Robert Kjötar

Evaluating Shore Power for Merchant Vessels: Economic Viability and Compliance with IEC/IEEE 80005 Standards

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Author: Robert Kjötar
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ABSTRACT:

The marine industry is increasingly transitioning toward energy-efficient technologies to reduce both greenhouse gas emissions and operational costs. A key enabler of this shift is shore connection-based cold ironing, where vessels connect to the harbor's electrical grid while docked, thereby reducing the use of onboard auxiliary generators that produce harmful emissions. Shore connection is also essential for charging a ship's batteries while it is docked. Although onboard fuel-based generation has traditionally been more cost-effective, tightening fuel regulations and recent EU policies have introduced emission-based taxation and incentives that are accelerating the adoption of shore connection systems.

This thesis, conducted in collaboration with WE Tech Solutions, explores the implementation of shore power systems in accordance with the IEC/IEEE 80005 standard series. A mixed-method approach is applied, combining quantitative economic analysis and qualitative technical assessment. A case study on a vessel operating primarily in EU ports quantifies potential cost savings from shore power utilization. Additionally, a technical review of an early WE Tech low-voltage shore connection delivery evaluates its compliance with emerging international standards and identifies areas for design improvement.

Based on these findings, an internal selector tool was developed to support early project stages by evaluating technical requirements. A comparison of current and future cost savings between onboard power generation and shore connection has been presented, focusing on Finland, Belgium, the Netherlands, and France. The findings show that shore connection systems can provide clear economic benefits, particularly for vessels operating within the European Union. In line with EU Regulation 2023/1805, the use of shore power will become mandatory by 2030 for specific ship categories mentioned. Additional vessel categories may follow under future regulation. The results of this thesis provide both technical guidance and economic rationale for integrating shore power systems into newbuild and retrofit projects.

KEYWORDS: Merchant shipping, shore connection, standardization, cost saving, emission reduction

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ABSTRAKT:

Den marina industrin genomgår i allt större utsträckning en omställning mot energieffektiva teknologier för att minska både växthusgasutsläpp och driftkostnader. En central möjliggörare i denna övergång är landström, där fartyg ansluts till hamnens elnät när de ligger vid kaj. Detta minskar behovet av att använda fartygens hjälpgeneratorer, vilka genererar skadliga utsläpp. Landström är även avgörande för att kunna ladda ombord installerade batterier. Trots att bränsledrivna generatorer traditionellt har varit mer kostnadseffektiva, har skärpta bränsleregler och nya EU-policyer infört utsläppsbaserade skatter och incitament som driver på utvecklingen och användningen av landströmsystem.

Denna avhandling, som genomförts i samarbete med WE Tech Solutions, undersöker implementeringen av landströmsystem i enlighet med standardserien IEC/IEEE 80005. En blandad metodansats har tillämpats, där kvantitativ ekonomisk analys kombineras med kvalitativ teknisk utvärdering. En fallstudie av ett fartyg som huvudsakligen trafikerar hamnar inom EU kvantifierar potentiella kostnadsbesparingar vid användning av landström. Därtill genomförs en teknisk granskning av en tidigare leverans av ett lågspänningslandströmsystem från WE Tech, i syfte att utvärdera dess överensstämmelse med framväxande internationella standarder samt identifiera möjliga förbättringsområden i designen.

Utifrån dessa resultat har ett internt urvalsverktyg utvecklats för att stödja de inledande faserna i projektgenomförandet genom att analysera tekniska krav. En jämförelse mellan nuvarande och framtida kostnadsbesparingar vid användning av landström kontra ombord generering har presenterats, med fokus på Finland, Belgien, Nederländerna och Frankrike. Resultaten visar att landströmsystem kan erbjuda tydliga ekonomiska fördelar, särskilt för fartyg som opererar inom Europeiska unionen. I enlighet med EU-förordning 2023/1805 kommer användningen av landström att bli obligatorisk senast år 2030 för vissa angivna fartygskategorier. Ytterligare fartygstyper kan komma att inkluderas i framtida regleringar. Avhandlingens resultat ger därmed både tekniskt stöd och ekonomisk motivering för att integrera landströmsystem i nybyggnads- och ombyggnadsprojekt.

NYCKELORD: Handelsfartyg, landström, standardisering, kostnadsbesparing, utsläppsminskning

Preface

The completion of this thesis marks a milestone in my electrical engineering career, which has been ongoing since I began my studies at Novia University of Applied Sciences in 2019. I would like to thank all the teachers, colleagues, and fellow students during this time for their collaboration and support.

During my thesis work, Dr. Mustafa Alrayah Hassan Ibraheem from the University of Vaasa was appointed as my academic supervisor, and Olli Herlevi served as my instructor at WE Tech Solutions. I wish to express my utmost gratitude to both for their helpful insights, valuable discussions, and constructive critique.

I also want to thank WE Tech Solutions for the opportunity to conduct my master's thesis in collaboration with their organization, as well as all those who generously shared their time and provided me with valuable support. Being part of a forward-thinking and innovative environment such as WE Tech has been both a privilege and an enriching learning experience.

This journey has not only deepened my academic knowledge and professional skills, but also contributed significantly to my personal growth. The challenges, responsibilities, and experiences throughout this process have shaped me into a more confident, resilient, and goal-oriented individual.

Finally, I am immensely grateful to my family, friends, girlfriend and all those who supported me throughout this journey. Thank you all for your contributions to this important milestone in my academic and professional life.

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Abbreviations

CH_4 = Methane
CO_2 = Carbon dioxide
DWT = Deadweight tonnage
Genset = Engine and generator combination
HFO = Heavy fuel oil
LSMGO = Low sulfur marine gas oil
MGO = Marine gas oil
MW = Megawatt
N_2O = Nitrous oxide

NOx = Collective term of nitrogen oxides NO and NO_2
SFOC = Specification fuel oil consumption
SO_2 = Sulfur dioxide
TEN-T = Trans-European Transport Network
ULSFO = Ultra-low sulfur fuel oil
VLSFO = Very low sulfur fuel oil

1 Introduction

Marine shipping accounts for over 80% of the world's trade volumes (UN trade & development, 2019). According to the IEA (2023), shipping is responsible for about 2% of global emissions. The International Maritime Organization (IMO) has introduced requirements for emission reductions in the maritime industry, aiming to support the temperature goals set under Article 2 of the Paris Agreement. Several milestones have been set for the coming decades, with the ultimate objective of achieving carbon neutrality around the year 2050. This transition requires shipowners to gradually adapt to new energy efficient technologies.

Article 10 of Directive 2023/1804 EU specifies targets for its member states to have at least one installation capable of supplying electricity to the ship at shore, also referred to as cold ironing, by 31 December 2024 for TEN-T core inland waterway ports and TEN-T comprehensive inland waterway ports by 31 December 2029 (EU, 2023a). Furthermore, EU regulations mandate that, from 1 January 2030, container ships and passenger vessels over 5,000 GT must use shore power or alternative zero-emission technologies while berthed in ports covered under Article 9 of the Alternative Fuels Infrastructure Regulation. By January 1 January 2035, this requirement will extend to all EU ports equipped with shore power infrastructure, regardless of port size or vessel traffic (EU, 2023b). Currently, EU directives do not explicitly mandate shore-side electricity requirements for LNG carriers, LPG carriers, or tankers. In parallel, major ports like Rotterdam are proactively encouraging most sea-going vessels to connect to shore power while at berth, highlighting how local initiatives can accelerate infrastructure development (Port of Rotterdam, n.d.).

In addition to international standards, classification societies such as DNV impose technical standards for shore connection installations, often referencing IEC rules (DNV, 2024). This thesis, commissioned by WE Tech Solutions, focuses on the standardization of shore connection concepts in the maritime sector. The objective is to identify current developments in the utilization of shore connections, evaluate their benefits, and specify technical requirements for a standardized WE Tech shore solution in terms of components and compliance with both current and emerging standards.

1.1 Problem Statement

The common practice of running auxiliary generator sets while at port consumes fossil fuel and generates harmful emissions. Ships emit substantially more sulfur oxides than, for example, diesel engines commonly used in road transport. This is because merchant vessels usually rely on heavy fuel oils for combustion (Innes & Monios, 2018). In a study of ship emissions in the port city of Samsun, Turkey, during 2010–2015 concluded that ships were responsible for 12% of the NOx emissions and 5% of the SO2 emissions (Alver et al., 2018). One way to reduce the emissions at berth is by using shore power connections, which allow ships to consume electricity from the local grid instead of running onboard generators. In line with evolving EU regulations, the installation of shore connection systems will become mandatory for certain categories of ships, enabling both cold ironing and battery charging. To this end, ship owners should benefit from cost savings by using power shore connections, considering the lower cost of electricity and the reduced emissions-related expenses, compared to running onboard auxiliary generators while docked.

WE Tech Solutions recognizes the need to define and standardize the shore connection solutions provided, ensuring compliance with current maritime classification societies and IEC standards. Therefore, the primary problem addressed in this research is the need to evaluate the international standards, such as IEC/IEEE 80005. This thesis is intended to technically define the requirements in the shore connection product provided by WE Tech.

1.2 Research Purpose

By studying the positive effects of shore connection utilization, such as cost savings and emission reductions, this research aims to accelerate the adoption of greener maritime solutions. Additionally, by assisting WE Tech Solutions in developing a standardized solution, this work aim to increase shore connection utilization and ensure that the WE Tech solution offering is aligned with international standards. Specifically, this research will:

- Identify current shore connection capabilities and ongoing developments.
- Estimate shore connection cost savings compared to onboard generation.
- Define a standard solution concept that aligns with relevant standards, ensuring compliance for both systems below 1 MVA and equal to or exceeding 1 MVA.
- Ensure the proposed standard supports future scalability, addressing the needs of various ship types and harbor conditions.

1.3 Scope and Limitations

This thesis examines shore connection installations for seagoing merchant vessels, as these represent the majority of WE Tech’s project deliveries. Passenger vessels and smaller vessels, such as ferries and inland ships, are not the focus of this study. In addition, the thesis does not extensively address shore-side infrastructure, as the primary focus is on onboard equipment and its interface with harbor systems. However, limited basic information, such as typical voltage levels in the shore infrastructure, is provided to support the discussion. Additionally, the thesis does not cover the interoperability of onboard energy storage systems combined with shore connection utilization.

1.4 Research Methodology

This study adopts a mixed-method approach, incorporating both qualitative and quantitative research strategies to provide a comprehensive analysis of shore connection systems. This includes a theoretical exploration of shore connection concepts by analyzing existing research, industry standards, and the development of green corridors. It also involves an examination of international standards, such as IEC/IEEE 80005-1 and -3, to ensure compliance with both operational and dimensional requirements.

In addition to theoretical exploration, an applied case study approach is used. The research also consists of a case study where shore connection capability has been implemented. The technical data of a selected vessel is analyzed, and a comparison calculation is conducted to determine the actual cost savings achieved utilizing shore connection compared to auxiliary generators. Based on the results, savings are forecasted for the future, specifically for the year 2030.

1.5 Thesis Structure

This thesis consists of seven main chapters, each building upon the previous to develop an understanding of the importance of having standard-compliant solutions in shore power applications. Chapter 1 introduces the topic by presenting the background, problem statement, research purpose, scope and limitations, and the methodologies applied in the study. Chapter 2 reviews literature covering technologies related to shore connection systems and developments. Chapter 3 presents a case study of economic savings related to shore connection utilization. Chapter 4 reviews various incentives provided to harbors and vessels for effective shore connection implementation. Chapter 5 examines the applicable international standards, the IEC/IEEE 80005 series, and their requirements related to low- and high-voltage shore connection systems. Chapter 6 presents an existing shore connection solution and evaluates its compliance with applicable standards. Furthermore, sizing and component selection are discussed, and an internal calculation tool is developed. Chapter 7 discusses current and future shore connection developments based on the author’s own analysis and the material from the previous chapters. Chapter 7 also concludes the thesis by summarizing the key insights and outlining areas for further research to support continued advancement in shore power integration.

2 Literature Review

The purpose of this chapter is to provide a background on the technologies, initiatives, and developments that are shaping the implementation of shore power solutions in the maritime sector. Chapter 2 begins by examining onboard energy-saving technologies, particularly those developed by WE Tech. It continues by exploring the general concept of shore connection, its technical evolution, and the efforts made in ports to support its use. Furthermore, a case study is presented to evaluate the economic feasibility of shore power compared to traditional onboard generation, providing practical insight into the costs and benefits for shipowners. The chapter concludes by exploring the concept of green corridors, showcasing how designated low-emission shipping routes are being developed to drive the transition toward more sustainable maritime transport.

2.1 WE Tech Energy Saving Solutions

One of the main energy-saving solutions delivered by WE Tech is the permanent magnet shaft generator system. The generator is mounted on the propulsion shaft and rotated by the main engine, supplying power to the WE Drive (DC-switchboard). The permanent magnet generator is suitable for two-stroke slow-speed applications while maintaining high efficiency. It is star-connected through the WE Tech Star Point Breaker Cabinet, while the other end of the windings connects to the AC/DC converter(s) supplying the WE Drive. The WE Drive can be used to supply power to the ship's main switchboard, reducing or eliminating the need for continuous operation of the auxiliary generators. This leads to reductions in emissions, fuel consumption, and equipment wear. The auxiliary generators can instead be reserved for backup use, such as during peak electrical loads. Additionally, the WE Drive can supply heavy consumers, for example bow thrusters, fans, pumps etc. with the advantage of frequency control, achieved through DC/AC converters. Both the shore connection and the shaft generator supplies are usually connected in parallel to the same AC/DC converter as they will not be utilized simultaneously. To ensure only one source is applied at a time, an interlock prevents simultaneous closing of shore connection and shaft generator circuit breakers.

