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OPTIMISATION DES OPÉRATIONS DU SYSTÈME AUXILIAIRE ÉLECTRIQUE D'UN VRAQUIER DE TAILLE « HANDYSIZE »

OPTIMIZATION OF AUXILIARY ELECTRIC OPERATIONS OF A HANDYSIZE BULK CARRIER

Mémoire de maîtrise
Spécialité : génie électrique

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Avril 2022

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RÉSUMÉ

L’industrie maritime transporte 80% des marchandises mondiales. De plus, c’est le mode de transportation le plus efficace en termes d’émission de dioxyde de carbone (CO_2) par tonne-kilomètre de cargaison transportée. Cependant, cette recherche montre qu’un vraquier de taille *handysize* émet au minimum l’équivalent de 650 voitures légères par jour par navire.

En effet, les navires marchands ont besoin d’électricité pour faire fonctionner leurs machineries lourdes comme les grues de pont. L’électricité est aussi nécessaire pour les essentielles et les services généraux comme l’éclairage, les cuisines, les ordinateurs de bord, les électroménagers, etc. Cette consommation d’énergie peut être comparée à celle d’une petite ville. Historiquement, l’électricité a toujours été générée par des génératrices au diesel sur des navires marchands. Cependant, il serait plus efficace et environnemental de connecter le navire au réseau électrique disponible sur terre. Ce processus s’appelle l’alimentation à quai. Plusieurs techniques existent pour réaliser cette connexion, mais elles sont souvent très dispendieuses et comportent de nombreux défis.

Ce document présente une revue étendue de littérature sur la décarbonation de l’industrie maritime et propose l’alimentation à quai comme la prochaine étape vers une industrie maritime verte. Une analyse forces, faiblesses, opportunités et menaces (FFOM) de l’alimentation à quai est discutée. Une étude de l’impact de l’alimentation à quai sur un vraquier sec montre que l’indicateur d’intensité de carbone (IIC) de l’Organisation Maritime International (OMI) peut être réduit de 7,8%. Ensuite, une étude multi objectif a permis d’identifier les meilleures solutions pour éliminer les émissions des navires au port. L’étude de cas fondé sur de vrais profiles de consommation d’énergie a révélé qu’une connexion basse tension combinée à une petite batterie de 60 kWh peut éliminer les émissions du navire au port. Cette solution réduirait les émissions de 5,5 tonnes de CO_2 par jour par bateau pour un investissement initial de 323 k$. Le système de gestion des câbles pourrait aussi être installé à quai plutôt que sur le navire diminuant ainsi les frais pour les armateurs de moitié. Une analyse technico-économique montre que le projet aurait un retour sur l’investissement de 15 ans pouvant être réduit à 6 ans si le projet était subventionné à 50%.

Finalement, le potentiel de l’alimentation à quai pour réduire des émissions de gaz à effet de serre (GES) sur la route commerciale du Saint-Laurent et des Grands Lacs est important. De plus, les bénéfices de l’alimentation à quai sont largement augmentés grâce au coût abordable de l’électricité au Québec. Alors que le futur de la décarbonation de l’industrie maritime n’est pas encore définie, l’alimentation à quai est une mesure qui peut être implémentée dès maintenant et qui peut à coup sûr diminuer les émissions de CO_2 de la marine marchande.

ABSTRACT

The shipping industry carries 80% of worldwide commerce. Furthermore, it is the most efficient means of transportation in terms of emissions of carbon dioxide (CO_2) per ton-kilometer of transported cargo. However, this research shows that a handysize dry bulk carrier emits at least the equivalent of 650 light cars per day per ships.

Indeed, ships need electricity to keep heavy equipment working like their deck cranes. They also need it for essentials and crew services such as lighting, cooking, computers, laundry, etc. This energy consumption can be compared to the one of small cities. Historically, the electricity of such a ship always had been generated by the on-board diesel generators (DG). Yet, a more efficient and environmentally friendly way to supply electricity to the ship would be to connect the ship to the onshore electrical network. This process is referred to as shore power, cold ironing (CI), alternative marine power (AMP), onshore power supply (OPS) or shore-to-ship (SSP). Many ways exist to perform this connection; however, they can be extremely expensive and include many challenges.

This document presents an extensive literature review of shipping decarbonization and proposes shore power as the next step toward green shipping. The strengths, weakness, opportunities, and threats (SWOT) analysis of shore power is discussed and a policy impact study of shore power on a dry bulk carrier showed that the carbon intensity index (CII) of the International Maritime Organization (IMO) could be reduced of 7.8% with shore power. Then, a multi-objective approach permitted to find the best solution to eliminate the emissions from the ship in port. The test case with real load profiles revealed that a low voltage connection combined with a small battery of 60 kWh can eliminate emissions from the ship in port. This solution reduces the carbon emissions of 5.5 tons of CO_2 per day per ship for a capital expenditure (CAPEX) of 323 k$. If the cable management system was installed on shore instead of on the ship, the CAPEX could be reduced by half for shipowners. A technical-economic study estimated a payback period of 15 years that could be reduced to 6 years if the project was subsidized at 50%.

Finally, the potential of shore power to reduce greenhouse gas (GHG) emission in the St. Lawrence River and Great Lakes maritime route is massive and the affordable electricity price in Quebec further increases the benefits of shore power. While the future of maritime decarbonization is unclear, shore power is a measure that can be implemented by now and in which the benefits it can achieve in terms of emission reductions are guaranteed for maritime transportation.

ACKNOWLEDGEMENTS

First of all, I must thank my research director Professor João Pedro F. Trovão for giving me the opportunity to do a master's in electrical engineering. João achieved to spark my desire for scientific knowledge and encouraged me since the beginning into the pursuit of my postgraduate studies. His support enabled me to develop all the skills required to become a young researcher.

I am also immensely thankful to David Williams, my project supervisor at Fednav. David has played a major role during the research project by providing excellent advice and mentorship. He shared with passion its impressive expertise and understanding of the shipping industry and the project would not have been as successful without him.

I am also indebted of Professor Carlos Henggeler Antunes which provided a valuable assistance to the project. His unmatched knowledge of mathematics enabled be to expand my comprehension of modelling, optimization, article writing and more.

I would also like to show my gratitude to the entire Fednav team, Martin Krafft, Dana Wandschneider, Antoine Marcotte, Marie-Andrée Giguère, Normand Laforce, Caterina Accardi, Alex Halarides, Mandeep Singh Makkar, Alexi Dorais and many others who supported my research. A special thanks to the Anglo Eastern team and more particularly Anand Vijay, who spent a lot of time and effort to support the project.

I am also immensely grateful to the e-TESC Lab team, Prof. Minh Cao Ta, Prof. Maude Josée Blondin, Prof. Ruben Gonzalez-Rubio, Prof. Ahmed Khoumsi and all the other members for their help in difficult times and support throughout the project. I would also like to thank my colleague Pascal Messier who has been a confidant and a great friend during my master's research.

Most importantly, none of this could have happened without my family and friends who encouraged me in pursuing my master's studies and to follow my convictions till the end.

With the COVID-19 pandemic, we had to adapt our methods of communication and to work in a different manner. I would like to thank everybody for their attention and support of my work during this difficult time.

This work is supported by the Canada Research Chairs Program (950-230672), by the Mitacs Accelerate Program (IT17570), and in part by Fednav. It also received support from FCT, the Portuguese Foundation for Science and Technology under project UIDB/00308/2020.

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AMP: Alternative Marine Power
CAPEX: Capital Expenditure
CI: Cold Ironing
CII: Carbon Intensity Index
CO_2: Carbon dioxide
DDP: Deterministic Dynamic Programming
DDSC: Dry Docking Supply Connection
DG: Diesel Generator
DWT: Dead Weight Tonnage
EEDI: Energy Efficiency Design Index
EMR: Energetic Macroscopic Representation
EMS: Energy Management Strategy
GHG: Green House Gases
HIL: Hardware In the loop
HV: High Voltage
HVSC: High Voltage Supply Connection
ICCT: International Council on Clean Transportation
ICE: Internal Combustion Engine
IMO: International Maritime Organization
ISCA: Improved Sine Cosine Algorithm
LNG: Liquefied Natural Gas
LV: Low Voltage
LVSC: Low Voltage Supply Connection
MEPC: Marine Environment Protection Committee
MCR: Maximum Continuous Rating
MINLP: Mixed-Integer Non-Linear Programming
MOMINLP: Multi-Objective Mixed Integer Non-Linear Programming Problem
NO_x: Nitrogen Oxides
NSGA: Non-Dominated Sorting Genetic Algorithm
OPEX: Operational Expenditure
OPS: Onshore power supply
PM: Particulate Matter
PF: Power Factor
ROI: Return On Investment
RoRo: Roll-on/Roll-off
SEEMP: Ship Energy Efficient Management Plan
SLR: Systematic Literature Review
SFOC: Specific Fuel Oil Consumption
SOLAS: Safety of Life at Sea
SO_x: Sulfur Oxides
SOF: Statement of Fact
SSE: Shore Side Electricity
SSP: Shore-To-Ship Power
SWOT: Strengths, Weaknesses, Opportunities, And Threats
UNCTAD: United Nations Conference on Trade and Development

WPSP: World Port Sustainability Program
WS: Weighted sum

CHAPTER 1

1 INTRODUCTION

1.1 Context and Problematic

The energetic transition has begun in many countries of the world and the challenge is considerable. However, some economic sectors are still in the dark about which energy or measure will decarbonize their activities. Indeed, it is particularly the case of transoceanic ships. While the hydrogen and batteries are a promising combination for ferries or short sea shipping, it is still not economically feasible to use these technologies for long oceanic crossing which can last many weeks. Many long-term options are envisioned to decarbonize the industry; however, they are far from being accessible on a large scale by now. Nevertheless, the maritime industry will need to comply with new international environmental regulations that are becoming more and more constraining. Indeed, the IMO has the objective to reduce emissions of CO_2 per transport work of 40% by 2030 and annual emissions of 50% by 2050. To fulfil its goals, the IMO has set environmental indicators that can measure the theoretical environmental effectiveness of a ship and the real environmental effectiveness of a ship operations. Therefore, the pressure on shipowners to lower their carbon footprint is important, and they will need to find technologies and measures that can reduce GHG emission from their ships.

