converter units.

Given that each unit requires two 40-foot containers, the combined installation would require 4 units × 2 containers per unit = 8 × 40-foot containers.

5.9 Cost assessment

This section provides indicative cost ranges for key electrical infrastructure components required for the three OPS scenarios under consideration. The values represent high level budgetary estimates and should be treated as order-of-magnitude figures. They exclude external cabling, installation, commissioning, and civil works unless otherwise stated.

5.9.1 Frequency converters and transformers

Cost estimates for complete containerized OPS systems, including static frequency converters, transformers, switchgear, and design are summarized below:

Low Scenario: 8 MVA (3 + 5 MVA)

- 3 MVA converter/transformer unit: approx. 1.5 M€
- 5 MVA converter/transformer unit: approx. 2.2 M€
- Total (indicative): approx. 3.7 M€

Medium Scenario: 20 MVA (13 + 7 MVA)

- 13 MVA unit: approx. 4.2 M€
- 7 MVA unit: approx. 2.6 M€
- Total (indicative): approx. 6.8 M€

High Scenario: 57 MVA (50 + 7 MVA)

For systems including SFCs:

- 7 MVA unit: approx. 2.6 M€
- 50 MVA unit (MV connection): approx. 13.7 M€
- 50 MVA unit (LV connection): approx. 16 M€
- Total (indicative): approx. 16.3–18.6 M€

For a 15 kV configuration without frequency conversion:

- Pricing requires supplier input but is expected to be significantly lower than SFC-based solutions.

Switchgear and control system costs are included in the containerized system prices above. Major cost drivers include required fault level/short-circuit ratings, which determine whether primary (higher cost) or secondary (lower cost) switchgear is required.

5.9.2 High-voltage step-down transformers (130 kV / 10 kV)

The pricing of 130 kV-class transformers is highly specification-dependent and generally requires supplier quotations.

- As a reference, a 10 kV input, 20 MVA transformer is typically 250–300 k€, depending on specification.
- At 132 kV, the transformer frame and clearances are significantly larger, and therefore the price is expected to be substantially higher, though no firm estimate is available at this stage.

5.10 Indicative cabling costs

Indicative dimensioning and pricing for required cabling (grid to station and station to berth) can be provided separately. These costs typically depend on:

- Cable rating and conductor size
- Route length and installation method (buried, ducted, subsea, etc.)
- Thermal constraints and soil conditions
- Redundancy requirements

An indicative pricing is that cabling for 16 MVA can cost between 3–5 kSEK per meter, including civil work and the cables.

6 Discussion

6.1 Use by ports: a decision-support toolkit for planning, procurement, and phased build-out

For ports and terminal operators, the results can be applied as a structured front-end design tool in three ways.

First, the reference architectures per power tier provide a validated starting point for concept selection and stakeholder alignment. Rather than initiating each OPS project as a bespoke design exercise, ports can map their expected operational profile (single vs. multiple simultaneous connections; seasonal peaks; berth allocation constraints) onto one of the concept tiers and immediately identify the dominant design drivers: grid connection voltage level, converter topology (single block vs. modular parallel units), harmonic mitigation strategy, and protection/earthing philosophy. This reduces time-to-decision and mitigates the frequent failure mode where early civil/electrical layout decisions unintentionally block later expansion.

Second, the component matrices (scalable vs. non-scalable components) support procurement strategies that explicitly address obsolescence risk. In OPS projects, several subsystems scale efficiently via parallelization (e.g., modular converter line-ups, some switchboard arrangements), whereas others often become replacement-driven at higher tiers due to thermal limits, fault-level constraints, or compliance requirements (e.g., certain cable cross-sections and routing constraints; transformer MVA limits and impedance choices; harmonic filter sizing and tuning; short-circuit withstand ratings). By making these breakpoints explicit, ports can specify which assets should be sized for the end-state (or at least for the next tier) and which assets should be treated as "replace-on-upgrade" with minimal stranded cost.

Third, the guidance supports credible business case development by linking technical choices to lifecycle cost drivers. For many mid-sized ports, the dominant OPEX exposure may not be energy volume (kWh) but peak power demand charges/tariffs and contracted capacity levels, particularly where OPS introduces short, high-power events. The inclusion of BESS integration pathways enables ports to evaluate whether a buffer strategy can reduce required subscribed capacity, smooth ramp rates, and mitigate tariff exposure, while simultaneously improving power quality performance during connection and load transients. Importantly, this does not require a universal recommendation to deploy storage; rather, it provides a decision logic: storage becomes most relevant where grid capacity is constrained, reinforcement lead times are long, or where tariff structures penalize short-duration peaks disproportionately.