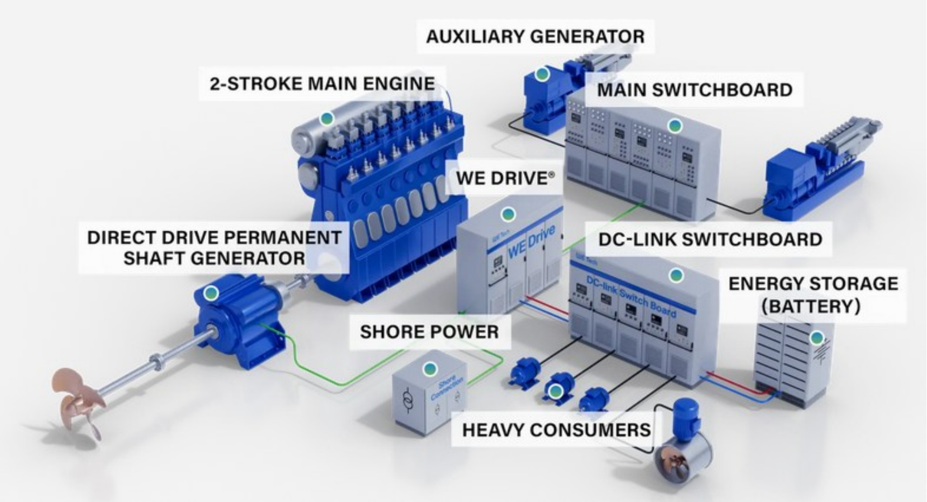


Figure 1 WE Tech Solution Four. (WE Tech Solutions, n.d.)

As mentioned in Chapter 1, vessel types such as LNG carriers are not yet covered by EU directives related to shore connection capabilities. However, WE Tech Solutions has observed that some newbuild vessels of these types are already preparing, such as installing an extra empty switchgear cubicle with prepared busbars, to allow for potential retrofitting of shore connection solutions in the future.

2.2 Electrical Distribution on Ship and Shoreside

According to IEEE (2023), electrical power system architectures on ships vary depending on the vessel type. Radial architecture is commonly used in merchant vessels or ships with less demanding electrical networks. In contrast, zonal architectures are typically employed in naval warships and ships with more complex systems where interruptions can have serious consequences and are therefore intolerable. In radial architecture, the vessel’s electrical system is based around a central main switchboard, which is typically divided into at least two parts. This division allows for network isolation in the event of a failure on one side. Power generation and electrical loads are distributed equally across both sides of the bus.

For safety and redundancy, a separate emergency power bus is required to supply critical loads in the event of a failure in the main switchboard's power supply. The emergency switchboard and its power source, either an electrical generator set or an energy storage system, should for safety and accessibility reasons, be located on the highest possible deck that is continuous and free of obstacles. (IEEE, 2023)

The electrical system on a vessel may involve multiple voltage levels, using either AC, DC, or a hybrid system, depending on the ship's power requirements. The appropriate voltage levels are determined on a case-by-case basis. As ships typically operate in different harbors with varying electrical grid standards, the IEEE (2023) recommends selecting the vessel's electrical network frequency based on the harbors in which it will operate, ensuring compatibility with shore connections without additional equipment.

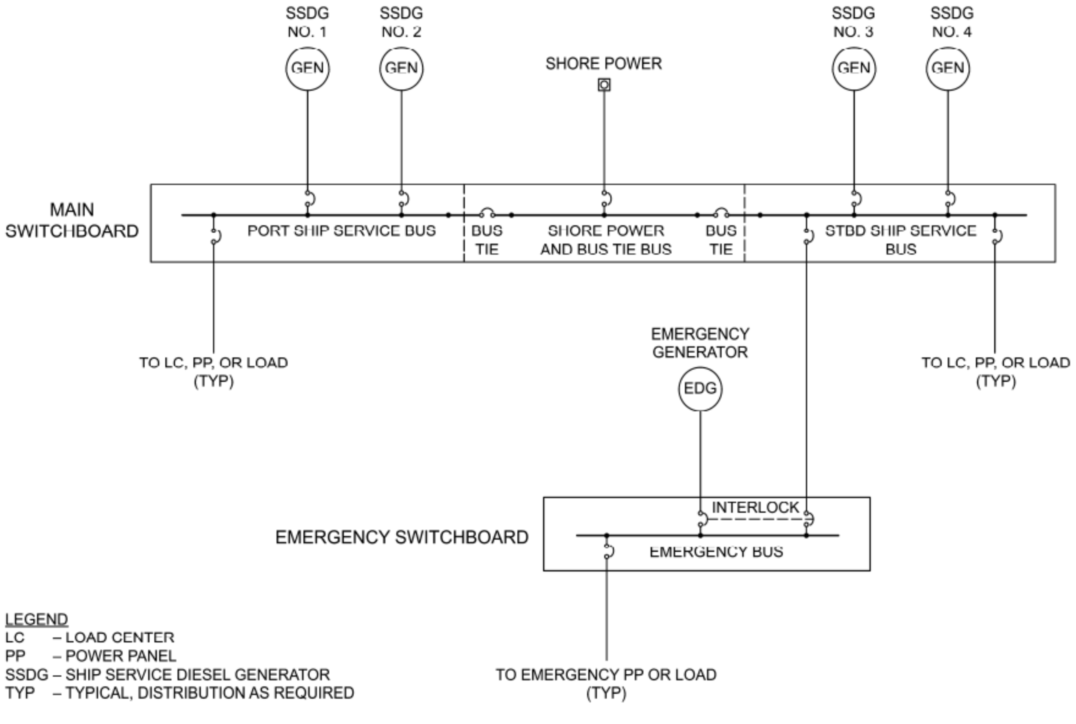


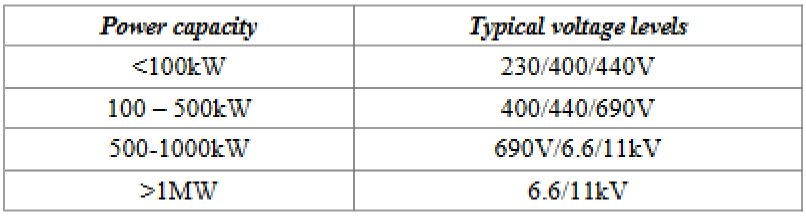
Figure 2 Radial power system for a commercial marine ship. (IEEE, 2023)

It is important to note that while these recommendations by IEEE (2023) provide general guidelines, the specific rules and requirements of the marine classification society that classifies the ship must be adhered to.

2.3 Shore Connection Concept

Through the collaboration of IEC, ISO, and IEEE, international standards have been developed to align shore-side and shipboard electrical installations. The shore connection concept enables ships to connect to the land-based utility grid while at berth, supplying onboard systems with power without the need for auxiliary generators. This is achieved by connecting cables from the port's electrical infrastructure to the ship's electrical distribution system. A key challenge in implementing shore power systems is the global variability of power network configurations. Ships also tend to have different distribution voltage levels onboard depending on the needed power capacity, as displayed in Table 1.

Table 1 Typical distribution voltage levels on ships. (Vrzala et al., 2022)



Power capacity	*Typical voltage levels*
<100kW	230/400/440V
100 – 500kW	400/440/690V
500-1000kW	690V/6.6/11kV
>1MW	6.6/11kV

Since ships may travel between ports with significantly different shore-side electrical characteristics, compatibility becomes a clear issue. To successfully use shore power, the voltage and frequency must be matched between the port supply and the ship's electrical system. This mismatch can be resolved using transformers and frequency converters (Vrzala et al., 2022). Figure 2 illustrates a DC microgrid setup, which enables connection to both 50 Hz and 60 Hz shore networks using frequency converters.

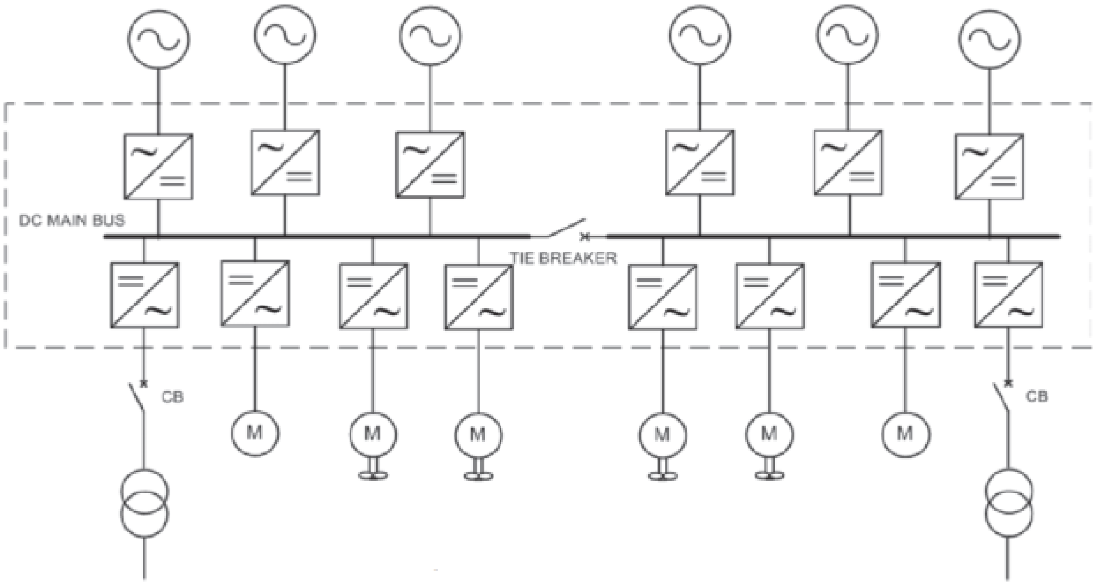


Figure 3 DC main switchboard. (Prenc et al., 2016)

The goal of equipping major EU ports with shore connection capability is progressing. As presented in Figure 3, it can be noted that currently 35% of TEN-T European core ports are equipped with shore connection possibility totaling 407 berths. 6% of TEN-T European comprehensive ports are equipped with shore connection possibility (European Environment Agency, 2024). A detailed list of the ports shown in Figure 3, including information on their shore connection services, is available on the European Alternative Fuels Observatory website (European Alternative Fuels Observatory, 2024).

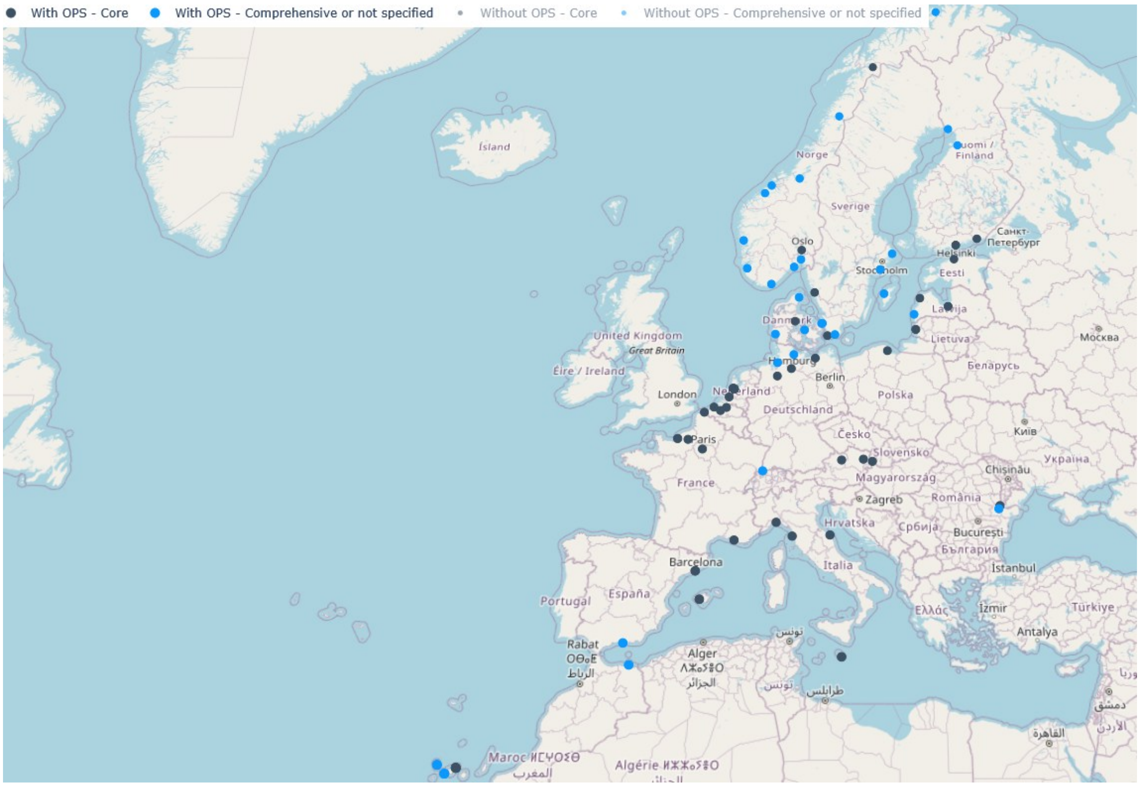


Figure 4 TEN-T Ports providing shore connection services. (European Environment Agency, 2024)

It shall be noted that emissions can be reduced if the shore power supply is primarily sourced from renewable energy. However, as noted by Prevljak, (2024), some European ports still rely on fossil-fuel-based power generation, which only shifts the emissions rather than eliminating them.