In Quebec and Ontario, the energetic transition of the maritime industry is still in its first stages. Only two projects of electric ferries are active in Ontario and none in Quebec while representing the easiest maritime means of transportation to electrify. Moreover, a large number of transoceanic merchant ships are cruising through the St. Lawrence River to access the ports of Quebec, Montreal, Toronto, Thunder Bay and many others, but only a hand of ships can use the green electricity of the two provinces. Indeed, ships need to burn diesel to produce electricity in port while the provinces produce electricity coming from hydroelectric power or nuclear and thus, emitting nearly no GHG.

The process of connecting ships to shore electricity is historically called cold ironing (CI), but also known by shore power, alternative marine power (AMP), shore-to-ship power (SSP) and onshore power supply (OPS). Shore power enables ships to shut down their diesel engines while in port and supply the electric demand with the shore electricity. Therefore, up to 100% of GHG emissions from the ship can be reduced. While the electricity used to supply the ships is not necessarily coming from renewables, it tends to be much less polluting than the electricity generated in the ship. Shore power is a mature technology that is widely commercially available. The economic and environmental potential of this measure is huge. Indeed, a transoceanic bulk carrier can consume more than 1.5 tons of diesel per day in port, which, based on this work, is at least the equivalent of 650 light cars per day per ship in port. Further, the emissions can double or even triple proportionally to the ship's power demand in port.

Despite its outstanding advantages, shore power still is not seriously adopted on the commercial road of the St. Lawrence River and Great Lakes. Even if large investments are required for such projects, the environmental advantages exceed the costs. Beside the GHG emissions, the air pollutant emissions and noise from the ships in port have harmful effect on health of the population near ports and can be reduced with shore power. Then, the berth electrification opens the way to the ships of the future. Like electric vehicles required a network of charging stations to expend, ships will also need a shore power network to supply their power demand, recharge their batteries, and more. Moreover, once the shore power infrastructure is in place, the operational cost tends to be much lower especially in Quebec. The low cost of electricity could also increase the competitiveness of Quebec ports.

Since its first wider use in the years 2000, shore power has progressed but is still not available on a large scale in the world. Although technical issues have been overcome and that shore power international standards were developed, the cost of installation still is a major challenge for ports and shipowners. Over the last years, the research has gained interest into multiple topics about shore power like how microgrids in ports are integrating renewables and shore power [1][2][3][4][5]. On the ship side, the research has investigated design and energy management of hybrid ships using shore power [6][7][8][9].

This research is done under the e-TESC Lab [10]. The laboratory team has a long history of sustainable mobility studies mostly directed toward hybrid and electric cars, but also trucks and trains. While small hybrid boats have already been studied by the laboratory [9], this document is the wider development of a new research axis and establishes a base framework for hybrid and electric marine systems research.

1.2 Research question

To supply ships in electricity while they are in port, different methods can be used. The IEC/IEEE international standard [11][12] enables high voltage connections and low voltage connections. Also, the choice of the frequency to cover the different ships will have a considerable impact on the installation cost of land installation and on how the system will be operated. Then, a high voltage connection enables to transfer a lot of energy to the ship and has a high-power capacity. However, the high voltage connections are much more expensive and require specialists to handle the electrical equipment. On the other side, low voltage installations are much more affordable and easier to use, but they are limited in power. Nevertheless, energetic accumulation systems of electricity such as Li-Ion batteries have the capacity to supply high power demands and energetic demands, which enables to supply ships with more affordable shore power systems. Therefore, the selection of a shore power system for a ship requires to make complex design choices.

Additionally, the handysize bulk carriers that are cruising through the St. Lawrence River and Great Lakes to deliver cargo all around the world are built according to special requirements at the level of their weight, length, width, and available space for cargo. Indeed, the seaway lock system of the St. Lawrence River and Great Lakes limits the size of the ships, and any augmentation of the ship's weight or engine room space will result into a diminution of the quantity of cargo that can be transported, and therefore, an income loss. Also, these ships are calling at industrial harbor areas which are different from the one used by other ship types such as container ships, cruise ships, fishing ships. Further, some bulk carriers are implicated in a commercial sector called the tramp trade. It means that the ships do not have a fixed path or that their destination is not known long in advance. Finally, the studied bulk carriers are equipped with deck cranes, which cause high power demands in port when the cargo is loaded or discharged.

Considering the specific restrictions of oceangoing bulk carriers of the St. Lawrence River and Great Lakes, and the specifications of shore power, we formulate the following research question:

- What is the best-suited methodology and design that can be used to give shore power capabilities to a newly built handysize dry bulk carrier of the St. Lawrence River and Great Lakes?

The studied dry bulk carrier should have a capacity of 35,000 deadweight tonnage (DWT) and equipped with four deck cranes. The proposed system must be the most technically, environmentally, and economically as effective possible**.**

1.3 Research project objectives

Therefore, the general objective of the project is to find the best-suited methodology and design that can be used to give shore power capacities to a newly built handysize dry bulk carrier of 35,000 DWT with four deck cranes in a way that the proposed system is technically, environmentally, and economically viable. To answer this question, three sub-objectives are formulated below.

1.3.1 Detail the energy demand at berth

The first sub-objective is to detail the energy demand of a typical dry bulk carrier while at berth. The dry bulk carrier can operate one to four deck cranes while at berth in loading/discharging operations or it can be at rest only requesting the hoteling demand.

1.3.2 Find the best CAPEX vs. GHG emissions trade-offs

A mathematical model describing the CO_2 emissions of a vessel at berth needs to be developed in relation to the CAPEX required for different combinations of multiple energy sources like the grid, batteries, and on-board gensets.

Then, a multi-objective analysis must be performed using the appropriate algorithm to find a Pareto front exposing all the best suitable solutions that can solve the CAPEX vs. GHG emission relation and find a good trade-off between the economy and environment.

1.3.3 Make a technical-economic study of the selected solution

Finally, a technical-economic study needs to be performed to confirm the economic viability of the project. Many aspects need to be analyzed like the CAPEX, operational expenditure (OPEX), return on investment (ROI), and payback period. Sensitivity analysis of the fuel price, and electricity price. will also give important details on the future viability of the selected solution.

1.4 Contributions

This work has enabled to provide important contributions to the shore power research. First, it presents a roadmap proposition for the maritime sector to lower its carbon emissions followed by a clear, concise, and comprehensive review of the green technologies in the maritime industry. Good insights and future trends for the maritime industry emissions reduction are provided. The impact of shore power on international environmental regulations and incentives is assessed with a real case study of a dry bulk cargo carrier emission analysis [13]. Then, this work proposes a multi-objective approach to select and size shore power systems using an exhaustive model detailing shore power sizing and energy consumption [14]. The method enables to diminish the CAPEX of shore power projects. Also, it is one of the rare studies that models a low voltage shore power connection for ships. Finally, this work presents a technical-economic analysis of shore power solutions for ships.

1.5 Document plan

First of all, the context and the problematic of shipping decarbonization and shore power are introduced in the Chapter 1 followed by the research question and the general contributions. Then, the literature review of the Chapter 2 details the electrical and mechanical systems on ships, and how are the dry bulk carriers of the St. Lawrence River and Great Lakes are situated regarding shore power. Thereafter, the Chapter 3 presents the study of maritime industry decarbonization, and shore power followed by a SWOT analysis. The chapter is also supported by a case study on a real dry bulk carrier to measure the impact of shore power on the principal international environmental regulations. Then, Chapter 4 presents the load measurement process and results for Fednav's bulk carriers. The Chapter 5 analyses the different shore power systems for ships and proposes a methodology to follow when shipowners design a shore power system. The methodology has the goal to optimize the initial capital investment and the GHG. Finally, the Chapter 6 concludes the document with a summary of the results, contributions, and future works.

CHAPTER 2

2 STATE-OF-THE-ART

The study of shore power and shipping decarbonization starts with a basic understanding of shipboard electrical and mechanical systems. Since the first use of electricity on ships in the 1880s [15], the electrical load on ships has never stopped growing. While only used for the auxiliaries at the beginning, electricity also found its path to become the main source of power for propulsion on certain types of ships. The safety principles to design an electrical system is similar for every ship type, but the characteristics of the electrical systems can be very different. Indeed, commercial ships can range from few hundreds of DWT up to 400,000 DWT [16] and their electrical systems are also very different one from another. This literature review covers the state-of-the-art on ship electrical and mechanical basic architectures and the literature review of maritime shipping decarbonization is presented in chapter 3.

2.1 Ship power train architectures

Every ship power train architecture can be classified in four different categories [17]:

- Mechanical-drive: most commercial ships are designed with a mechanical drive nowadays. It consists of a segregated power system in which the propulsion prime mover has a direct coupling to the propeller. The ship's service load is supplied by service DGs.
- Electrical-drive: The ship's propeller is coupled to electrical motors. These propulsion motors are supplied by DGs separated from the service load DGs.
- Integrated-electric: In integrated-electric architectures, the dedicated propulsion DGs and service load DGs are all connected together.
- All-electric: When all loads that are normally supplied by: the boilers, the hydraulic systems, and compressed air, are converted to electric, the ship becomes completely electric.

Mechanical-drive is the most common type of architecture for commercial applications because it is the most efficient solution in terms of operational costs and initial capital investment. The mechanical-drive layout is shown in Figure 2.1 and is composed of two systems: The propulsion system and the auxiliary system. The propulsion system is made of a prime mover used to propel the ship. This prime mover is generally a two-stroke main engine. Then, the auxiliary system is made of multiple smaller four-stroke prime movers coupled to generators in series to generate electricity for the ship service load. The combination of the four-stroke prime mover and a generator is a DG set. DGs can also be referred to as gensets. In this configuration, the DG directly supplies an AC distribution system. Finally, a shore connection is often used to supply the ships load in port or when the ship is in dry docking.