6.2 Use by shipping companies: standardized requirement setting and fleet/port interoperability

For ship operators, the main value of the guidance lies in providing a common technical framework for setting requirements and reducing interface risk when operating across multiple ports.

A recurring challenge in OPS projects is that ship-side readiness and shore-side system design are often developed in parallel but without sufficient coordination. This frequently leads to mismatches in voltage and frequency compatibility, connection procedures, power-quality limits, and load-transfer sequencing. By basing the shore-side concepts on IEC/IEEE 80005 interoperability principles and by explicitly defining verification and acceptance criteria—such as limits for harmonics, ramp rates, and step-load response—the guidance enables shipping companies to formulate clearer, more consistent requirements towards ports and suppliers. In practice, this supports: (i) defining realistic ship acceptance envelopes that ports can design against, and (ii) reducing the need for port-specific adaptations when vessels operate across different terminals.

The tiered approach also supports fleet transition planning. Many operators will, for an extended period, operate mixed fleets that combine vessels with relatively low hotel loads, vessels with increasing levels of electrification, and vessels requiring high-power battery charging. The use of power tiers allows this diversity to be handled in a structured way. Instead of communicating fixed design points, operators can express expected development paths as parameter ranges, while ports can plan OPS systems with modular capacity and staged expansion that accommodates incremental growth and mixed simultaneous connections.

7 Conclusions

This pre-study examined how scalable, flexible, and economically robust OPS systems can be planned for mid-sized ports facing stricter regulations, increasing vessel electrification, and uncertain future power demand. The work combined a review of international standards with stakeholder input from both a shipping company and a port authority, and produced conceptual OPS solutions for low- (< 6 MW), medium- (6-16 MW), and high-power (> 16 MW) scenarios. Across these analyses, several overarching conclusions emerged.

A central finding is that successful OPS deployment depends primarily on system-level planning and scalability-oriented design, rather than on individual technical components. Early choices regarding grid-connection voltage, converter level, transformer sizing, spatial layout, and power-quality control largely determine whether future upgrades can be implemented without extensive reconstruction. Notable technical breakpoints include:

- the shift from 10 kV to 130 kV grid connections at around 20 MW,
- the transition from LV to MV converter platforms at approximately 12–13 MVA,
- a practical transformer-size limit of roughly 16 MVA.

These thresholds have direct implications for long-term expandability.

Scalability remains essential for accommodating rising power demand, parallel vessel calls, and the transition toward hybrid or fully electric vessels. The study shows that while some components can be modularized or expanded stepwise – such as converter or transformer blocks and BESS units – others, including certain cable sizes, switchgear short-circuit ratings, grid-voltage levels, and LV converter systems, may require full replacement once higher power levels are reached.

The findings further indicate that early design decisions strongly influence long-term operational flexibility, regulatory compliance, and power-quality performance. Grid-connection strategy, cable-duct arrangements, switchgear siting, and converter topology are especially consequential in multi-berth or high-power installations. In this context, modular OPS architectures offer several advantages, including improved partial-load efficiency, phased investment opportunities, and enhanced harmonic performance when applying coordinated phase-shift strategies.

Finally, the study confirms that BESS can play a selective but valuable role. When dimensioned according to realistic operational patterns and local grid limitations, a BESS can mitigate peak power demand, support system dynamics, alleviate grid constraints, and reduce exposure to power-based tariffs. Integrating the BESS at the DC stage of the converter system provides the greatest efficiency and flexibility, but its use should be justified by local conditions rather than applied universally. While compliance with IEC/IEEE 80005 and EMSA guidelines remains essential for safety and interoperability, current standards do not fully address scalability, multi-berth expansion, or component-level upgrade paths – gaps that this study helps clarify.

7.1 Recommendations and future work

Based on these findings, OPS development in mid-sized ports should adopt a tiered and future-oriented planning approach. Even when implementing low- or medium-power installations initially, civil works, spatial planning, and grid-connection arrangements should be established with higher future power levels in mind. For procurement, ports should prioritize verifiable technical performance – such as harmonic limits, transient behaviour, partial-load efficiency, and modular expandability – over prescribing fixed system configurations. Strong early coordination between ports, ship operators, and grid operators is also essential to align assumptions on voltage, frequency, power-quality envelopes, and operational sequencing and to reduce interface risks and redesign needs.