2.4 Shore Connection Development in Finland

Finland has seen continued development of shore power infrastructure and the establishment of green corridors to other ports. The Port of Rauma currently provides nine 6.3 kV, 50 Hz shore connection points distributed across four berths. Each connection has the possibility to provide a maximum power output of 1.25 MVA. The power socket is of Cavotec PC6 type, and the installations are compliant with the IEC/IEEE 80005-1 standard. (Port of Rauma, n.d.)

With financial support from the European Union, ports around Helsinki have also made progress. Shore power installations were completed at South Harbor (Helsinki) in the summer of 2021. At the time of construction, it was recognized that international standards for shore power systems were still under development, and all available connections might not align entirely with current standards (Port of Helsinki, 2021). Vuosaari Harbor (Helsinki) commissioned its first shore power system in late 2023. More recently, in June 2024, the Port of Travemünde completed a similar installation. As a result, Finnlines Ro-Ro/cargo vessels M/S Finnmaid, Finnstar, and Finnlady can now utilize shore power connections at both ends of their sailing routes (Port of Helsinki, 2024).

Figure 5 M/S Finnmaid is attached to the onshore power supply system in Quay C at Vuosaari Harbour. (Port of Helsinki, 2024)

2.5 Green Corridor Concept

Green corridor shipping is an approach within the maritime industry that focuses on establishing specific trade routes dedicated to zero-emission operations. This initiative relies on cooperation between public and private sector stakeholders. These corridors utilize strategically selected routes often near sustainable fuel sources and shore connection possibilities. By concentrating on selected routes, green corridors offer a practical path for advancing zero-emission practices and accelerating the industry’s broader decarbonization objectives (Getting to Zero Coalition, 2021).

Green corridors promote progress toward zero-emission goals by bringing together key stakeholders in the shipping sector, including fuel producers, vessel operators, cargo owners, and regulatory authorities. These initiatives aim to stimulate investment in zero-emission fuel production and harbor infrastructure while fostering business and policy frameworks that support sustainable shipping practices. Some green corridor projects have moved beyond the conceptual stage into planning and early implementation phases, with defined targets and fuel strategies. However, significant challenges remain, particularly in fuel supply chain development, economic viability, and the need for robust policy support. Overcoming these barriers is essential for green corridors to become effective models for zero-emission maritime operations and to support the establishment of a sustainable global shipping network. (Global Maritime Forum, 2023)

While net-zero emission fuels represent a key step forward, some projects are already advancing fully electric short-distance maritime transportation. One example is the DFDS Group that has announced a 1 billion € investment to build fully electric ferries operating on the Dunkirk–Dover and Calais–Dover routes. These ferries are designed to transport both passengers and cargo, with expected launches between 2030 and 2035. Both the French and United Kingdom governments are expected to collaborate with DFDS to develop appropriate shore charging infrastructure. (DFDS, 2024)

The Gothenburg North Sea Corridor, established in 2022, links the North Sea Port, Rotterdam in the Netherlands, and Gothenburg in Sweden, with potential for additional participating ports. This totals in approximately 2,500 km between Belgian and Swedish ports, the corridor demonstrates the viability of long-distance, near-zero emission shipping. DFDS plans to deploy two ammonia-fueled Ro-Ro vessels along this route, with supporting port and inland transport operations largely electrified, including the use of electric trucks. There is also a significant focus on expanding renewable electricity generation for shore connection needs. (North Sea Port, 2024)

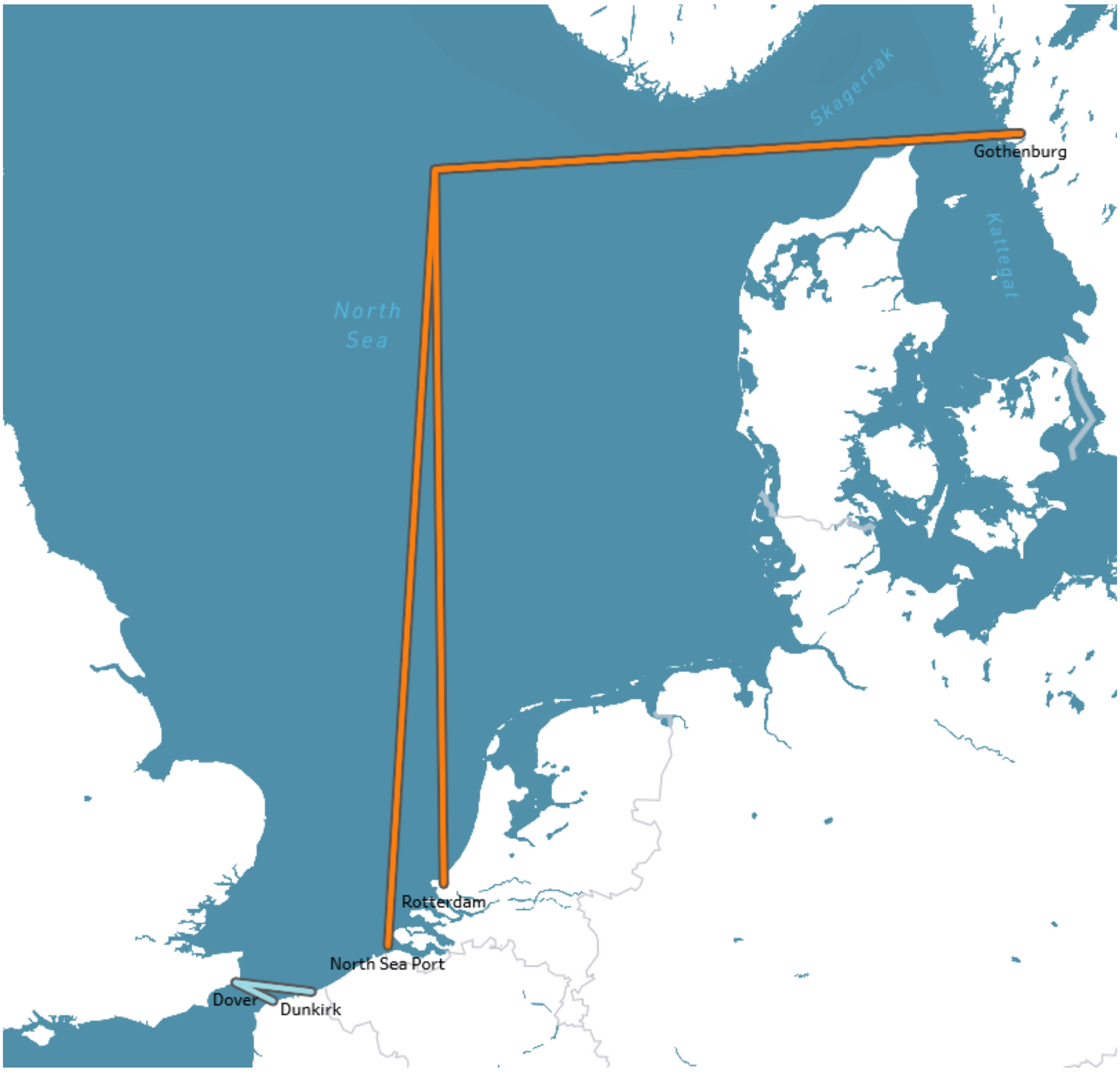


Figure 6 Green Corridor Routes. (IMO, 2024)

In the context of a green corridor initiative between the Port of Helsinki and the Port of Tallinn, three shipping companies are collaborating to reduce emissions, despite typically being competitors. This joint effort underscores the importance of industry cooperation in advancing sustainable maritime solutions (Ahlskog, 2024).

3 Economic Case Study

A case study on the Port of Busan by Jeong & Kim (2022) revealed that while shore connection significantly reduces emissions, it can sometimes be more expensive than onboard power generation, depending on fluctuations in fuel and electricity prices. Despite these fluctuations, compliance with emission regulations is becoming a key concern for shipowners. This chapter analyzes the economic viability of shore connection compared to onboard auxiliary generator use. A case analysis is conducted on a merchant vessel equipped with shore connection capability. In this scenario, it is assumed that the vessel connects to the planned shore power infrastructure at the Port of Le Havre, France. Installation work is currently ongoing, and three shore connections, each with a peak capacity of 13 MVA, are expected to be operational by 2025 (Mandra, 2024). In addition to Le Havre, the case vessel is also expected to make port calls at the Port of Rotterdam (Netherlands) and the Port of Antwerp (Belgium). To have a comparison country located in Northern Europe, Finland is included. Therefore, electricity prices in four countries are considered, France, the Netherlands, Belgium, and Finland.

Since the implementation of the IMO 2020 regulations, the allowable sulfur content in marine fuels was reduced from 3.5% to 0.5% to mitigate sulfur oxide emissions. In response, many vessels without scrubbers changed from HFO to low-sulfur alternatives such as VLSFO. This transition reduced the total sulfur oxide emissions in shipping by about 70% (IMO, 2021). Moreover, within EU ports, the sulfur content limit is even stricter at berth, capped at 0.1% by mass (European Union, 2016). Compliant fuels for use at berth in EU ports include for example LSMGO and ULSFO.

The price of shore connection equipment is excluded from this analysis. Implementing shore power systems do not eliminate the need for auxiliary generators, which remain necessary for backup power. The comparison focuses solely on fuel and electricity costs while providing electricity to the ship at berth.

3.1.1 GAMS

GAMS is used to calculate the economic difference between running auxiliary gensets and utilizing shore connection at the ports in the case study. GAMS stands for General Algebraic Modeling System. It is a high-level programming language and closed-source software system intended for modeling and solving mathematical optimization problems. GAMS is widely used in fields such as economics, engineering and operations research for decision support and optimization applications (GAMS, 2024). GAMS is employed in this case study to establish a scalable and futureproof modeling environment for potential extensions involving optimization.

3.1.2 Vessel Data

The vessel analyzed in this study is a 22.554 DWT chemical tanker operating primarily in European waters. Its main electrical system runs on 450 VAC at 60 Hz and is equipped with shore connection possibility provided by WE Tech. The vessel is equipped with two Wärtsilä 8L20 auxiliary diesel gensets operating on MDO fuel. Each genset have an output capacity of 1,420 kWe, providing a combined total of 2,840 kWe (Wärtsilä, n.d.). According to a shipowner interview, the vessel's electrical load during berthing including hotel load, pumps, fans, and other systems typically ranges from 1,200 to 1,500 kW under normal conditions (*Conversation with Shipowner*, 2025). For the economic calculations presented in the following sections, an average power demand of 1,350 kW is assumed. While port stay duration can vary due to multiple factors, data from UNCTAD (2019), indicates that liquid bulk carriers stayed an average of 22.5 hours in port in 2018, based on a study of the top 25 global ports by traffic and segment. The upcoming economic assessment assumes a 24-hour stay.

3.1.3 EU’s Emissions Trading System

Since 2024, large ships (5,000 gross tonnage or above) that begin or end a voyage in an EU member state, including time spent at berth, are required to purchase and use emission allowances under the EU Emissions Trading System (ETS), a cap-and-trade mechanism. Voyages that start or end outside the EU are subject to 50% coverage of the total emission contribution, whereas voyages between two EU ports are fully covered. The emissions currently regulated under the EU ETS include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), although CH_4 and N_2O will only be included from 2026 onward. Shipowners are obligated to report emissions, and starting in 2025, they will be required to surrender allowances covering 40% of their verified 2024 emissions. This coverage increases to 70% in 2026 (for 2025 emissions) and reaches full compliance at 100% in 2027 (for 2026 emissions and beyond). (European Commission, n.d.)

The price of carbon allowances has risen significantly in recent years. In 2017, the average price per ton of CO_2 was 5 €. By 2020, it had increased to 25 €, and in 2023, it peaked at 83 € (EEA, 2024). The most recent pricing data from 2023 (83 €) will be used in the economic calculations of this study. The indicated price follows the ETS market and is fixed across EU regions. Previously, implementing fuel-saving technologies offered shipowners direct economic benefits through lower fuel costs. With the EU ETS, such improvements now also offer indirect economic benefits by reducing the need to surrender emission allowances.