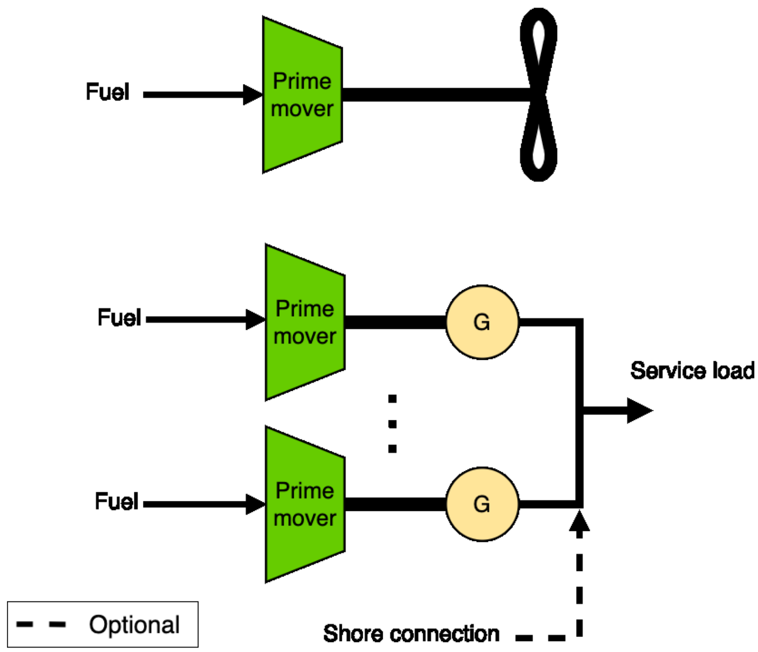

Figure 2.1: Mechanical-drive architecture (adapted from [15] and [18])

Generally, heavy fuel oil is supplied to the propulsion two-stroke prime mover. Since heavy fuel oil is very viscous, a system composed of settling fuel oil tanks, purifiers, and heaters cleans and heats up the oil so that it can become fluid and be supplied to the main engine. Higher quality oil like diesel oil will not require such process before being supplied to the prime mover.

Figure 2.2 presents a more detailed picture of a commercial main engine and the rest of this paragraph briefly describes the role of the main components. The turbocharger is used to augment the air pressure in the scavenged airspace of the main engine so the air entering the cylinder can be greater. The exhaust gas coming from the main engine makes the turbo turn which activates a compressor that creates an air vacuum. However, auxiliary blowers need to start at the engine start up or when the engine load is low to compensate the turbocharger low air pressure. This is one of the main electric loads on the service DGs when the ship departures. The air entering the system needs to be cooled by an air cooler. This cooler is cleaned by a water spray system called the chemical air cleaner and stores the dirty water in the chemical water tank. A main lube oil pump circulates the oil in the main engine. The pumped oil is used to cool the engine and lubricate the bearings, camshaft, and camshaft drive. The oil is cooled by freshwater coolers. Finally, the pistons are fired up following a specific sequence to make the engine's shaft turn through the con-rod and camshaft.

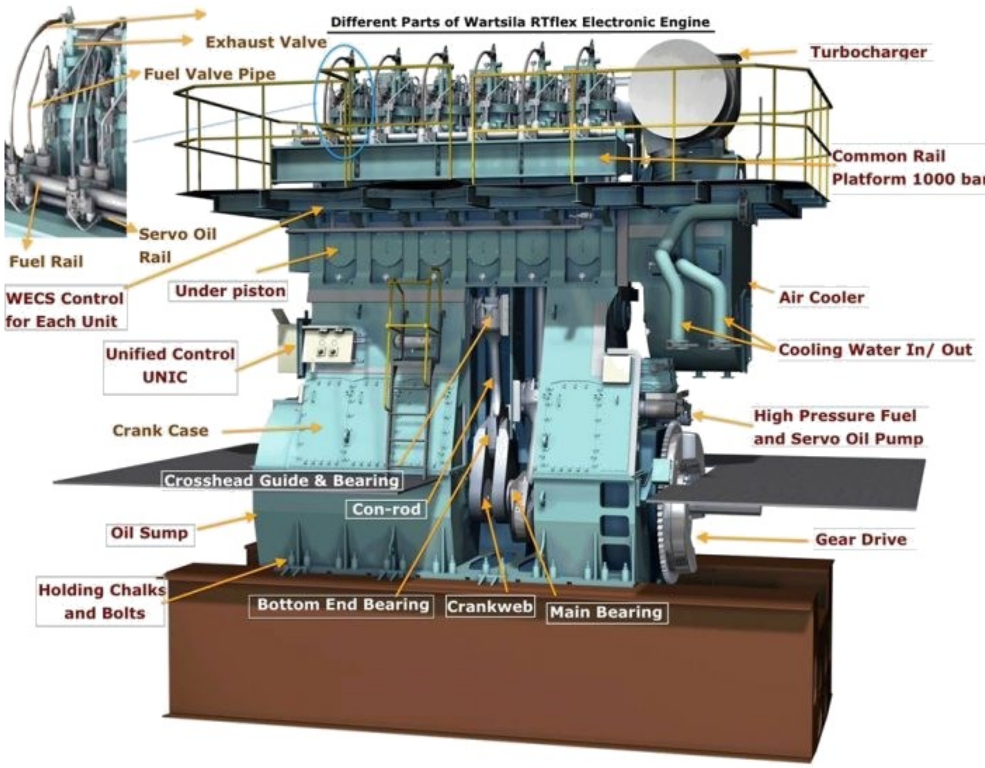

Figure 2.2: Typical two-stroke ship main engine [19]

The auxiliary system generates electricity with diesel generators. There exist different types of generators such as DC exciter, AC exciter, and static exciter, but most modern synchronous generators on ships use a brushless exciter [17]. Indeed, brushless exciters eliminate the need for brushes and slip rings which can cause short circuits and augment the operational cost. Furthermore, generators with brushless exciters do not need an external power source since they generate their own power to excite the main windings of the generator.

A brushless exciter has two main systems: the pilot exciter and the main exciter. This combination is required to amplify the current produced by the pilot exciter so the main exciter can generate enough current to excite the rotor windings of the generator. The pilot exciter uses permanent magnets on the rotor to generate a small AC current on the stator.

Figure 2.3 presents a brushless excitation system. In more details, the pilot exciter's permanent magnets fitted to the rotor of the generator produce a small AC current in the pilot exciter's stator when the prime mover is started. After, this AC current is converted to DC to produce another magnetic field on the main exciter. The main exciter can be seen as an inverse generator since the magnetic field is produced on the stator instead of on the rotor. This enables to transfer the current to the rotor main exciter armature without brushes or slip rings. Then, a diode bridge on the rotor rectifies the current to produce the generator exciting current. This diode bridge is also called the diode wheel since it lies on the rotor. An automatic voltage regulator system is used to control the exciter current of the pilot exciter and the resulting output voltage of the generator.

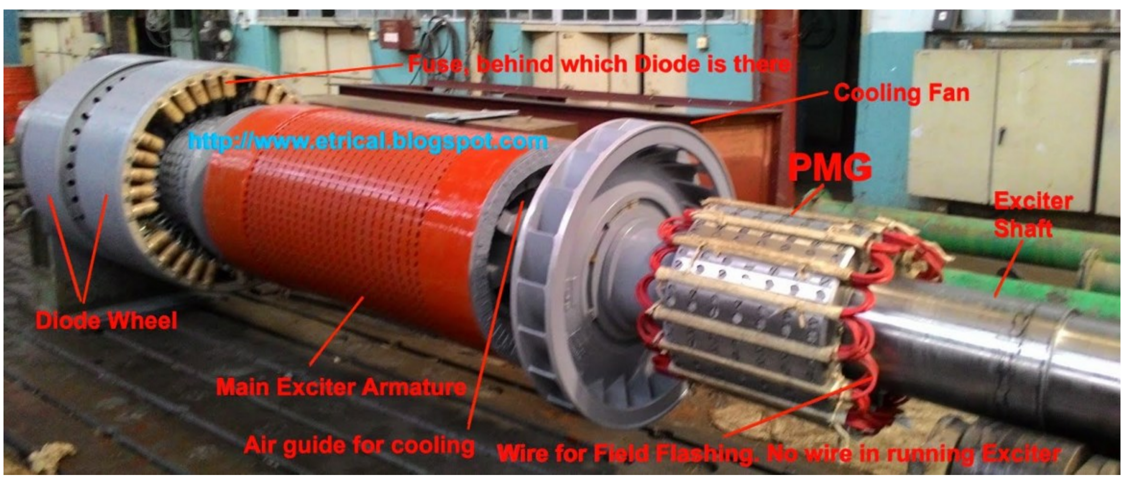

Figure 2.3: Brushless excitation system [20]

On this kind of configuration, the prime mover of the DG must keep a constant rotating speed since it will dictate the frequency of the main bus. Therefore, a governor is used to control the amount of fuel supplied to the engine. There are three types of governors: mechanical, hydraulic, and electric. The electric ones are the more precise and quicker one to react. Like the main engine, the auxiliary generators are equipped with a cooling system, fuel system and a turbocharger to augment the air pressure in the cylinder. The DGs can be fuelled with heavy oil or with diesel oil. Figure 2.4 presents a typical DG in the maritime industry.

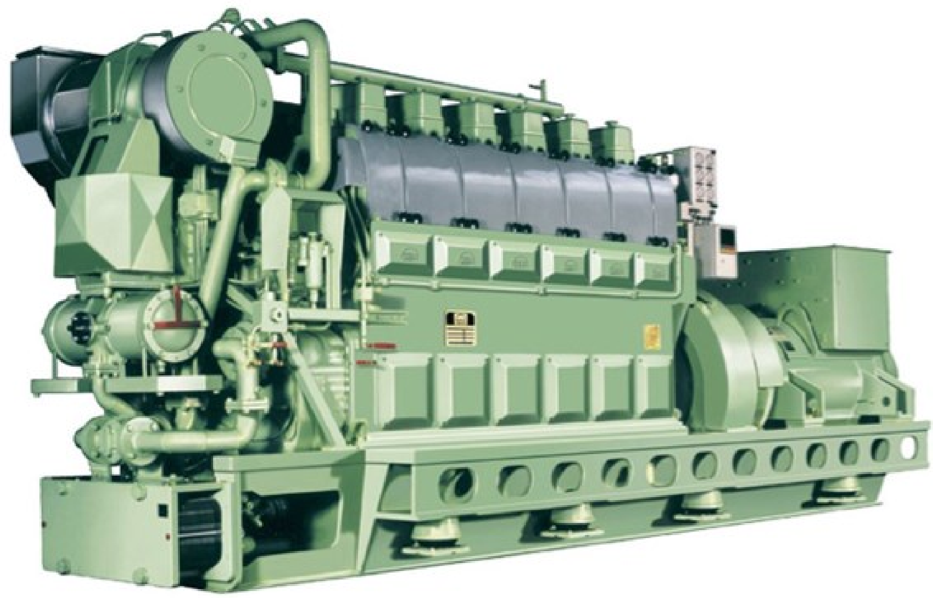

Figure 2.4: Typical marine diesel generator [21]

In older systems, the DGs needed to be synchronized manually with the help of a synchroscope and synchronizing lamps when the operators wanted to operate multiple DGs in parallel. This process is required in AC system, so the main bus frequency stays constant. Nowadays, the synchronization is done automatically, but the synchroscope and synchronizing lamps are still present for backup.