Future research and development should target several areas that remain insufficiently understood:

- Evolving power-based tariff structures and their implications for OPS economics and design.
- Long-term BESS degradation under OPS-specific duty-cycling patterns.
- Technical and economic breakpoints that govern component scalability and upgrade paths.
- The development and performance of multi-connection OPS systems.
- The emerging role of ports as energy nodes, linking vessels, energy storage, and industrial loads.

The study also identifies opportunities related to waste-heat recovery from transformers and converters. Port-side buildings, compared with containerized units, offer superior conditions for integrating heat-recovery technologies. Future work should examine how recovered heat can be used to support terminal heating or generate new value streams, thereby improving the overall energy-efficiency and economic viability of OPS investments.

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9 Annex

9.1 Annex A

When running an optimization model, input data should always be retrieved from the local DSO and/or other relevant parties to ensure that fees, costs, and parameters are correct. For this study, the BESS model is adopted from Xun, Tang [18] and values are estimates. The numerical example is shown below.

An example of electricity unit price is shown in Figure 14.

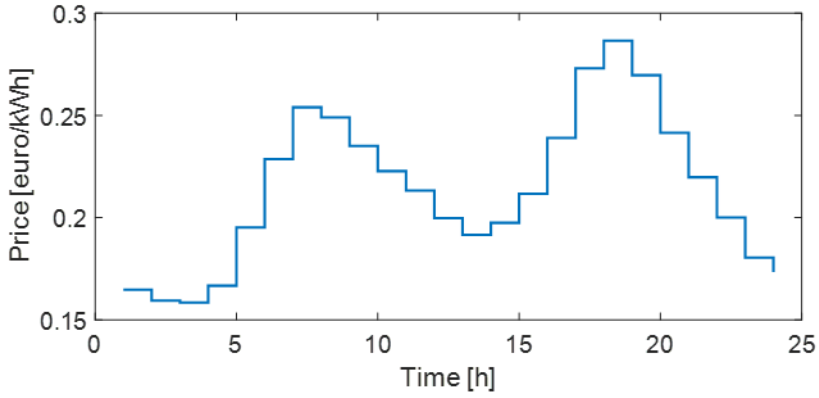

Figure 14 Electricity unit price [19]

The cost parameters used in this numerical example are as follows:

- fixed grid fee of 116.77 €/month;
- electricity distribution fee of 0.00558 €/kWh [20];
- peak power capacity/demand fee of 6.15 €/kW, calculated based on the highest hourly average power demand within the billing month;
- and battery unit price of 200 €/kWh [19].

The network tariff is assumed for a high-voltage connection at the 10kV-level (HSP 10 kV) for business customers in Gothenburg, Sweden [20]. All network fees are reported excluding VAT. Unless otherwise stated, energy tax is not considered in the economic assessment.

This was run in a MATLAB optimization model, and the results are shown in Table 8. Indicative modelling results suggest that integrating BESS can reduce total daily operating costs by approximately 5–7%, primarily through reductions in peak power demand charges.

Table 8 Optimization model results (run in MATLAB)

High		**Without BESS**	**With BESS**
	Grid peak [MW]	57	27.39
	BESS size [MWh]	0	90.02
	BESS cost [Euro/day]	0	6288.9
	Fixed fee [Euro/day]	3.84	3.84
	Distribution fee [Euro/day]	2123.94	2123.94
	Peak power capacity fee [Euro/day]	11518.37	5534.11
	Purchase cost [Euro/day]	76925.28	70676.28
	Total cost [Eur/day]	90571.43	84627.07
	Cost reduction [%]	/	6.56

Medium		**Without BESS**	**With BESS**
	Grid peak [MW]	20	11.89
	BESS size [MWh]	0	24.67
	BESS cost [Euro/day]	0	1723.5
	Fixed fee [Euro/day]	3.84	3.84
	Distribution fee [Euro/day]	824.28	824.28
	Peak power capacity fee [Euro/day]	4041.53	2401.75
	Purchase cost [Euro/day]	30275.12	28236.44
	Total cost [Eur/day]	35144.77	33189.81
	Cost reduction [%]	/	5.56

Low		**Without BESS**	**With BESS**
	Grid peak [MW]	8	4.88
	BESS size [MWh]	0	9.49
	BESS cost [Euro/day]	0	662.97
	Fixed fee [Euro/day]	3.84	3.84
	Distribution fee [Euro/day]	333.21	333.21
	Peak power capacity fee [Euro/day]	1616.61	985.96
	Purchase cost [Euro/day]	12254.59	11449.4
	Total cost [Euro/day]	14208.25	13435.38
	Cost reduction [%]	/	5.44