3.1.4 Onboard Auxiliary Engine Generation Cost

The vessel is equipped with selective catalytic reduction and rely mostly on MGO for running the auxiliary engines. During the first half of 2024, the average MGO price at the Port of Rotterdam was 751 € per metric ton (Ship & Bunker, 2025). Port of Rotterdam is specifically selected due to pricing data availability and the fact that the case vessel frequently make port calls in this harbor. The SFOC of the Wärtsilä 8L20 engine, according to the ISO 15550:2016 standard, is 193.4 g/kWh (mechanical output) at 100% load. The genset has a maximum electrical capacity of 1,420 kWe, and to achieve the vessel harbor load of 1,350 kWe, operating a single genset at approximately 95% load is sufficient. According to the Wärtsilä engine configurator, the SFOC is 193.4 g/kWh at 100% load and 192.8 g/kWh at 85% load. Since the value at 95% load is not explicitly stated, it is estimated to be approximately 193.1 g/kWh (mechanical). Converting from mechanical to electrical power, the 8L20 genset have a generator efficiency of 0.96. The corresponding SFOC for electrical output is then 201,1 g/kWh. The vessel is also equipped with a 500 kWh battery pack designed to assist with peak-shaving. However, in the event of a battery being out of service or in a low state of charge, an additional genset would need to be started if the onboard electrical demand exceeds 1,420 kW. This is considered an exceptional scenario, and for the purpose of the following calculations, it is assumed that only one genset remains in operation during the entire berth stay. The total fuel cost during berth stay is calculated using Equation (1).

$$Cost\_gen = Th * Lh * SFOC * (F\_price/1000) \tag{1}$$

Where;

- Th = Time in harbor (hours)
- Lh = Electrical load during harbor stay (kW)
- $SFOC$ = Specific fuel oil consumption (g/kWh)
- F_price = Fuel oil price (€ per metric ton)
- Divided by 1000 to get fuel price per kilogram

The emission factor for MGO is 3.206 kg CO_2 per kg of fuel (Stolz et al., 2021). Since the vessel in this case study operates between EU ports, its emissions are subject to the full extent of the EU ETS without any deductions. The total cost of CO_2 allowance is calculated according to Equations (2), (3) and (4).

$$EM_{kw} = SFOC * Ef \tag{2}$$

$$Emission\_tot = E = Th * Lh * Em\_kw \tag{3}$$

$$Emission\_cost = E = Emission\_tot * Allowance / 1000 \tag{4}$$

Where;

- Em_{kw} = CO_2 emitted per kW generated (kg)
- $Emissions\_tot$ = Total CO_2 emitted during 24h port stay (kg)

- Allowance = 83 € per CO_2 metric ton (according to 2023 rates)

As described in Chapter 3.1.3, shipowners must gradually increase the share of their emissions for which allowances are purchased: 40% for emissions in 2024, 70% in 2025, and 100% in 2026 and beyond. These are expressed in Equations (5) through (7):

$$Emission\_2024 = E = Emission\_cost * 0.4 \tag{5}$$

$$Emission\_2025 = E = Emission\_cost * 0.7 \tag{6}$$

$$Emission\_2026 = E = Emission\_cost \tag{7}$$

Finally, the total cost can be calculated based on the applicable annual allowance rate, as shown in Equations (8), (9), and (10).

$$TotalCost\_2024 = E = Emission\_2024 + Cost\_gen \tag{8}$$

$$TotalCost\_2025 = E = Emission\_2025 + Cost\_gen \tag{9}$$

$$TotalCost\_2026 = E = Emission\_2026 + Cost\_gen \tag{10}$$

Based on these calculations, the total cost for one 24-hour port stay would have been approximately 5,487 € in 2024, 5,998 € in 2025, and 6,508 € in 2026.

3.1.5 Shore Connection Supply Cost

In a study by Costa et al. (2022), interviews were conducted with various Swedish ports, and it was commonly understood that they do not aim to profit from shore power use or even recover the investment in infrastructure. Instead, they aim only to cover the connection work and maintenance costs. The expected additional cost will not be considered as there is not sufficient data available. According to Eurostat (2024), electricity prices for non-household consumers with annual consumption between 500 MWh and 2,000 MWh in the first half of 2024 were as follows: France 0.1711 €/kWh, Belgium 0.1780 €/kWh, the Netherlands 0.1986 €/kWh, and Finland 0.0928 €/kWh (excluding VAT). The shore power cost for each country, based on these electricity prices, is calculated using Equations (11) through (14). It should be noted that due to the volatility of electricity prices, the static values from the first half of 2024 are used for the 2025 and 2026 cases as well. However, greater savings from using shore connection are observed in later years due to the increasing percentage requirements for CO_2 allowance payments, even though the CO_2 price is held constant at the 2023 level. Thus, while these projections incorporate real 2024 electricity prices, they reflect an approximation with allowance cost adjustments.

$$Cost\_sh\_fr\ = E = Th * Lh * E\_price\_fr \tag{11}$$

$$Cost\_sh\_nl\ = E = Th * Lh * E\_price\_nl \tag{12}$$

$$Cost\_sh\_be\ = E = Th * Lh * E\_price\_be \tag{13}$$

$$Cost\_sh\_fi\ = E = Th * Lh * E\_price\_fi \tag{14}$$

Where;

- E_price_fr = Average kWh price of France first half of year 2024
- E_price_nl = Average kWh price of the Netherlands first half of year 2024
- E_price_be = Average kWh price of Belgium first half of year 2024
- E_price_fi = Average kWh price of Finland first half of year 2024

The estimated electricity cost for a 24-hour port stay would amount to 3,007 € in Finland, 5,544 € in France, 5,767 € in Belgium, and 6,435 € in the Netherlands.

3.1.6 Conclusion

Comparing the costs of onboard power generation from the auxiliary generator opposed to shore power usage during docking is done with the same three sets of equations for each country.

$$Savings\_FI\_2024\ = E = TotalCost\_2024 - Cost\_sh\_fi \tag{15}$$

$$Savings\_FI\_2025\ = E = TotalCost\_2025 - Cost\_sh\_fi \tag{16}$$

$$Savings\_FI\_2026\ = E = TotalCost\_2026 - Cost\_sh\_fi \tag{17}$$

The positive side of the y-axis in Figure 5 represents cost savings, while the negative side indicates losses.

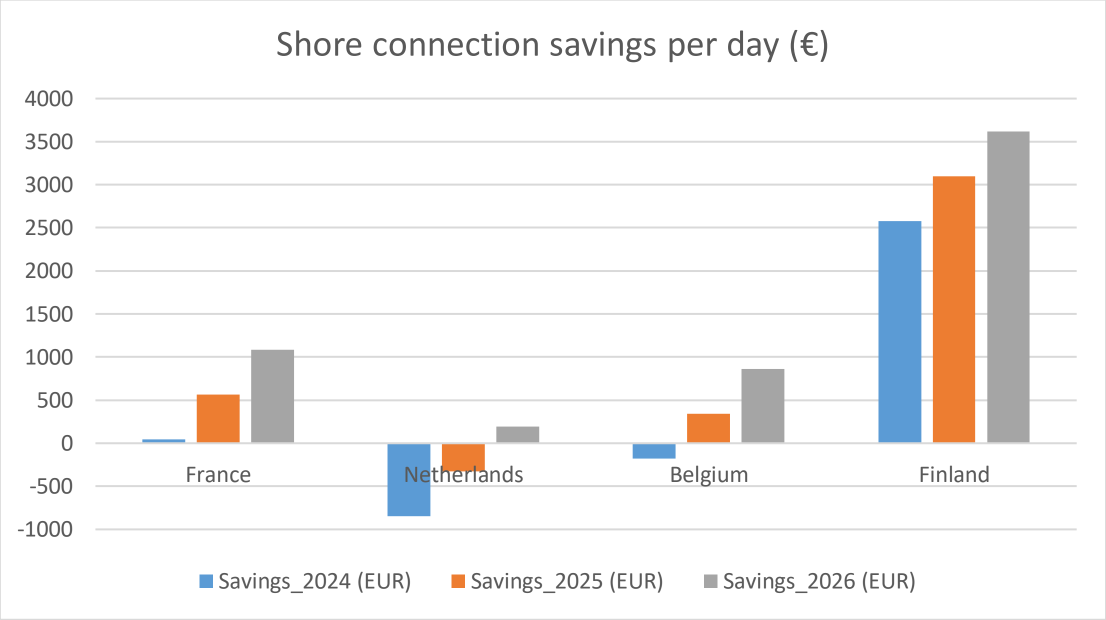


Figure 7 Projected shore connection savings per day 2024–2026.

As previously mentioned, France, Netherlands and Belgium are countries where the case study vessel typically operate. The study used an average electricity price of the first half of 2024, not differentiating between weekdays, weekends, day or night market prices. Years 2025 and 2026 use the same fixed average electricity price from 2024, however, CO_2 allowance responsibility increase is considered.

Finland is the only country where, during 2024, shore power is significantly more economically advantageous than onboard power generation. This is the result of an average low electricity price. From 2026 onwards, however, it becomes more cost-effective in all evaluated countries to utilize shore connection, largely due to the increasing CO_2 allowance requirements imposed by the EU ETS.

The allowance rate is projected to continue rising in the coming decade (BloombergNEF, 2024). Analysts anticipate that the price of CO_2 allowances may reach approximately 120 € per metric ton by 2030, a 145% increase from the 2023 level (Dimitrova, 2024).

Electricity prices are expected to decline until 2030 if EU Member States succeed in meeting the renewable energy targets outlined in their National Energy and Climate Plans (NECPs). According to Navia Simon & Diaz Anadon (2025), this would lead to an estimated 60% reduction in electricity prices for Nordic countries, 31% in Belgium, and 41% in the Netherlands. Such reductions would also help stabilize the electricity market and reduce volatility. The projected 2030 electricity price reductions in combination with the projected 2030 CO_2 allowance price of 120 € per metric ton are included in the case study equations, further enhancing the economic viability of shore connection, as shown in Figure 6. Specifically, the saving increase for the Netherlands is 1874% compared to 2026 levels, 398% for Belgium and 171% for Finland. It should be noted that the 2024 price of MGO was used in the calculation, as no reliable forecast study was available. France is not included as it was not mentioned in the 2030 electricity price reduction study.

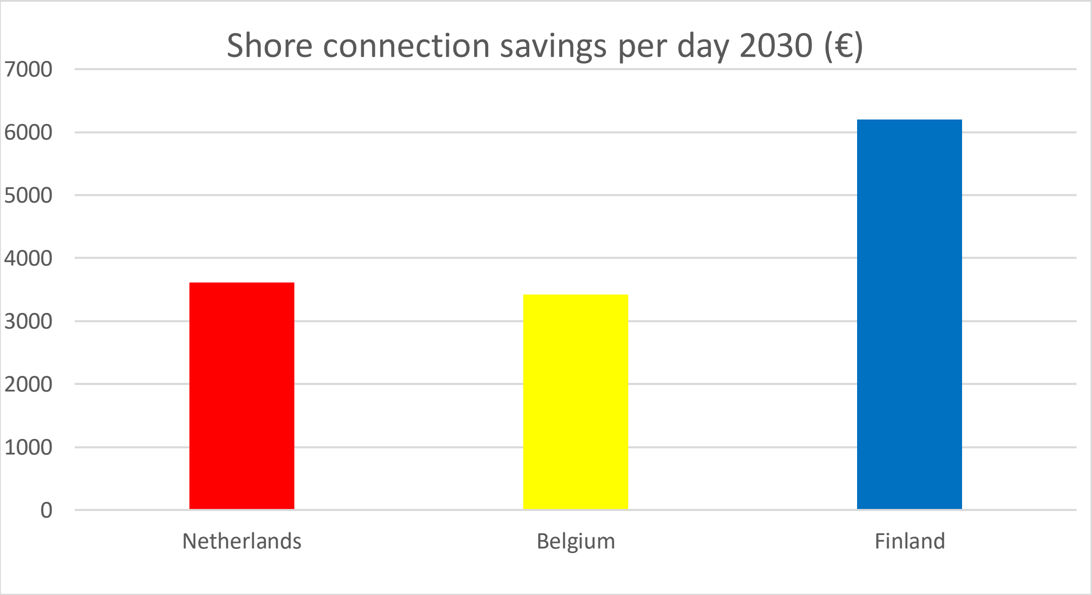


Figure 8 Projected shore connection savings per day 2030.

4 Incentives for Supporting Shore Connections

Funding from organizations such as the Connecting Europe Facility (EU) and the Environmental Protection Agency (US) has, in recent years, been allocated to support shore connection projects. Incentives can generally be divided into two categories: harbor infrastructure development and vessel system integration (for shipowners). Based on the economic calculations presented in Chapter 3, it can be observed that with appropriate incentives, the investment in shore power systems can result in immediate cost savings for shipowners.

4.1 Incentives for Harbor Developments

In anticipation of the 2030 requirement to use shore power while at berth, the EU has granted 18.8 million € in funding for shore power development across several major ports, including Gothenburg, Stockholm, Bremerhaven, and Aarhus (Ports of Stockholm, 2024). Additionally, a 2.2 million € grant was awarded to the Ports of Trelleborg and Lübeck through a collaborative project. Notably, the project in Trelleborg includes the integration of two wind turbines to supply a significant share of the electricity required, ensuring a climate-friendly power source for the shore connection systems (Port of Trelleborg, 2025).

In the United States, the Port of San Diego secured a significantly larger investment of 59 million $, with an additional 28 million $ contributed by partners including the San Diego Air Pollution Control District and the port authority itself. This brings the total funding package to 86 million $. While not exclusively marked for shore power infrastructure, the funds will also support the electrification of harbor operations, including shuttle vans and heavy-duty trucks. Collectively, these initiatives aim to substantially reduce emissions within the port area. (Rodriguez, 2024)

4.2 Incentives for Vessel Owners

While EU ports can apply for various funding initiatives to support shore power infrastructure, vessel owners have also, in some cases, received funding either directly or indirectly. Some states offer direct financial support for shore connection use. For example, an aid scheme approved by the European Commission, with a total budget of 570 million € and active until 31 December 2033, allows shipowners to receive a 100% discount on general system charges when using shore power in Italian ports (European Commission, 2024). While energy consumption (kWh) is still charged, other grid-related costs, such as distribution charges, are excluded, effectively providing free access to the shore power network. There are also examples of funding for onboard equipment installations. In one case, a Swedish shipowner received 50% funding of the cost to install a 6.6 kV shore connection system for operating cargo pumps during unloading. This was achieved through a co-funding between a national Swedish government program and an EU initiative (Fatima, 2022). In Denmark, a port that services approximately 5,500 fishing vessels and 700 merchant vessels annually has introduced a fixed-price electricity scheme for shore power usage. This stable and affordable pricing model encourages shipowners to connect to shore power, benefiting both the port and the local community through reduced emissions and lower noise levels (Interreg North Sea, 2024).