An alternative that mechanical-drive ships are considering is the addition of a shaft generator enabling the service load to be supplied by the main prime mover while the ship is at sea, and thus completely shutting down the DGs. This configuration enables to reduce tremendously the maintenance cost of the DGs. Indeed, after approximately one year of running time, a DGs must have major maintenance overhaul. Further, the fuel consumption will be optimized since two-stroke main engines are more efficient than four-stroke DGs. Lastly, the shaft generator might be used as a motor to increase the ship’s propulsion power, if it’s needed. This shaft generator system is typically called a "shaft generator with power take in (PTI)/power take off (PTO)" [22]. It is presented in Figure 2.5:

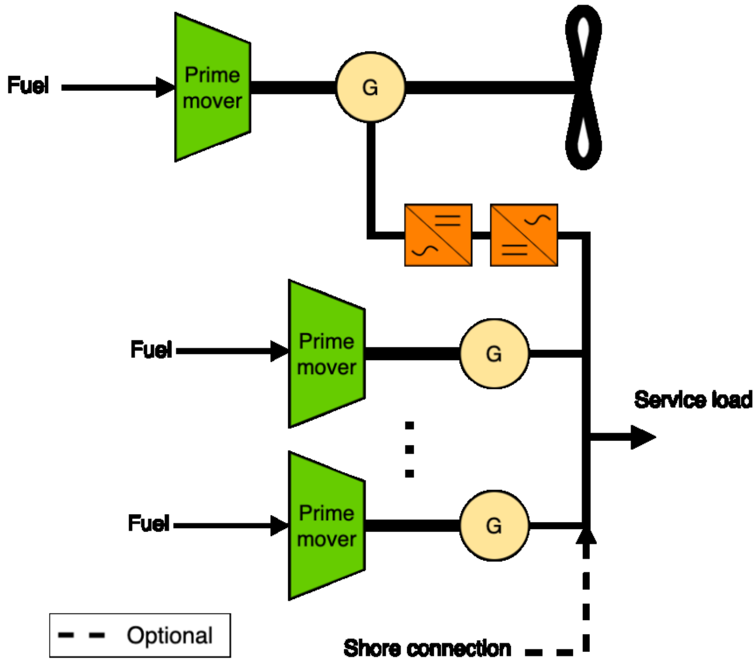

Figure 2.5: Mechanical-drive architecture with PTI/PTO

A major flaw of DGs in maritime applications is their low efficiency. For safety purposes, the DGs are designed for the maximum loads, but they are rarely operated in these areas whereas it's at maximum load that they are the most efficient. To overcome this issue, future generation of mechanical-drive architectures are considering replacing one of the DG with a marine battery as shown in Figure 2.6.

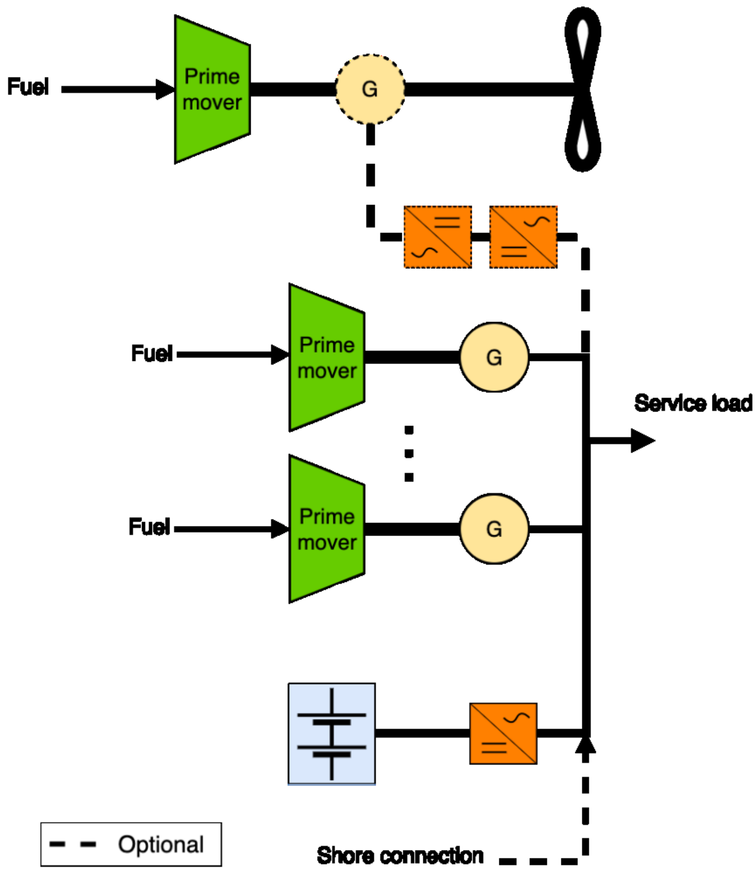

Figure 2.6 Mechanical-drive architecture with a DG replaced by a marine battery

The objective of the battery is to supply high power demands so the DGs can be operated at their most efficient level. The shore power connection will also benefit from the battery since power peaks will be supplied by the battery instead of the grid reducing the electrical cost of power and the size of the shore power connection. Also, the battery will be recharged during low power demands of the auxiliary system enabling to reduce emissions and OPEX of the ship. Furthermore, the DC link will facilitate the integration of renewables, such as solar panels or wind turbines.

Electrical-drive, integrated-electric, and all-electric architectures all use electric motors for the ship's propulsion and DGs to generate the electricity. A variable frequency drive enables the operator to change the rotating speed of the propeller and to use it at its most efficient point. Also, integrated-electric ships are equipped with many DGs to better match the load and optimize fuel consumption. Figure 2.7 presents a scheme of an integrated-electric architecture.

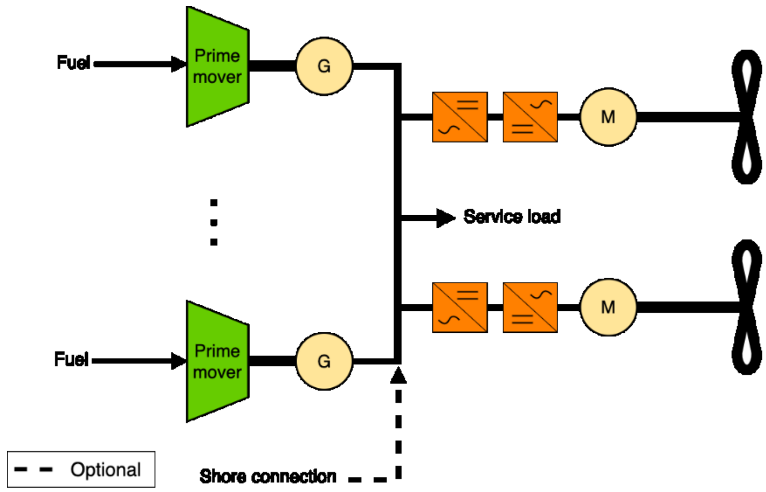

Figure 2.7: Integrated-electric architecture

As discussed previously, the difference between electric-drive and integrated-electric architectures is that electric-drive has dedicated DGs to supply the propulsion electric motors. Since the architecture is like integrated-electric, the scheme of electric-drive is not presented. The all-electric architecture is not presented for the same reason. Electric-drive, integrated-electric and all-electric ships have the advantages of better control of the ship due to the fast response of electric motors compared to main engines, reduction in noise and fuel consumption in certain cases. Nowadays hybrid configuration can integrate batteries and fuel cells to the power train as presented in Figure 2.8.

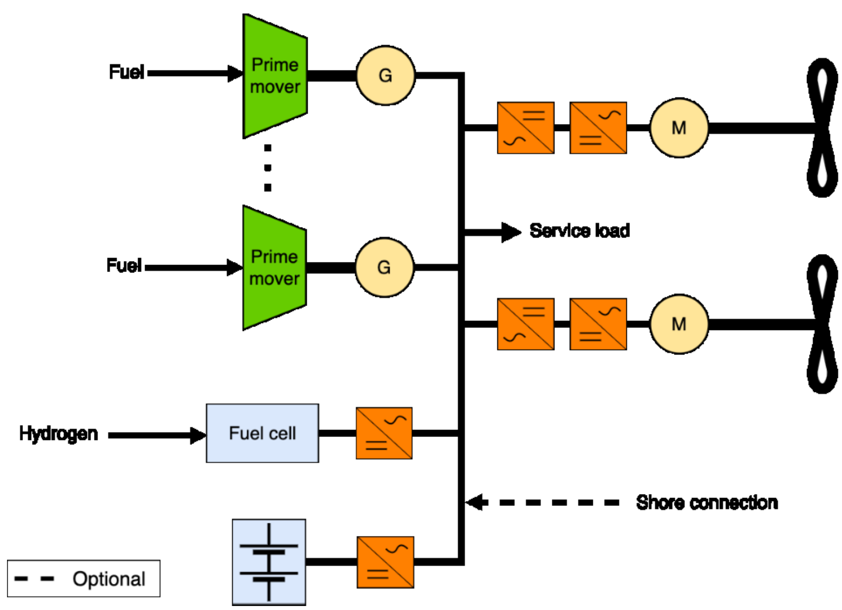

Figure 2.8: Integrated-electric architecture with fuel cells and batteries connected to the main bus

While hydrogen is still in early stages of developments, it is considered as a key step toward the development of zero-emission ships (ZES). Indeed, if the DGs are withdrawn from the power train of Figure 2.8, the ship would not emit GHG while sailing or in port. Nonetheless, DGs can be kept onboard for emergency purposes.

The next section takes a step deeper into the electrical system on ships.