5 Shore Connection Standards

The shore connection standards are a collaborative work between the International Electrotechnical Commission (IEC), the Institute of Electrical and Electronics Engineers (IEEE), and the International Organization for Standardization (ISO). This chapter examines the requirements outlined in the standards for both low-voltage and high-voltage shore connection power systems to assess whether future solutions provided by WE Tech need to be modified compared to the earlier delivered solution. Marine classification societies often incorporate these standards into their guidelines. However, suppliers of equipment must specifically ensure that their products are approved by the relevant classification society of the vessel in question.

It is important to note that not all vessel types are yet covered by the shore connection standards. For instance, the IEC 80005-1 standard addresses approximately 52% of the world's currently operating vessels (Rotterdam, 2023). Furthermore, the IEC/IEEE 80005-3 standard specifically applies to seagoing vessels and does not extend to inland vessels.

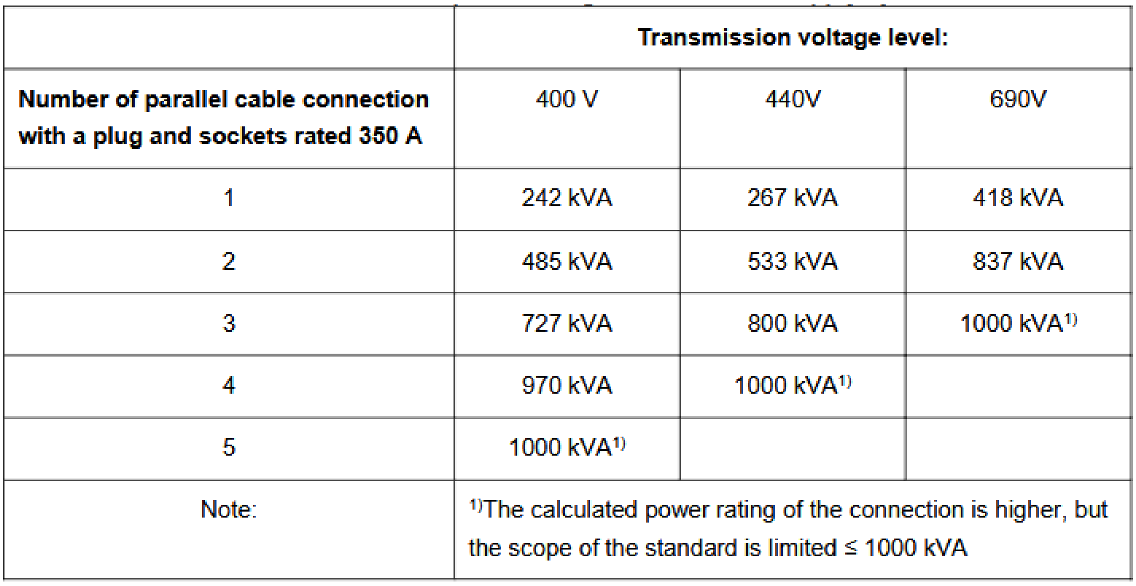
5.1 Low Voltage Shore Connection Standard (<1 MVA)

The IEC/IEEE 80005-3 standard outlines regulations for shore connections under 1 MVA. It is expected that the official release will occur during 2025, and it will be referenced in future classification rules.

5.1.1 IEC/IEEE 80005-3

The IEC/IEEE 80005-3 standard complements the already published 80005-1 high-voltage standard, though it is still in the draft stage and subject to change before its official release. The draft standard is reviewed in a recent article from DNV titled "Assessment of the Current Draft Proposal on Low Voltage Shore Power Standards.". Like 80005-1, the 80005-3 standard structures its main body as general requirements applicable to all ship-to-shore installations, with annexes at the end addressing specific vessel types and their unique requirements. It is noted that if a vessel covered by the 80005-1 annexes requires a connection of less than 1 MVA, the 80005-1 standard will take precedence to promote interoperability. The standard currently recommends the use of 690V 60 Hz, 440V 60 Hz, 400V 50 Hz, or 480V 60 Hz shore power supplies to eliminate the need for additional equipment. Some design specifications, such as the requirement for galvanic separation, are similar to those outlined in 80005-1. The goal of LVSC is to establish a unified approach for both vessels and shores regarding technical requirements, encouraging the use of standardized plug configurations for vessels that fall within this standard. Additionally, it aims to introduce scalability, as ships will be allowed to connect only a certain number of cables based on the required kVA, unlike HVSC systems, as specified in Table 2.

Table 2 Parallel cable setup LVSC. (Rotterdam, 2023)



	Transmission voltage level:		
Number of parallel cable connection with a plug and sockets rated 350 A	400 V	440V	690V
1	242 kVA	267 kVA	418 kVA
2	485 kVA	533 kVA	837 kVA
3	727 kVA	800 kVA	1000 kVA1)
4	970 kVA	1000 kVA1)	
5	1000 kVA1)		
Note:	1)The calculated power rating of the connection is higher, but the scope of the standard is limited ≤ 1000 kVA		

Suppliers of shore connection systems must account for these requirements when designing distribution cabinets, particularly in terms of plug and socket quantity. When multiple cables are used, each must be equipped with individual overload or short-circuit protection, in addition to a single main circuit breaker. For the vessel example described in Chapter 3, this would require the use of two cables when employing the recommended plug connectors rated at 350 A.

5.1.2 Plug configurations

IEC 60309-5 defines the plug and socket dimensions, as well as pin configurations, for LVSC systems. It recommends a default current rating of 350 A per plug-socket combination. The standard also outlines a suggested pin layout applicable to all ships using LVSC systems with a rated capacity of less than 1 MVA. Figure 9 illustrates the recommended plug and socket configuration along with examples of commonly used connectors.

Figure 9 LVSC plugs and sockets. (Rana et al., n.d.)

5.2 High Voltage Shore Connection Standard (≥ 1 MVA)

The high-voltage shore connection (HVSC) standard applies to vessels equipped to handle connections with a rated capacity equal to or exceeding 1 MVA. Figure 10 illustrates a single-line diagram of a shore-to-ship electrical interface.

Circuit breakers (1, 11, 4, 9), located at both the shore-side and ship-side terminals, are used to isolate the connection in the event of faults and some can also serve earthing functions. Transformers (2, 10) are generally required to match the voltage levels between the shore supply and the vessel's onboard electrical system while providing galvanic isolation. Protective relays (3, 8) are installed on both ends of the system to continuously monitor power flow and to trip circuit breakers automatically in the event of a fault.

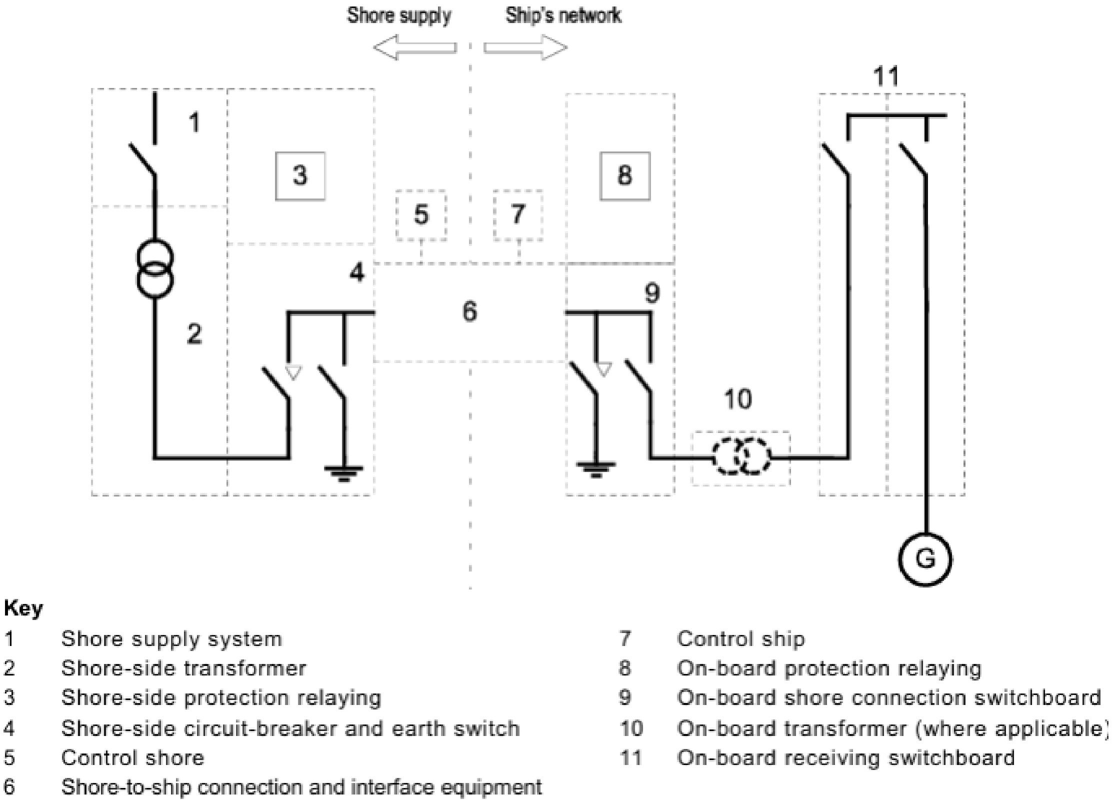


Figure 10 Example HVSC single line diagram. (IEC et al., 2019)

5.2.1 IEC/IEEE 80005-1

This section summarizes the key requirements from the IEC/IEEE 80005-1 standard concerning shore connection systems for high-voltage shore power (HVSC).

If the shore power connection is implemented via cables, a socket and plug type must be used that prevents incorrect connection. Connectors must comply with IEC 62613-1 or IEC 60309-1 standards and must be marine-certified to align with the 80005 series requirements.

The onboard shore connection circuit breaker must provide overcurrent, short-circuit, and undervoltage protection. It shall be interlocked with all onboard generator circuit breakers, unless a synchronizing check relay allows simultaneous closing. Furthermore, the breaker shall be interlocked with earthing switches in both connecting ends if such is existing. For vessels with a main switchboard voltage exceeding 1000 VAC, an earthing switch is required on the vessel's receiving switchboard. Additionally, galvanic isolation is mandatory for all HVSC connections, typically implemented using a transformer on the shore side.

An emergency stop button must be located at the onboard shore connection switchboard and at the point of interconnection between the shore and the vessel. Breakers must trip within a maximum of 0.2 seconds in the event of safety loop circuit opening. All protection and safety systems shall be hardwired. Nominal shore supply voltages shall be standardized to either 6.6 kV AC or 11 kV AC. If voltage conversion is necessary, this equipment must be installed onboard the vessel. The HVSC system must be rated for a maximum short-circuit fault current of 16 kA RMS for 1 second and 40 kA peak, unless otherwise specified in the vessel-specific annexes.

The standard recommends using a single cable for systems rated up to 6.5 MVA, unless otherwise specified in vessel annexes. For specific vessel types such as container ships, LNG carriers, and tankers, parallel feeding is described, as shown in Table 3. Unlike LVSC systems, HVSC-connected vessels must always utilize all available installed shore connection sockets, regardless of the required power level. (Rotterdam, 2023)

Table 3 Parallel cable setup for HVSC vessels.

	Container	LNGc	Tanker	Not specified
Minimum cable amount	2	3	3	1
Power (MVA)	≤ 7.5	≤ 10.7	≤ 10.8	≤ 6.5

For the tanker vessel presented in Chapter 3, Annex F of the 80005-1 standard specifies that three parallel cable connections are required for the HVSC connection.

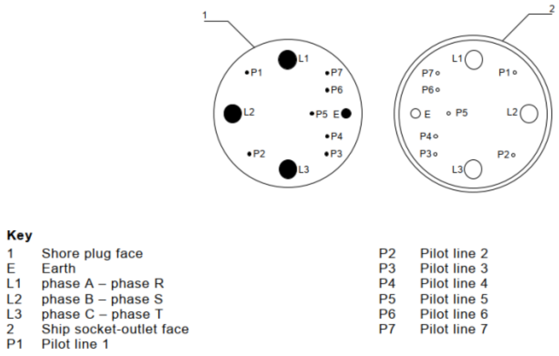
The onboard shore connection switchboard must be constructed in accordance with IEC 62271-200, classified with service continuity level LSC1, and equipped with the following instrumentation and protection features:

a) voltmeter: all three phases;
b) short-circuit devices: tripping and alarm;
c) overcurrent devices: tripping and alarm;
d) earth-fault indicator: alarm; and
e) unbalanced protection for systems with more than one ship inlet.
(IEC/IEEE, 2019, p. 33)

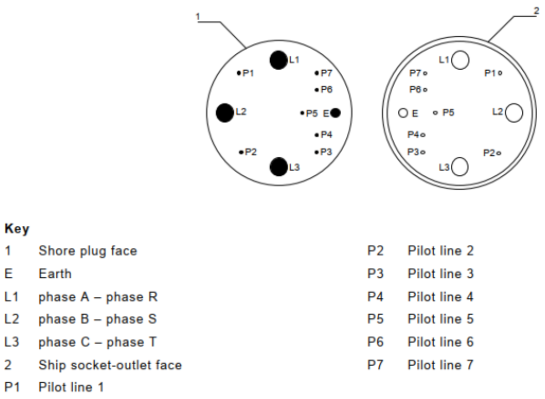
5.2.2 Plug configurations

IEC 62613-1 defines the shore connection plug and socket dimensions and pin configurations for HVSC systems. These configurations vary between ship types, which is an important consideration for suppliers delivering plug and socket systems for shore connections exceeding 1 MVA. The IEC/IEEE 80005-1 standard refers to IEC 62613-1. Figure 11 illustrates the typical pin configurations for various vessel types covered in the annexes of the IEC/IEEE 80005-1 standard.

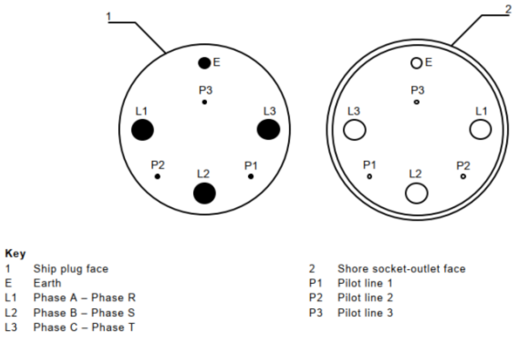
Roll-on Roll-off (Ro-Ro)
cargo ships and Ro-Ro passenger ships



Liquefied Natural Gas Carriers (LNGC)



Container ships



Tankers

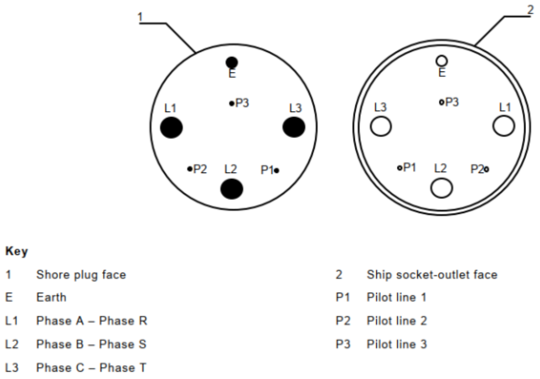


Figure 11 HVSC plugs and sockets.

Although a standardized socket and plug configuration similar to what is being promoted for LVSC, most terminals are currently constructed to accommodate a specific vessel type. Therefore, plug and pin configuration differences for HVSC systems remain not a significant issue. Pin configurations by vessel type are further compiled and presented in Appendix 3.

6 Shore Connection Technical Implementation

The technical scope of a shore connection system generally includes, as separate units, the initial connection point (or plug interface), a shore-side switchboard equipped with necessary protective and control devices, and potentially a shore transformer. This chapter will assess the WE Tech shore connection solution installed onboard the vessel described in Chapter 3. The evaluation aims to determine whether the system aligns with current IEC/IEEE 80005 shore connection standards.

6.1 Previous Delivered Project

The installation consists of a low-voltage shore connection switchboard rated at 500 A, a standalone cabinet with an operating voltage range of 400–450 VAC at 50–60 Hz. The cabinet includes an integrated shore socket and is paired with a shore plug, delivering power to a step-up transformer configured for 500 V. The transformer enables suitable AC/DC conversion for integration with the WE Drive DC system.

The cabinet has an ingress protection rating of IP44, making it appropriate for both industrial and marine environments. It is equipped with instrumentation, as illustrated in Figure 12, including a voltmeter (1P2), an ammeter (1P1), and a phase sequence indicator (1P3). Selector switches (1S2 and 1S1) to change between phase readings, while switch 1S3 toggles between local and remote-control modes. In local control, spring-loaded motor circuit breaker Q14 can be operated by push buttons 1SH1 and 1SH2. The breaker is equipped with thermal overload protection with delay, prolonged overcurrent protection, instantaneous overcurrent protection, an undervoltage coil, and a remote position status indicator (open/closed).

The integrated female socket (XP1) is mounted directly in the cabinet and features a push-and-pull mechanism compatible with the loose delivered male plug. The plug includes three phase pins, one earth pin, and two auxiliary pilot pins for communication.

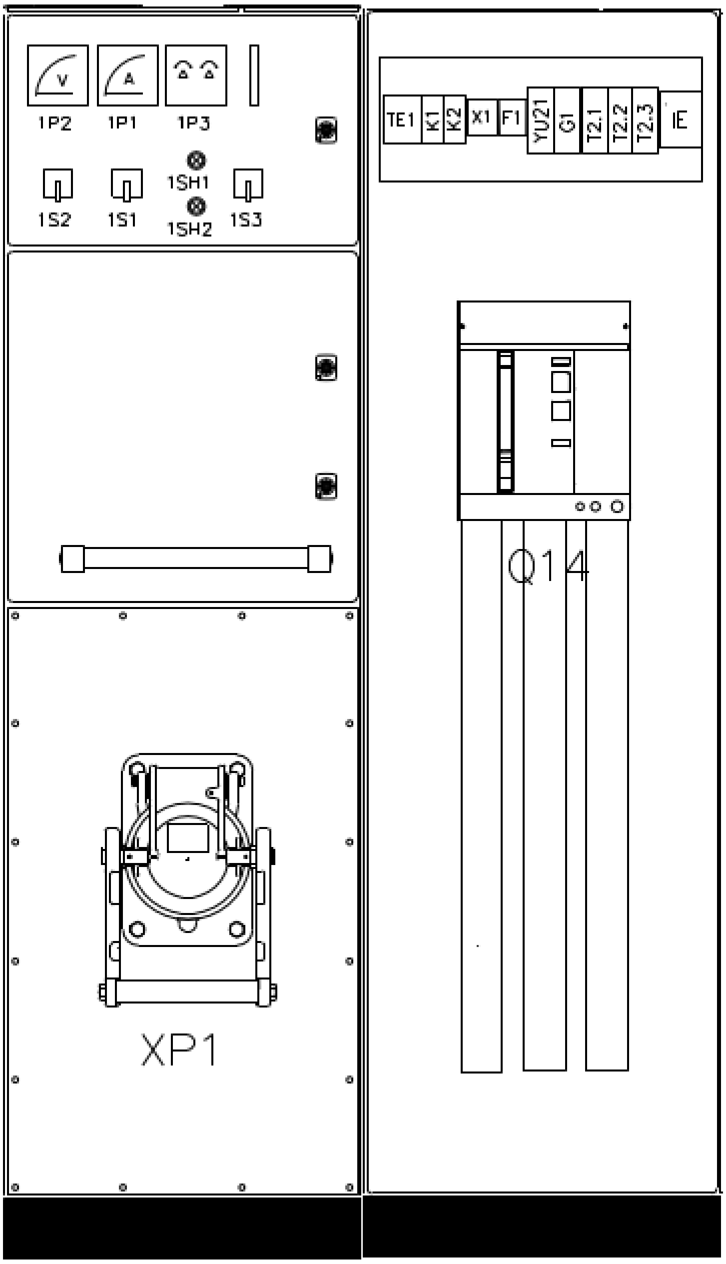


Figure 12 Front-facing SC cabinet layout, outside (left) and inside (right).

6.2 Compliance Assessment

A compliance matrix has been compiled to evaluate the onboard shore connection solution against applicable requirements derived from relevant standards.

Table 4 Summary of requirements related to shore connection integrator.

Requirements	**IEC/IEEE 80005-3 (LVSC < 1 MVA)**	**IEC/IEEE 80005-1 (HVSC > 1 MVA)**
Voltage Levels (AC)	400 V 50 Hz, 440 V 60 Hz, 480 V 60 Hz, 690 V 50 or 60 Hz or both.	6.6 kV or 11 kV.
Plug and Socket Type	IEC 60309-5 (350A per plug).	IEC 62613.
Instrumentation	Voltmeter (3-phase), circuit-breaker, earth-fault indicator (if onboard transformer), each individual connector to have short-circuit protection.	Voltmeter (3-phase), circuit-breaker, earth-fault indicator, each individual connector to have short-circuit protection.
Circuit Breaker features	Motor-operated. Overcurrent, short-circuit, and under-voltage protection.	Motor-operated. Overcurrent, short-circuit, and under-voltage protection.
Safety and Interlocks	Main and individual feeder breakers are interlocked at both ends.	Interlock with earthing switches at both ends. If >1 feeder, both connections shall trip in case of a fault.
Cable Connections	Scalable connection, based on kVA demand, up to 5 feeders.	All available sockets must be connected. Depending on ship type, up to 3 feeders.
Fault Handling (trip activation)	Cable over tension, loss of safety circuit, emergency stop, protection relay trip, and earth fault (ships without onboard transformer).	Cable over tension, earth fault, loss of safety circuit, emergency stop, protection relay trip and parallel connection unbalance monitoring.
Required Emergency Stops	Ship control station, vicinity of plug socket, vicinity of ship inlet, cable management control locations, shore and ship circuit breaker vicinity.	Ship control station, vicinity of plug socket, cable management control locations, shore and ship circuit breaker vicinity.
Short-circuit Current	16 kA for 1 s, and the maximum peak short-circuit current is 40 kA.	16 kA for 1 s, and the maximum peak short-circuit current is 40 kA if not otherwise specified in annexes.

When compared to the upcoming IEC/IEEE 80005-3 standard, the shore switchboard delivered as part of the project has a few deviations. Since a low-voltage shore transformer is installed onboard, the system should include an earth-fault indicator with an associated alarm. In addition, the current switchboard cabinet lacks an emergency stop function, which is a required safety feature. Furthermore, with a nominal current capacity of 500 A, the system should feature at least two 350 A plugs to comply with the standard's scalability principle. Lastly, the plug and socket arrangement does not include the required four pilot pins, which are essential for implementing the safety loop scheme specified in the standard. It should be noted that 80005 does not explicitly specify a requirement for a separate ship inlet socket box, but it is recommended depending on the location of the shore connection switchboard onboard the ship.

6.3 Sizing and Component Selection

The design depends on whether the shore switchboard is a standalone unit or integrated into the WE Drive. In both cases, a compact layout that minimizes space while maintaining functionality is required. It shall be noted that the solution must always comply with the applicable marine classification requirements for the specific project.

Transformers, filtering units, and any interface with the WE Drive frequency converter must be compatible with the rated shore power capacity and meet short-circuit protection requirements.

6.3.1 Electrical Dimensioning

If IEC 80005-3 is implemented as outlined in the current draft, and the recommendation for using parallel feeders in scalable shore power connections is adopted, shipboard shore connection switchboards will need to be equipped with multiple sockets, each corresponding to a separate feeder. Each feeder must be protected by an individual circuit breaker, interlocked with a main circuit breaker to ensure proper isolation and fault protection. The main circuit breaker covers the common bus interconnecting the outgoing feeders. Both the main breaker and the individual breakers shall be dimensioned according to project-specific requirements.

As stated in IEC 80005-1 and its Table 3, HVSC reception switchboards are required to support multiple sockets when using parallel feeding for certain vessel types. To assist with determining the appropriate number of plugs and sockets in accordance with applicable standards, an Excel-based equipment selector tool has been developed as shown in Appendix 3.

6.3.2 Mechanical Dimensioning

The physical size of the cabinet increases by approximately 570 mm per additional socket compared to the original design shown in Figure 12 in case the harbor interface occurs in this cabinet. Figure 13 presents an example of a LVSC switchboard equipped with three plugs, resulting in a total cabinet length of 1710 mm. Possibly, the sockets could be located in a separate inlet receptable box located on deck to make connection easier.

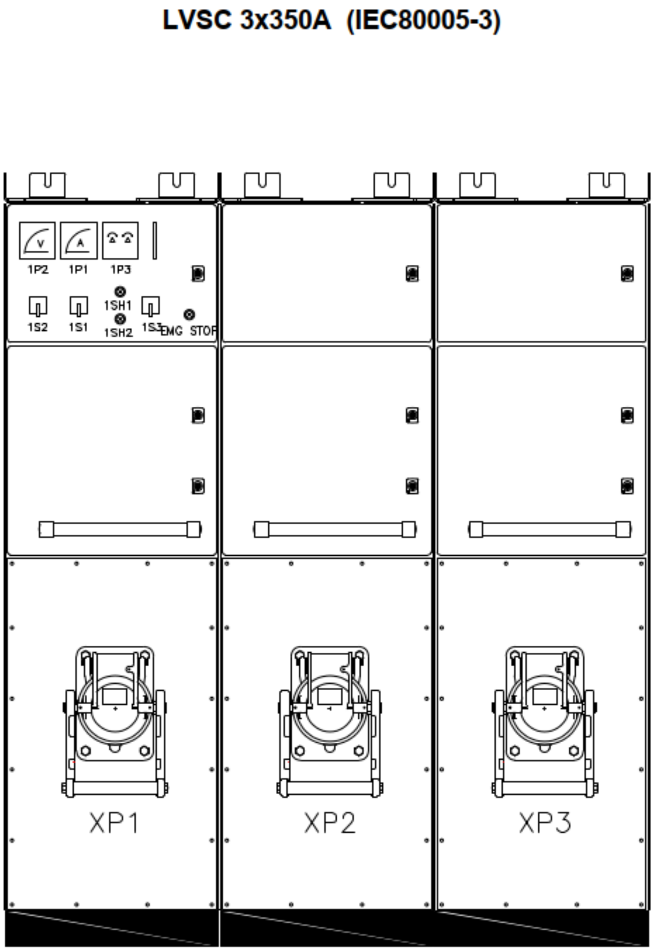


Figure 13 Example LVSC reception switchboard.

A similar sizing principle applies to HVSC switchboards. However, IEC standards impose stricter requirements on busbar clearance distances for high voltage applications, which may lead to further cabinet enlargement. These considerations must be addressed by the cabinet designer to ensure compliance and maintain safe operating conditions.