2.2 Ship electrical system

There is a wide variety of types of ships all requiring specific electrical systems based on their needs. Indeed, large cruise ships will have high voltage[1] distribution systems because of their very high electric load while handysize merchant ships might only require low voltage distribution systems. Small ships like tugs, small ferries, handysize dry bulk carriers, and handysize tankers, generally operate on AC 400 V, 440 V or 690 V 50/60 Hz three-phase distribution systems. Larger ships or ships presenting very high electric load like cruise ships, offshore drilling ships, Ro Pax, and large dry bulk carriers, normally use AC 3.3 kV, 6.6 kV or 11.1 kV 50/60 Hz three-phase distribution systems. However, the high-level view of electrical distribution system and electrical drawings are similar. Figure 2.9 presents a 440 V AC three-phase electric distribution system. While it is a specific example, other distribution system will be based on similar principles.

[1] High voltage in the maritime industry includes any voltages higher than 1000 V.

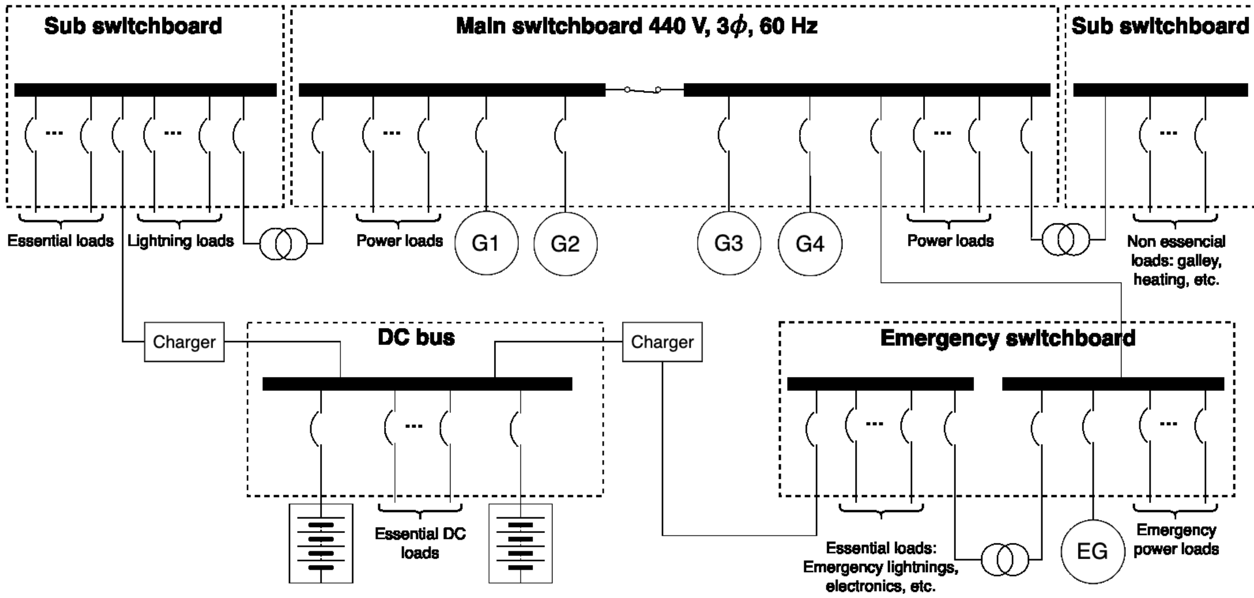

Figure 2.9: AC 440 V three-phase ship electric distribution system supplied by generators (G) and an emergency generator (EG)

Most of the ships in the world use DGs to supply their auxiliary load or propulsion load into the case of electric-drive, integrated-electric and all-electric ships. The electricity is supplied by DGs coupled in parallel that are turned on and off by the mechanical engineers to fit the electric load.

A main characteristic of a ship distribution system is the separation of the main bus bar in two sections by a closed bus tie. As many other things on a ship, everything is done to augment resilience and safety. The separation of the ship into two sections provides redundancy and a way to supply the essential loads in different manners if something happens to the primary source of power. The loss of power to essential loads and equipment can cause the ship to become uncontrollable and endanger the crew. This loss of power is called a *blackout*. If a blackout occurs, the emergency generator will start automatically. If it does not, the crew members are trained to start it manually. The emergency switchboard is supplying essential loads such as radio equipment, navigation lights, and spare steering gear hydraulic pumps. It is normally powered by the main bus bar but can be powered by the emergency generator in the case of a major fault on the main bus or in a blackout. Also, all important equipment or machinery comes in pairs of two with one in standby. The standby unit can be connected to the other feed bus or to the emergency switch board depending on its importance.

The DC switchboard is powered by the battery charger and the batteries themselves. Therefore, when a blackout occurs, the batteries can still power the essential loads while the emergency generator is started. They can generally provide 4 to 5 hours of autonomous operations.

Despite being similar, the grounding is also different from land to further protect the ship's electrical system. First, the ground is replaced by the ship's hull. On land, the neutral is used to detect any ground fault, causing the breakers to trip and fuses to open. This situation will lead to a loss of power, but the safety of the humans is not put in immediate danger. However, it is different on a ship. When a blackout occurs, the control of the ship is lost, and this could cause the ship to get in serious trouble putting the safety of the crew in more danger than before.

To lower the risk of a loss of power, most of the ship's equipment is not grounded to the neutral. As shown in Figure 2.10, this enables to make the electrical system single ground fault resilient. It will require a second ground fault to create a short circuit that will trip the breakers. Electrical insulation leaks are therefore regularly checked to ensure crew safety. While the electrical machinery is not connected to the ground for equipment safety, their casing is for human safety hence limiting the effect of charge accumulation. There is one exception concerning the neutral wire. It is generally integrated to 120 V sub switchboards to improve human safety with a dependent protection system.

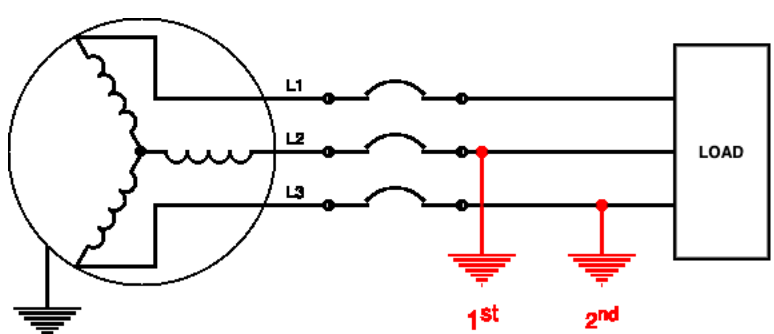

Figure 2.10: Ground fault on ships

Since this work is focused on dry bulk carriers sailing in the St. Lawrence River and Great Lakes, the following section introduces bulk carriers.

2.3 Bulk carriers

Bulk carriers are merchant ships that are designed to transport freight in bulk such as grain, coal, ore, and steel. They store the cargo in large cargo holds that are protected by hatch covers. Bulk carriers are often equipped with deck cranes as shown in Figure 2.11 or with a discharge boom conveyer to give them the capacity of discharging their own cargo. They operate in different modes, but the principal ones are seagoing, loading/discharging, departure/arrival, and rest in port.

They can be classified in different sizes: small (<15,000 DWT), handysize (15,000 DWT-35,000 DWT), handymax (35,000 DWT-50,000 DWT), supramax, (50,000 DWT-60,000 DWT), Panamax (maximum size for the Panama Canal), Suezmax (maximum size for the Suez Canal), Capesize (too large for the Panama and Suez canals), and very large (>200,000 DWT). For example, the Federal Columbia in Figure 2.11 is a handysize dry bulk carrier of 34 500 DWT.

Figure 2.11: Federal Columbia dry bulk carrier

In 2019, there were 11 373 bulk carriers registered in the world fleet, and the average age of the fleet was 9 years. They represent 11.8% of the world fleet by vessel. However, bulk carriers represent the biggest segment of the world shipping fleet by capacity with 842 438 thousand DWT and 42.6% of the world shipping fleet capacity [23] [24].

In Canada around the St. Laurence River and Great Lakes area, a special fleet of bulk carriers called the Lakers are very active. The freshwater and clement environment of the Great Lakes have favored the construction of huge bulk carriers that can carry important amounts of cargo very efficiently. Furthermore, the Lakers called the Salty are the bulk carriers that come out of the Great Lakes to travel the St. Lawrence River and make ocean-crossing trips. They are smaller than the large freshwater Lakers to fit the locks in the St. Lawrence Seaway. Lakers are unique vessels that are shaped in function of the special environment they navigate. Indeed, Lakers generally are ice-classed ships because of the rough winter. This study will focus on the bulk carriers of handysize like the Salty.

On the high level, bulk carriers electrical design is regulated by the International Convention for Safety of Life at Sea (SOLAS) of the IMO [25]. Over the years, the power system of bulk carriers has evolved to gain in efficiency and power. Older vessels were powered by steam.

Bulk carriers of handysize are typically equipped with an AC three-phase internal bus. In North America, the internal bus is 440 V and 60 Hz. Figure 2.12 shows a typical dry bulk carrier that can use three DGs in parallel. Most bulk carriers are equipped with a shore power connection of low power to supply essential loads in dry-docking situations. Others can be equipped with a high-power shore power connection from which the energy can come when the ship is at berth.