6.4 Further Internal Developments

Initially, utilizing WE Drive frequency converters appeared to offer greater flexibility for shore connection. However, following discussions with the shipowner of the case study vessel, it became evident that connecting the shore power directly to the main switchboard would have been a more effective solution. This setup would also allow the shore connection to be used during dry-docking when the WE Drive water-cooling system is not operational. Additionally, onboard generation would not be an option during dry-docking due to the absence of a cooling medium. If frequency flexibility is required, an air-cooled frequency drive could be considered for this purpose. However, the 80005-3 standard stipulates that if a frequency converter is necessary, it should be installed onshore. There are already low voltage shore connection installations before the standard has been published, meaning that this compliance might not be fulfilled in some installations. Since different vessels may require different frequencies, the converter could also be located onboard the vessel. This aspect is expected to be clarified once the official publication of the standard is released.

7 Discussion

EU regulations currently mandate the installation of shore connection systems for container and passenger vessels. It is likely that similar requirements will be extended to tanker vessels soon. From the shipowner’s perspective, shore power offers not only regulatory compliance but also economic advantages through reduced costs when comparing fuel to electricity prices and through decreased wear on onboard engines, resulting in lower maintenance costs and longer component lifetimes. In contrast, ships and ports outside the EU may be slower to adopt shore power solutions, primarily due to the limited availability of shore-side infrastructure and the potential cost advantage of onboard power generation. In such regions, the main drivers for adoption are expected to be the development of shore power infrastructure, reduction of electricity prices, and state or port-level regulations and incentives.

Based on personal experience within the shipbuilding industry, shipping companies are often hesitant to invest in technical solutions with long payback periods or low perceived profitability. This observation aligns with the findings of Longarela-Ares et al. (2023), who noted that the likelihood of investment in technical upgrades diminishes as vessels age, particularly when the payback period exceeds the remaining operational lifetime. Similar findings are presented by Zis et al. (2016), who found that lower fuel prices significantly prolong the return on investment for exhaust gas cleaning systems. For example, when the price differential between low-sulfur fuel and heavy fuel oil is minimal, shipowners may prefer to use compliant low-sulfur fuels rather than investing in scrubbers. However, in the case of shore connection systems, it can be expected that vessels operating primarily within the EU will benefit from adopting such systems soon.

7.1 Result

As a result of this thesis, WE Tech now has a foundation to offer shore connection solutions aligned with applicable international standards. The developed calculation tool enables preliminary dimensioning of the shore connection system, which is often required already at the sales stage of a project. Additionally, the findings from the economic case study can be used to demonstrate potential cost savings when shore power is used instead of onboard fuel-based power generation. This information may support both technical justification and marketing efforts. The thesis also provides additional insights, such as the increasing regulatory pressure from the European Union to implement shore connection systems in ports. As a result, the number of affected vessel types and compliant harbors is expected to grow, further reinforcing the market potential for such solutions.

7.2 Further Studies

Several topics emerged during the writing of this thesis that, due to scope and time constraints, were not addressed in detail. Shore connection utilization remains a highly relevant subject in the maritime industry and is considered a key enabler in achieving emission reduction targets by minimizing pollution while also saving operational costs. The following areas are suggested for further research.

Firstly, a more comprehensive study could examine the broader environmental impact of shore connection systems, including both global emission reductions and localized air quality improvements in port cities. Secondly, if the shore power receiving switchboard is connected via the WE Drive rather than directly to the main switchboard, further investigation into the required interfacing could be conducted to ensure a safe and reliable shore power startup procedure. Thirdly, a comparative study could be conducted to evaluate ESS operation profiles in cases with and without shore power availability. It may be necessary, for example, to ensure that sufficient ESS capacity is maintained before entering port when shore charging is not possible, which could constrain ESS flexibility during the voyage. And lastly, the EU ETS system will include also methane and nitrous oxide emissions starting from year 2026, the increased cost impacts could further be investigated.

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Appendices

Appendix 1. GAMS equations

In the section below, the scalar input parameters are inserted; these values are altered for each case and serve as fundamental inputs for the equations in further sections.

```
SCALAR
    Th        "Time spent in harbor (hours)" / 24 /
    Lh        "Electrical load in harbor (kW)" / 1350 /
    E_price_fr     "Electricity price France (EUR/kWh)" /
0.1711 /
    E_price_nl   "Electricity price Netherlands (EUR/kWh)" /
0.1986 /
    E_price_be     "Electricity price Belgium (EUR/kWh)" /
0.178 /
    E_price_fi     "Electricity price Finland (EUR/kWh)" /
0.0928 /
    F_price   "Fuel price (EUR/ton)" / 751 /
    SFOC        "Specific fuel oil consumption (kg/kWh)" /
0.2011 /
    Ef        "Emission factor for MGO" / 3.206 /
    Allowance "Allowance CO2 year 2023 (EUR)" / 83 /;
```

The equation results are output in the listed variables below.

```
VARIABLES
    Cost_sh_fr       "Cost of using shore power FR (EUR)"
    Cost_sh_nl       "Cost of using shore power NL (EUR)"
    Cost_sh_be       "Cost of using shore power BE (EUR)"
    Cost_sh_fi       "Cost of using shore power FI (EUR)"
    Cost_gen      "Cost of onboard generation (EUR)"
    Em_kw         "Emissions per kW"
    Emission_tot  "Total emission during 24h stay"
    Emission_cost "Allowance cost due to emissions (EUR)"
    Emission_2024 "Emission cost for 2024"
    Emission_2025 "Emission cost for 2025"
    Emission_2026 "Emission cost for 2026"
    TotalCost_2024  "Total  cost  for  2024  (Emission  +
OnboardGenCost)"
    TotalCost_2025  "Total  cost  for  2025  (Emission  +
OnboardGenCost)"
    TotalCost_2026  "Total  cost  for  2026  (Emission  +
OnboardGenCost)"
    Savings_FR_2024 "Economic savings for FR in 2024"
    Savings_FR_2025 "Economic savings for FR in 2025"
```

```
    Savings_FR_2026 "Economic savings for FR in 2026"
    Savings_NL_2024 "Economic savings for NL in 2024"
    Savings_NL_2025 "Economic savings for NL in 2025"
    Savings_NL_2026 "Economic savings for NL in 2026"
    Savings_BE_2024 "Economic savings for BE in 2024"
    Savings_BE_2025 "Economic savings for BE in 2025"
    Savings_BE_2026 "Economic savings for BE in 2026"
    Savings_FI_2024 "Economic savings for FI in 2024"
    Savings_FI_2025 "Economic savings for FI in 2025"
    Savings_FI_2026 "Economic savings for FI in 2026";
```

The following section defines the mathematical relationships between input parameters and variables. Each equation represents a specific cost, emission, or savings calculation.

```
EQUATIONS
    ShorePowerCostFR        "Cost of using shore power in
France"
    ShorePowerCostNL        "Cost of using shore power in
Netherlands"
    ShorePowerCostBE        "Cost of using shore power in
Belgium"
    OnboardGenCost      "Cost of onboard power generation"
    Emission_kW         "Emission per kW"
    OnboardEmission     "Total emission onboard"
    EmissionCostEq      "Emission allowance cost equation"
    Emission_2024_eq    "Emission cost for 2024"
    Emission_2025_eq    "Emission cost for 2025"
    Emission_2026_eq    "Emission cost for 2026"
    TotalCost_2024_eq   "Total cost equation for 2024"
    TotalCost_2025_eq   "Total cost equation for 2025"
    TotalCost_2026_eq   "Total cost equation for 2026"
    Savings_FR_2024_eq  "Savings France 2024"
    Savings_FR_2025_eq  "Savings France 2025"
    Savings_FR_2026_eq  "Savings France 2026"
    Savings_NL_2024_eq  "Savings Netherlands 2024"
    Savings_NL_2025_eq  "Savings Netherlands 2025"
    Savings_NL_2026_eq  "Savings Netherlands 2026"
    Savings_BE_2024_eq  "Savings Belgium 2024"
    Savings_BE_2025_eq  "Savings Belgium 2025"
    Savings_BE_2026_eq  "Savings Belgium 2026"
    Savings_FI_2024_eq "Savings Finland 2024"
    Savings_FI_2025_eq "Savings Finland 2025"
    Savings_FI_2026_eq "Savings Finland 2026";
```

The equations are then expressed according to the following section.

```
ShorePowerCostFR..
    Cost_sh_fr =E= Th * Lh * E_price_fr;
ShorePowerCostNL..
    Cost_sh_nl =E= Th * Lh * E_price_nl;
```

```
ShorePowerCostBE..
    Cost_sh_be =E= Th * Lh * E_price_be;
ShorePowerCostFI..
    Cost_sh_fi =E= Th * Lh * E_price_fi;
OnboardGenCost..
    Cost_gen =E= Th * Lh * SFOC * (F_price / 1000);
Emission_kW..
    Em_kw =E= SFOC * Ef;
OnboardEmission..
    Emission_tot =E= Th * Lh * Em_kw;
EmissionCostEq..
    Emission_cost =E= Emission_tot * Allowance / 1000;
Emission_2024_eq..
    Emission_2024 =E= Emission_cost * 0.4;
Emission_2025_eq..
    Emission_2025 =E= Emission_cost * 0.7;
Emission_2026_eq..
    Emission_2026 =E= Emission_cost;
TotalCost_2024_eq..
    TotalCost_2024 =E= Emission_2024 + Cost_gen;
TotalCost_2025_eq..
    TotalCost_2025 =E= Emission_2025 + Cost_gen;
TotalCost_2026_eq..
    TotalCost_2026 =E= Emission_2026 + Cost_gen;
Savings_FR_2024_eq..
    Savings_FR_2024 =E= TotalCost_2024 - Cost_sh_fr;
Savings_FR_2025_eq..
    Savings_FR_2025 =E= TotalCost_2025 - Cost_sh_fr;
Savings_FR_2026_eq..
    Savings_FR_2026 =E= TotalCost_2026 - Cost_sh_fr;
Savings_NL_2024_eq..
    Savings_NL_2024 =E= TotalCost_2024 - Cost_sh_nl;
Savings_NL_2025_eq..
    Savings_NL_2025 =E= TotalCost_2025 - Cost_sh_nl;
Savings_NL_2026_eq..
    Savings_NL_2026 =E= TotalCost_2026 - Cost_sh_nl;
Savings_BE_2024_eq..
    Savings_BE_2024 =E= TotalCost_2024 - Cost_sh_be;
Savings_BE_2025_eq..
    Savings_BE_2025 =E= TotalCost_2025 - Cost_sh_be;
Savings_BE_2026_eq..
    Savings_BE_2026 =E= TotalCost_2026 - Cost_sh_be;
Savings_FI_2024_eq..
    Savings_FI_2024 =E= TotalCost_2024 - Cost_sh_fi;

Savings_FI_2025_eq..
    Savings_FI_2025 =E= TotalCost_2025 - Cost_sh_fi;
Savings_FI_2026_eq..
   Savings_FI_2026 =E= TotalCost_2026 - Cost_sh_fi;
```

Grouping of the multiple equations into a model and expressing solve for minimization of a variable, not necessary in these particular equations but could for further research be used in an optimization problem.

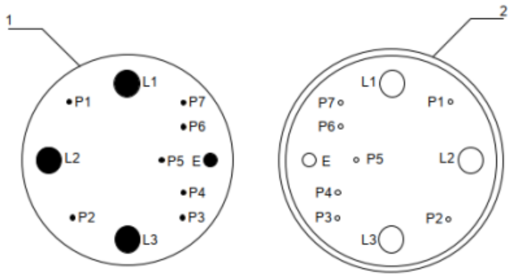
```
MODEL HarborSavings /
ShorePowerCostFR, ShorePowerCostNL, ShorePowerCostBE, Shore-
PowerCostFI,  OnboardGenCost,  Emission_kW,  OnboardEmission,
EmissionCostEq,
    Emission_2024_eq, Emission_2025_eq, Emission_2026_eq,
    TotalCost_2024_eq, TotalCost_2025_eq, TotalCost_2026_eq,
    Savings_FR_2024_eq,      Savings_FR_2025_eq,      Sav-
ings_FR_2026_eq,
    Savings_NL_2024_eq,      Savings_NL_2025_eq,      Sav-
ings_NL_2026_eq,
    Savings_BE_2024_eq,      Savings_BE_2025_eq,      Sav-
ings_BE_2026_eq, Savings_FI_2024_eq,
 160      Savings_FI_2025_eq, Savings_FI_2026_eq,
/;

SOLVE HarborSavings USING LP MINIMIZING Cost_gen;
```

Lastly, the results of the equations are displayed.

```
DISPLAY Cost_sh_fr.L, Cost_sh_nl.L, Cost_sh_be.L, Cost_gen.L,
        Emission_tot.L, Emission_cost.L,
        Emission_2024.L, Emission_2025.L, Emission_2026.L,
        TotalCost_2024.L, TotalCost_2025.L, TotalCost_2026.L,
        Savings_FR_2024.L,     Savings_FR_2025.L,     Sav-
ings_FR_2026.L,
        Savings_NL_2024.L,     Savings_NL_2025.L,     Sav-
ings_NL_2026.L,
        Savings_BE_2024.L,     Savings_BE_2025.L,     Sav-
ings_BE_2026.L,  Savings_FI_2024.L,  Savings_FI_2025.L,  Sav-
ings_FI_2026.L;
```