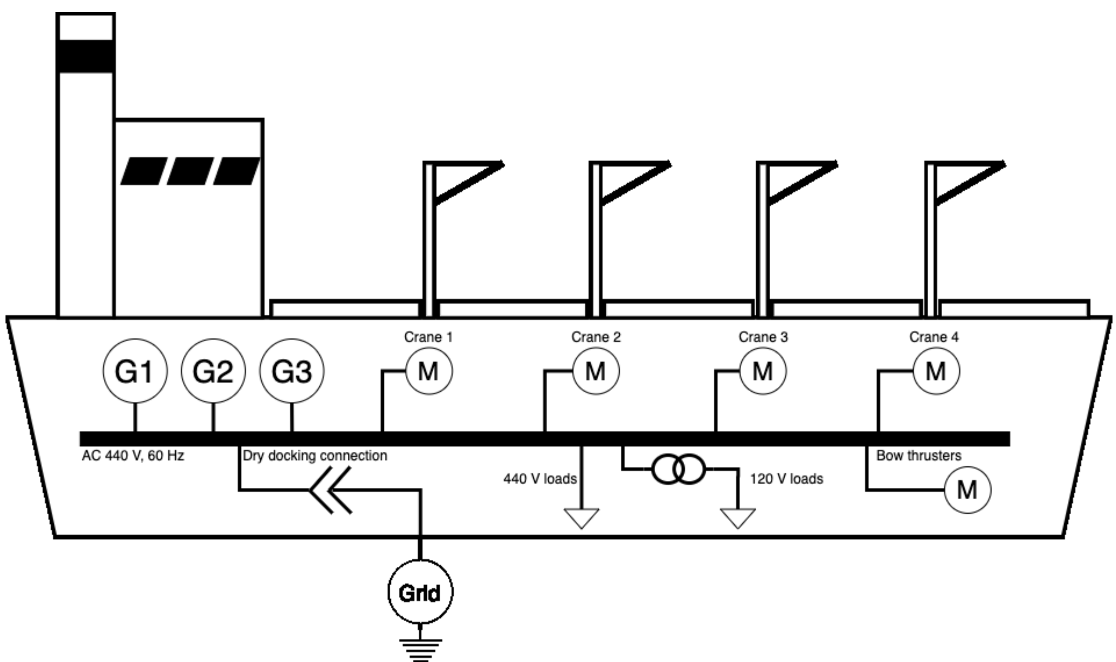

Figure 2.12: Typical handysize bulk carrier distribution system

The biggest load on a bulk carrier auxiliary system generally is the bow thrusters. The bow thrusters are made of an electric motor coupled to a propeller inserted on the low forward hull. The thrusters generally are controllable pitch propellers, giving them the ability to control the thrust with the pitch of the propeller. A variable frequency drive can also be used instead of a fixed pitch propeller. The bow thrusters are used to give more agility to the ship since it can displace the front of the ship in the left/right direction. Therefore, the ship does not rely on tugboats to dock in ports. It is also very useful in the lock systems or channels giving more control to the ship in narrow passages by compensating the suction effect that can make the ship curl when being too close to the shore.

Some bulk carriers rely on shore cranes and shore conveyers to load and unload the cargo. To gain flexibility in port calls and access ports or berths that are not fitted with loading or unloading equipment, deck cranes or conveyers can be fitted directly on the bulk carriers. The conveyers travel the cargo from the bottom of the ship to the shore. This system creates a high constant load power demand on the auxiliary system of the ship. Then, deck cranes are also used as another way to unload and load the cargo. Deck cranes can be less efficient than conveyers for cargo like grain and ore, but they enable the ship to load different types of cargo that cannot be handled by conveyers such as steel and miscellaneous objects. Deck cranes have three degree of freedom operated by a hydraulic or electric system creating a variation on the load of the auxiliary system: hoisting to lift or lower the load, luffing to raise or lower the jib, slewing to rotate the crane. Whether deck cranes use a hydraulic system or an electric system, cranes will use a lot of power during loading/discharging phases.

Another main load of bulk carriers in ports is the ballast pumps. Indeed, they are used to control the draft of the ship during loading and discharging operations by pumping enormous quantity of sea water in the ballast tank. Yet, the main use of the ballast is to provide more stability to the ship when its holds are empty by lowering the centre of gravity of the ship.

Next, the anchor windlass consists of a hydraulic system and is used when a ship is waiting at anchor near the port for its turn to come. Yet, with the more and more use of the “just in time” concept, ships pass less and less time at anchorage. The anchor and anchor windlass are also used to secure the ship when it cannot stay at the dock due to bad weather.

Other hydraulic systems are also requiring an important power input from the auxiliary system. Indeed, the hatch covers are opened and closed to give access to the cargo or to protect it and the mooring winches are used when the ship secures at the dock. When the ship is in an area with tides, the cables need to be tightened or loosen constantly by the mooring winches. Often, self-tensioning systems are used, but that requires a constant utilization of the mooring winches hydraulic pump and augments the load on the auxiliary system.

Finally, many large pumps or air compressor also present non-negligible loads of the auxiliaries. Examples of such loads are: the jacket cooling freshwater pump, the sea water service pump, the fire pumps, the air conditioning refrigeration pump, the main air compressor, the bilge pump, the auxiliary blowers, the main lube oil pump, and the main engine high-pressure pump.

To understand the state of the research on shore power and to determine how bulk carriers and shore power are positioned in the literature, the next section presents results of a systematic literature review (SLR) about shore power.

2.4 Systematic literature review about shore power

This SLR has been made to understand the state of the research on shore power nowadays and is based on "Kitchenham guidelines" [26]. By analyzing most of the shore power related articles in the literature with a systematic methodology, it has been determined that a lot of work can still be done to improve the shore power technologies and systems.

Using the research keywords: "Cold ironing," "On-shore Supply Power," "Alternative marine power," "Shore-to-ship power" and "Shore Connection Power" in different databases from the year 2000 till September of 2020, 525 studies have been analyzed. Based on the relevance of the content for shore power, 82 studies have been selected. Table 2.1 presents the summary of this extended process. The rest of this section presents and analyzes the relevant findings that resulted from the data analysis.

Table 2.1: Systematic literature review analyzed articles

Database	Number of search results	Number of relevant papers
IEEE Xplore	106	31
Science Direct	173	32
Springer Link	133	7
MDPI	83	10
Taylor and Francis Online	30	2
Total	525	82

The main motivation for shore power is its amazing GHG an air pollutant reduction in port areas and cities because it allows ships to turn off their engines at berth. Indeed, 57% of the articles analyzed in the SLR have environment as their first motivation or goal. China is the biggest contributor in the research sector of shore power with the third of the articles and ports being Chinese. That might be because they suffer a lot from the pollution effects caused by the intense marine traffic of this area.

Even if shore power was mentioned in articles since the 90s, the first relevant article analyzed in the SLR arrived in 2007 as it can be seen in Figure 2.13. Back then, articles were more concerned about the technical problems related to the technology.

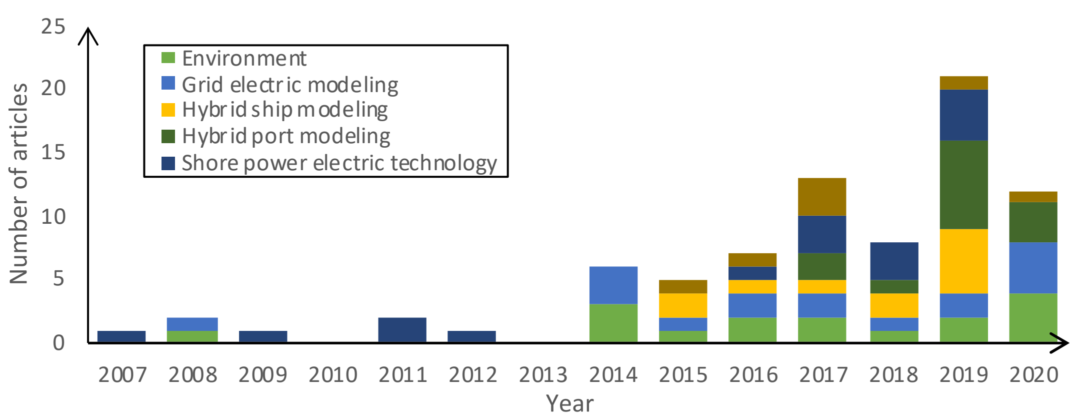

Figure 2.13: Number of studies about shore power in function of the studies year of publication and topic

Thanks to the arrival of new international standards on shore connection, namely IEC/IEEE P80005 part 1, 2 and 3 [11][27][12], high voltage supply connections (HVSC) made an impressive entry in the research world with 36% of the articles using this technology followed by 7% for low voltage supply connection (LVSC) and 3% for medium voltage direct current. The rest of the articles did not specify any shore power standard. The research on shore power technologies is still actual, and it is shown by the number of research and by the fact that the LVSC standard still is a draft. Also, medium voltage direct current technologies start to be more studied to respond to the growing interest for DC internal bus.

Since the arrival of the first mature shore connection technology at the beginning of the last decade, a growing interest in the domain has borne. However, a new challenge drives most of the research nowadays: the cost. Funding, high CAPEX and high OPEX are the main issues that many articles try to tackle down by trying to minimize the cost and emissions independently or at the same time.

Through all the SLR articles, many energy sources are studied like the grid, the on-board diesel engines, solar panels, wind turbines, batteries, and fuel cells. For port microgrids, designers usually work with the combination of the grid, solar panels, wind turbines, batteries, and the diesel engines inside the berthed ships. Hybrid ship designers tend to use the grid, the diesel engines, and batteries instead. Renewables do not appear as a suitable solution since they were used in a few articles.

To size the components of their systems, the designers used different mathematical techniques presented in Figure 2.14.

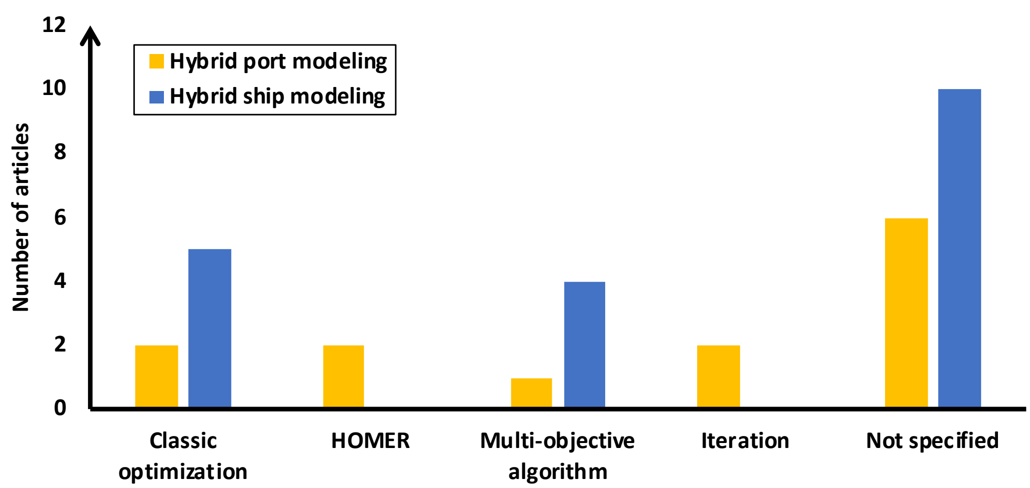

Figure 2.14: Sizing mathematical techniques used in the relevant studies

In the case of the port shore power design side, researchers used:

- Classic optimization techniques, which consist of determining the required capacity of the components with their associated formulas.
- HOMER, which is a software developed by a private organization.
- Multi-objective, which consists of determining objective functions to minimize or maximize such as CAPEX and emissions, and using an algorithm to find the best solution.
- Iteration, which works by iterating the mathematical model and select the best solution that has been found.

In the case of ship shore power design, classic optimization and multi-objective algorithms are generally used.

Only four articles used a multi-objective algorithm to design their system. This is a small quantity, and a lot of work can be done to improve the mathematical model. Table 2.2 dives into the objective functions to minimize and the multi-objective algorithms used to solve the problem.

Table 2.2: Hybrid ship modelling sizing mathematical technique, algorithms and objective functions

Article	Objective functions	Algorithm
Simultaneous energy management and optimal components sizing of a zero-emission ferry boat [28]	• CAPEX • OPEX	• ISCA
Strategy development for retrofitting ships for implementing shore side electricity [29]	• CAPEX • Environmental benefits	• NSGA-II
Hybrid fuel cell and battery propulsion system modelling and multi-objective optimization for a coastal ferry [30]	• OPEX • GHG	• Mixed integer
Optimal design of a hybrid electric propulsive system for an anchor handling tug supply vessel [31]	• CAPEX + OPEX + Lifecycle cost • Fuel consumption • GHG	• NSGA-II

Finally, energy management strategies and algorithms were used by the designers to optimize the power flow between the load and the different sources minimizing operational costs and emissions. Figure 2.15 presents the strategies used in the SLR articles.

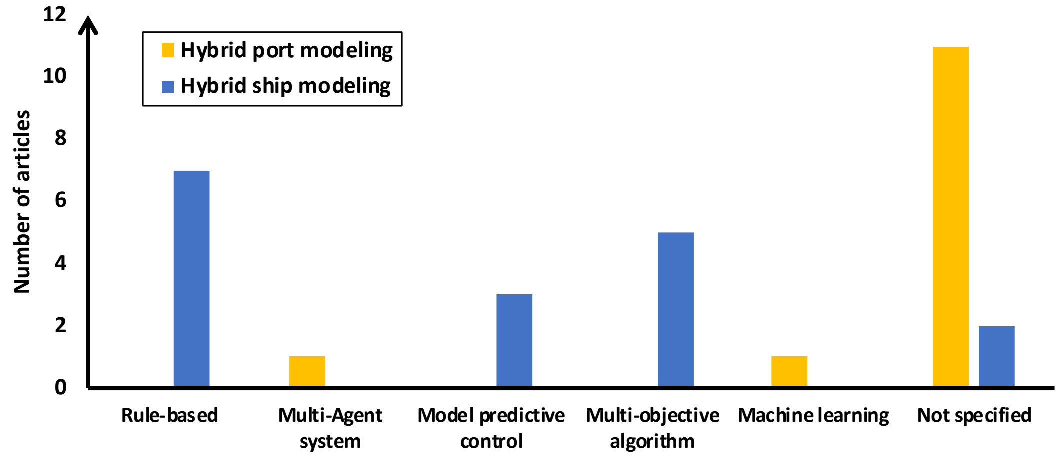

Figure 2.15: Energy management strategies used in the relevant studies

Since most of the power comes from the grid and renewables in the port microgrids, not much research has been done to try to manage the power on the shore. However, more could be done to match better the renewables window, do peak shaving with the batteries, and more.

For hybrid ship designers using shore power, it is the opposite scenario. Energy management strategies are studied by most of them. The rule-based strategy is the most common and the number of studies shows that this technic takes maturity. Multi-objective and model predictive control strategies are still in an early stage of research and need to be further investigated.

Finally, researchers studied a wide range of ship types as presented in Figure 2.16.

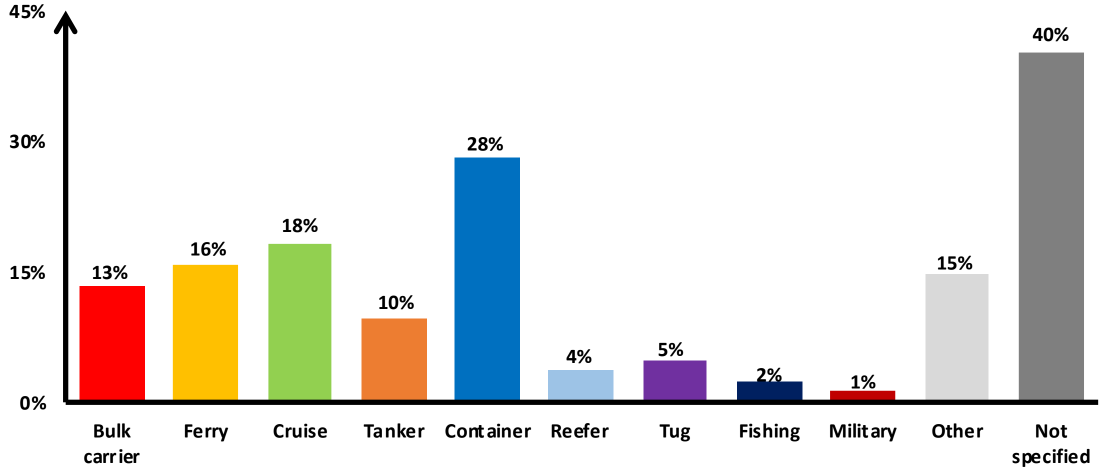

Figure 2.16: Analyzed ship types

Container ships are the most studied ships in this SLR. This might be caused by the fact that big container ships represent a good portion of the world maritime traffic. Since those huge ships generally operate on high internal bus voltages and are characterized by a smooth and constant power load at berth, they are good candidates for shore power HVSC applications. The cruise ships are also very good candidates because their power load in port is enormous due to the high hoteling demand. However, bulk carriers have not been studied much while they could benefit a lot from shore power. Indeed, they are often equipped with deck cranes which demands a lot of power and energy in loading/discharging operations. Because of this fluctuating high power demand, the system would benefit from a good energy management strategy to lower the cost of operation and demand on the local grid.

In short, the current state of research on shore power compliant systems is well documented in the literature and well advanced, but many aspects were not much investigated. Since environment is the main motivation for shore power and CAPEX its biggest weakness, a methodology should be put in place to reduce emissions and CAPEX simultaneously. Furthermore, LVSC has not been well covered by the current research and must be more detailed to give a cheaper solution to low power and low-voltage applications. This will extend the range of ships that will benefit from shore power. Only large ships work on high voltage such as 3.3 kV, 6.6 kV and 11.1 kV, and even if they consume a lot of power at berth, smaller ships could also benefit from the technology if the CAPEX was lower. Finally, new concepts could be proposed and studied to enhance the current systems.

The SLR indicated that a lot of work could still be made to lower costs and make this technology more efficient. A study using multi-objective algorithms to design the system would be appropriate considering the context of shore power. Bulk carriers present great challenges to connect to shore power especially if they use deck cranes during the loading/discharging process.

Next chapter presents a research paper [13] that details the literature review on shipping decarbonization. Since many different measures and technologies can be used by now to diminish and eliminate GHG of the maritime industry, it is required to understand what the different measures and technologies are, where they come from, what their potential is, and why shore power stands out compared to the other solutions. The paper contains a SWOT analysis to facilitate the comprehension of shore power and to put the pros and cons of shore power in perspective. Finally, the environmental performance study of a handysize bulk carrier is realized in this chapter.

CHAPTER 3

3 MARITIME INDUSTRY DECARBONIZATION

Foreword

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Date of acceptance: 7th of December 2021

State of acceptance: Final version published (doi: 10.1016/j.etran.2021.100150)

Journal: eTransportation – Elsevier journal

Reference: [13]

French title: Alimentation à quai en tant que premier pas vers la décarbonation de la marine marchande et impacts sur les règlementations environnementales d'un vraquier sec

English title: Shore power as a first step toward shipping decarbonization and related policy impact on a dry bulk cargo carrier

3.1 Abstract

Maritime shipping currently emits 2.89% of the world greenhouse gas (GHG) emissions and it is estimated that the sector will reach the road transportation level by 2060. International environmental regulations push the industry to lower their GHG emissions, but the feasibility and viability of future green energy is uncertain. This paper presents a road towards green maritime shipping by proposing shore power, also known as cold ironing or alternative marine power, as a key measure to decarbonize the industry. Therefore, transition pathways and the available measures to decarbonize the industry are analyzed. A theoretical description of shore power along with a strengths, weaknesses, opportunities, and threats (SWOT) analysis of the technology is discussed. The paper is also supported with a test case on a real bulk carrier to measure the score improvement of shore power on the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Index (CII). In summary, shore power can reduce

GHG and air polluting emissions at ports right now and across the world. The case of study determined that shore power could improve CII by 7.8% and policy modifications have been presented to include shore power in EEDI and EEXI calculations. Most of all, shore power can eliminate 100% of emissions of ships at berth right now. Furthermore, shore power is a prime mover for the development of new maritime applications like hybridization and electrification.

3.2 Introduction

The maritime transportation emissions are estimated to be 2.89% [32] of the global GHG emissions, 13% of the nitrogen oxides (NO_x) emissions, and 12% of sulfur oxides (SO_x) emissions [33]. This massive industry represents 80% of worldwide commerce and 70% of its total value [34]. Even though maritime shipping is known for releasing the fewest grams of CO_2 per ton-kilometer of cargo transported, it is estimated that sea transportation emissions will reach the road transportation level by 2060 [35]. Because ships are massive and sail for decades, it is hard to renew the world fleet with new technologies as quickly as the automotive industry does.

To tackle the problem, international efforts are underway. The IMO was initially concerned about maritime safety, but in 1954, they adopted the first convention on the environment: the "Convention for the Prevention of Pollution of the Sea by Oil," also known as OILPOL. Since then, environmental measures grew enormously at the IMO. In 2011, the adoption of two critical regulations during the Marine Environmental Protection Comity (MEPC) Resolution MEPC.203(62) [36] would significantly impact the future of shipping: the "Energy Efficiency Design Index" and the "Ship Energy Efficiency Management Plan". The EEDI deals with newly built ships efficiency, while the SEEMP is intended to enhance existing ships efficiency. According to EEDI, newly built ships of 400-gross tonnage or heavier will need to be 30% more efficient by 2025 compared to 2008 ships.

During MEPC.304(72) [36] of April 2018, the MEPC committee adopted an initial strategy to reduce GHG emissions from ships. The committee stated its "levels of ambition," amplifying previous declarations, and firmly expressing IMO's intent to:

- Peak GHG emissions from international shipping as soon as possible and reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008.
- Reduce the CO_2 emission per transport work of the international fleet by 40% in 2030 and 70% in 2050.
- Decline carbon intensity of ships through the implementation of further phases of the EEDI for new ships.