Appendix 2. HVSC vessel pin configurations

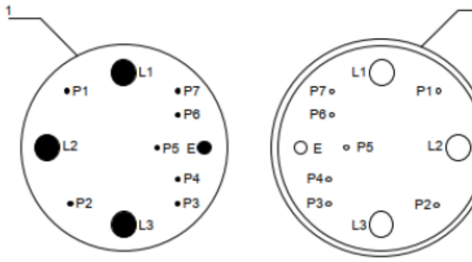
Roll-on Roll-off (Ro-Ro) cargo ships and Ro-Ro passenger ships



Key

1	Shore plug face
E	Earth
L1	phase A – phase R
L2	phase B – phase S
L3	phase C – phase T
2	Ship socket-outlet face
P1	Pilot line 1
P2	Pilot line 2
P3	Pilot line 3
P4	Pilot line 4
P5	Pilot line 5
P6	Pilot line 6
P7	Pilot line 7

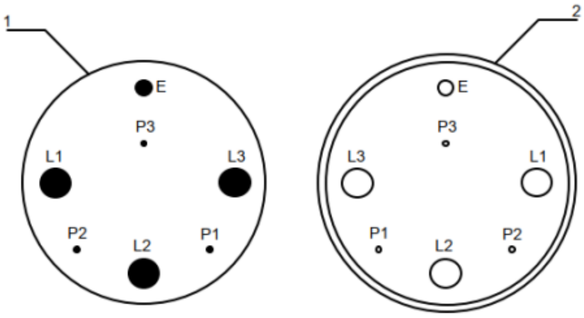
Liquefied Natural Gas Carriers (LNGC)



Key

1	Shore plug face
E	Earth
L1	phase A – phase R
L2	phase B – phase S
L3	phase C – phase T
2	Ship socket-outlet face
P1	Pilot line 1
P2	Pilot line 2
P3	Pilot line 3
P4	Pilot line 4
P5	Pilot line 5
P6	Pilot line 6
P7	Pilot line 7

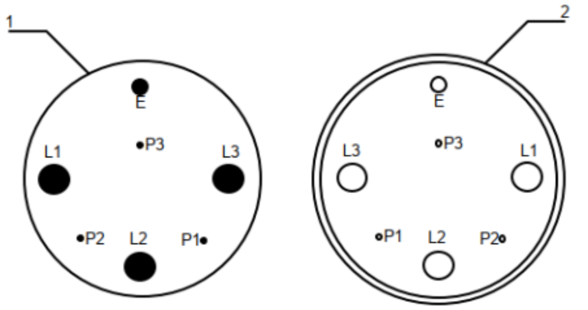
Container ships



Key

1	Ship plug face
E	Earth
L1	Phase A – Phase R
L2	Phase B – Phase S
L3	Phase C – Phase T
2	Shore socket-outlet face
P1	Pilot line 1
P2	Pilot line 2
P3	Pilot line 3

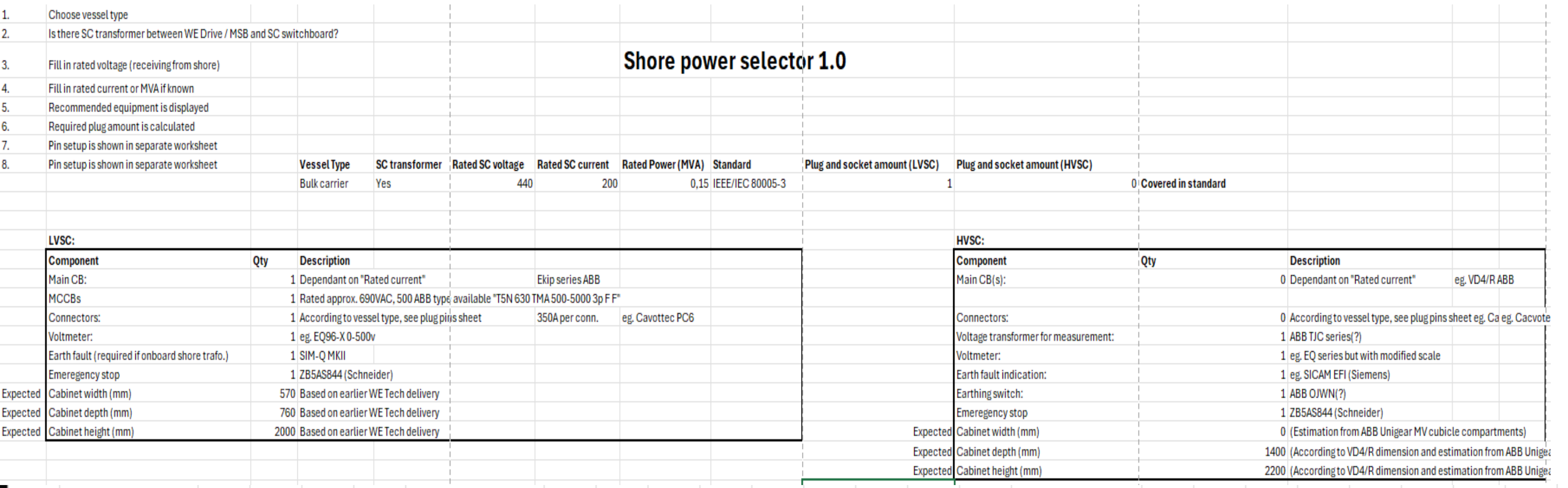
Tankers



Key

1	Shore plug face
E	Earth
L1	Phase A – Phase R
L2	Phase B – Phase S
L3	Phase C – Phase T
2	Ship socket-outlet face
P1	Pilot line 1
P2	Pilot line 2
P3	Pilot line 3

Appendix 3. Excel equipment selector tool



Shore power selector 1.0

1. Choose vessel type
2. Is there SC transformer between WE Drive / MSB and SC switchboard?
3. Fill in rated voltage (receiving from shore)
4. Fill in rated current or MVA if known
5. Recommended equipment is displayed
6. Required plug amount is calculated
7. Pin setup is shown in separate worksheet
8. Pin setup is shown in separate worksheet

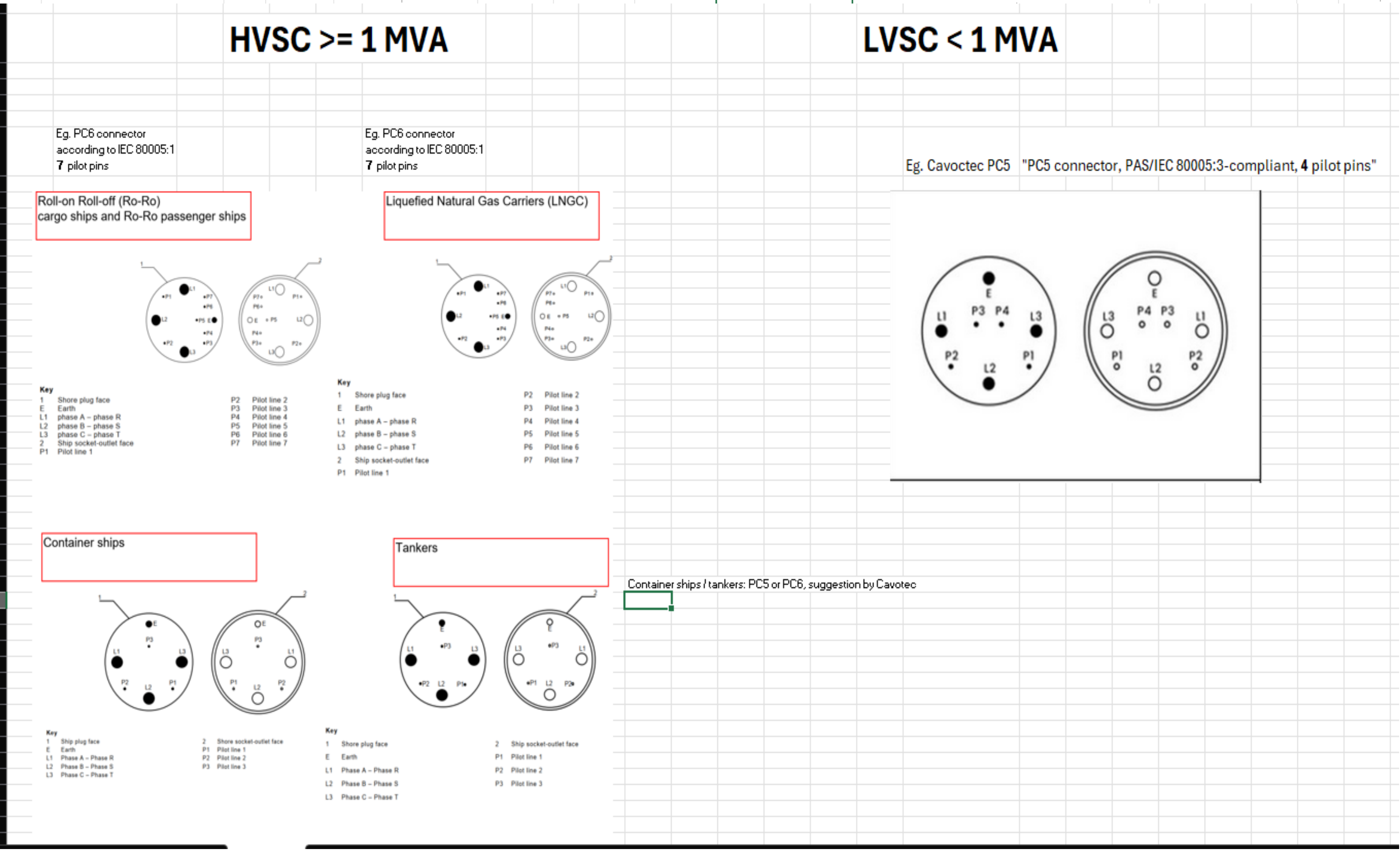
Vessel Type	SC transformer	Rated SC voltage	Rated SC current	Rated Power (MVA)	Standard	Plug and socket amount (LVSC)	Plug and socket amount (HVSC)	
Bulk carrier	Yes	440	200	0,15	IEEE/IEC 80005-3	1	0	**Covered in standard**

LVSC:

	Component	Qty	Description			
	Main CB:	1	Dependant on "Rated current"		Ekip series ABB	
	MCCBs	1	Rated approx. 690VAC, 500 ABB type	available "T5N 630 TMA 500-5000 3p F F"		
	Connectors:	1	According to vessel type, see plug pins sheet		350A per conn.	eg. Cavottec PC6
	Voltmeter:	1	eg. EQ96-X 0-500v			
	Earth fault (required if onboard shore trafo.)	1	SIM-Q MKII			
	Emeregency stop	1	ZB5AS844 (Schneider)			
Expected	Cabinet width (mm)	570	Based on earlier WE Tech delivery			
Expected	Cabinet depth (mm)	760	Based on earlier WE Tech delivery			
Expected	Cabinet height (mm)	2000	Based on earlier WE Tech delivery			

HVSC:

	Component	Qty	Description	
	Main CB(s):	0	Dependant on "Rated current"	eg. VD4/R ABB
	Connectors:	0	According to vessel type, see plug pins sheet eg. Ca	eg. Cacvote
	Voltage transformer for measurement:	1	ABB TJC series(?)	
	Voltmeter:	1	eg. EQ series but with modified scale	
	Earth fault indication:	1	eg. SICAM EFI (Siemens)	
	Earthing switch:	1	ABB OJWN(?)	
	Emeregency stop	1	ZB5AS844 (Schneider)	
Expected	Cabinet width (mm)	0	(Estimation from ABB Unigear MV cubicle compartments)	
Expected	Cabinet depth (mm)	1400	(According to VD4/R dimension and estimation from ABB Unigea	
Expected	Cabinet height (mm)	2200	(According to VD4/R dimension and estimation from ABB Unigea	



HVSC >= 1 MVA

Eg. PC6 connector
according to IEC 80005:1
7 pilot pins

Roll-on Roll-off (Ro-Ro)
cargo ships and Ro-Ro passenger ships

Key

1	Shore plug face	P2	Pilot line 2
E	Earth	P3	Pilot line 3
L1	phase A – phase R	P4	Pilot line 4
L2	phase B – phase S	P5	Pilot line 5
L3	phase C – phase T	P6	Pilot line 6
2	Ship socket-outlet face	P7	Pilot line 7
P1	Pilot line 1		

Eg. PC6 connector
according to IEC 80005:1
7 pilot pins

Liquefied Natural Gas Carriers (LNGC)

Key

1	Shore plug face	P2	Pilot line 2
E	Earth	P3	Pilot line 3
L1	phase A – phase R	P4	Pilot line 4
L2	phase B – phase S	P5	Pilot line 5
L3	phase C – phase T	P6	Pilot line 6
2	Ship socket-outlet face	P7	Pilot line 7
P1	Pilot line 1		

Container ships

Key

1	Ship plug face	2	Shore socket-outlet face
E	Earth	P1	Pilot line 1
L1	Phase A – Phase R	P2	Pilot line 2
L2	Phase B – Phase S	P3	Pilot line 3
L3	Phase C – Phase T		

Tankers

Key

1	Shore plug face	2	Ship socket-outlet face
E	Earth	P1	Pilot line 1
L1	Phase A – Phase R	P2	Pilot line 2
L2	Phase B – Phase S	P3	Pilot line 3
L3	Phase C – Phase T		

LVSC < 1 MVA

Eg. Cavoctec PC5 "PC5 connector, PAS/IEC 80005:3-compliant, **4** pilot pins"

Container ships / tankers: PC5 or PC6, suggestion by Cavotec