To complete its initial strategy, more measures to lower GHG from ships were proposed by the Intersessional Working Group on Reduction of GHG from Ships of the IMO. The new measures about the EEXI and the CII were agreed during MEPC(75) and adopted at MEPC(76). From 2023, existing ships will need to be about 20% more efficient, depending on the ship type, compared to 2008 baseline as presented in MEPC(75)/WP.3 [37][38]. Also, their carbon intensity will need to be reduced of at least 11% in 2026 compared to 2019 baseline as presented in MEPC(76)/WP.4 [39][38]. These measures further increase the urgency towards decarbonization and the pressure on shipowners to comply with more environmental regulations. Nevertheless, shipping companies could look at environmental regulations as opportunities because they can be beneficial for economic and environmental performances [8].

Figure 3.1 presents two emission forecast scenarios. The “business as usual” scenario shows a significant increase in CO_2 emissions, while the reduction effort scenario goes in the opposite direction. The IMO objectives are very ambitious and will require major changes in the industry at many levels. Since Phase 3 of EEDI, EEXI and CII will become effective by 2025, 2023 and 2023, respectively, the pressure is growing every day on shipowners to reduce their carbon footprint and the momentum toward greener technologies increases.

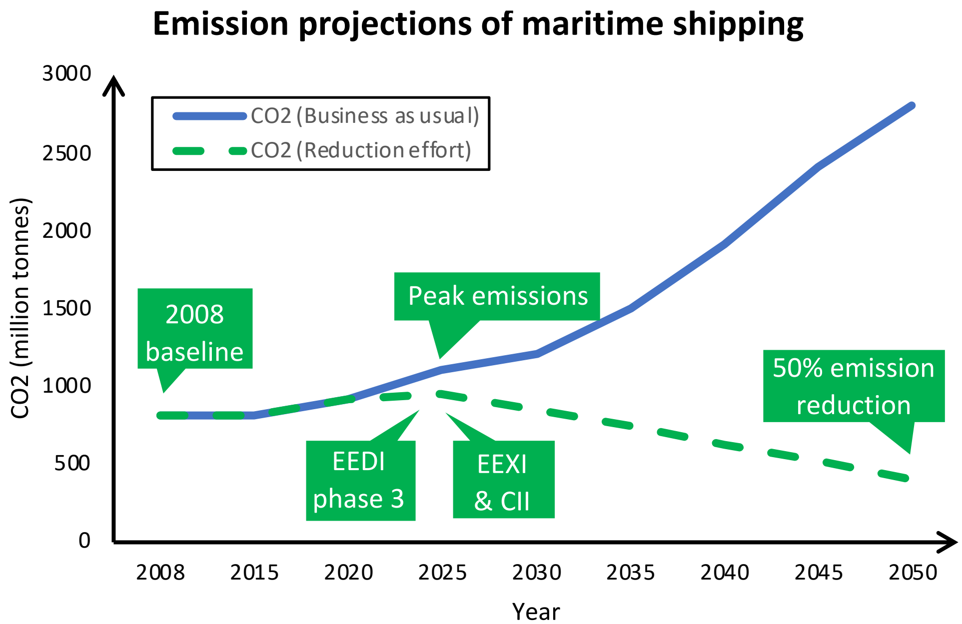

Figure 3.1: Maritime shipping emission reduction outlook and major steps

Other international organizations have implemented mechanisms to encourage shipowners and ship operators to green their fleet. The Clean Shipping Index (CSI) is a non-profit organization that developed a voluntary index using a questionnaire [40] to rate ships based on five main parameters: NOx, SOx, CO_2, Chemicals, Water and Wastes. Ships that attain a certain rating are eligible to financial support sponsored by different organizations. Also, the World Port Sustainability Program introduced the Environmental Ship Index (ESI) to give ships a rating based on a formula [41]. As for the CSI, the ships qualifying for a certain ESI rating access financial support from ports around the world that they visit. Unlike IMO's programs, both CSI and ESI are voluntary indicators. Gibson *et al.* work presents a very detailed description of all shipping environmental incentives and programs existing in the shipping industry before 2019 [42].

In May 2019, IMO adopted the resolution MEPC.323(74) [36] on "Invitation to Member States to encourage voluntary cooperation between the port and the shipping sectors to contribute to reducing GHG from ships." This resolution promotes the regulatory, technical, operational, and economic action in the port sector. Shore power, also known by Cold Ironing (CI), Alternative Marine Power (AMP) and Onshore Power Supply (OPS), is one of the key resolutions promoted by IMO to reduce GHG. Indeed, shore electricity is proven to be effective to reduce shipping emissions at sea and in ports [29][43]. Shore power exists since the early 2000s in the maritime sector. At first, the cruise industry wanted to reduce its environmental impact in fragile environments such as Alaska. Nordic countries were also the first to build hybrid ferries with power coming from the shore network. However, California state made shore power expand on a larger scale by adopting the "Ocean-Going Vessel At-Berth Regulation" [44]. As a solution to air quality issues, the state set up several measures to integrate shore power to all its major ports such as Los Angeles, Seattle, San Francisco, and San Diego. In 2020, 80% of the energy used by certain types of ships at berth needed to come from shore power or an equivalent environmentally friendly power source.

Early studies already estimated the fuel consumption in ports. Dalsøren *et al.* [45] found in 2009 that 5% of fuel consumption from ships are consumed when they are at berth. The analysis of the "Fourth IMO GHG Study" data [32] shows that an average of 16% of the CO_2 emissions occurs while ships are at berth or at anchorage. Considering the port side, the emission of the ships at berth can reach 50% of ships emissions in ports area [46]. Hall studied CO_2 emissions reductions associated with the use of shore power and found that Norway could reduce 99.5% of the CO_2 emissions of ships at berth because the grid energy comes from hydroelectric power [47]. Up to 97 % of the energy in the eastern part of Canada, i.e., Quebec, also comes from hydroelectric power [48]. Thus, emissions from ships at berth in the St. Lawrence River area could be nearly eliminated. Indeed, the Quebec grid carbon factor in 2017 was only 1.2 g of CO_2/kWh compared to 140 and 449 gCO_2/kWh for the Canada and US average, respectively [49][50]. Looking at the air quality, Mölders *et al.* found that 90% of NO*x* and SO_2 depositions in Prince William Sound, Alaska, were caused by ship emissions [51]. Progiou *et al.* found that 2% of NO*x*, 2.5% of SO*x* and 0.23% of particulate matter $(PM)_{10}$ of the total emissions of Greece were produced in the Port of Piraeus [52]. Finally, Zis *et al.* noted that shore power could deliver emission reductions of 48%–70% in port, and 3%–60 %, 40%–60% and 57%–70% reductions for CO_2, SO_2, NO*x* and black carbon (BC), respectively [53]. Therefore, air quality issues would be remarkably reduced with large usage of shore power.

However, only 4 ports have serious shore power infrastructure in Canada [54], and besides California, only a few states or countries invested in the technology on a large scale. Furthermore, the ports that are equipped with such a system generally only support cruise vessels or ferries and have no terminals for the merchant fleet. The bulk carriers represent 19.5% of the world fleet by vessel and is the largest segment [55]. Still, relatively few studies address their environmental issues. The bulk carrier's energy efficiency and operating point have been studied in [56], [57], [58] and [59]. Then, the impact of EEDI on bulk carriers and the best setups to fulfils IMO's requirements are investigated in [60] and [61]. Finally, bulk carrier yearly emissions and Energy Efficiency Operating Index (EEOI) values are assessed in [62] by Kanberoğlu and Kökkülünk.

Therefore, this paper addresses the literature about the shipping decarbonization and proposes shore power as a first step in this direction. To support this hypothesis, shore power is analyzed with a SWOT analysis. Then, the impact of shore power on international environmental regulations and incentives are investigated through a test case with a bulk carrier. The actual pros and cons on these policies are discussed and recommendations are formulated to further promote shore power.

The paper is divided in five sections. In Section 3.2, the author introduces the shipping decarbonization alongside actual policies driving the shipping industry and concludes on the importance of shore power. Section 3.3 dives deeper into the decarbonization pathways and analyzes the shore power with a SWOT analysis. Then, Section 3.6.1 presents the methods used to analyze the impact of shore power on environmental regulations. Afterwards, Section 3.7 presents the results of the research and discuss the policy implications of shore power. Finally, Section 3.8 concludes with the main findings of this paper, their implications, and future propositions.

3.3 Uncertain future of maritime shipping

Numerous options to decarbonize and develop zero-emission ships are available for the maritime industry, but none of them is emerging as a specific trend by now. For this reason, it is very complicated to predict which energy source will dominate in the future. However, specific scenarios are more plausible than others. Lloyd's Register "Zero-Emission Vessel: Transition Pathways" report [35] proposes three pathways that could lead to fully decarbonize the shipping industry:

- **Renewables**

  Hybrid systems like hydrogen and battery ships and other fuels generated by electric energy will dominate the world fleet by 2050, with most of the energy primarily generated on land or sea by renewables.

- **Biofuels**

  Biofuels like bio-methanol, bio-liquefied natural gas (LNG), and biogas will dominate the world fleet by 2050. The production will require more agriculture land use to sustain demand.

- **Equal mix.**

  The energy coming from renewables, biofuels, natural gas, and fossil fuels will be used by the world fleet; no energy source will dominate the others. In this scenario, the shipping industry is not fully decarbonized because fossil fuels are still used.

These pathways represent the high-level outlook of the energy supply chain. Depending on how the technology evolves in the future, one pathway may be dominated over the others. Therefore, questions are raised about how the shipping industry can be decarbonized and about what can be done right now.

3.4 Road toward zero-emission ships

Of all the freight transportation methods, shipping is the most conservative because these ships require substantial investments and operational costs. Furthermore, a merchant ship has a life expectancy of at least 25 years. Therefore, even if zero emission and economically competitive ocean-going ships would appear on the market now, there would still be many ships in 2050 emitting GHGs. Ship retrofits are a feasible option to reduce emissions using innovative technologies; however, it is unlikely to happen on a large scale because of the extra cost. Indeed, shipowners will prefer to focus on newly built ships [63].

Nevertheless, this considers a world where an economically competitive ocean-going zero emission vessel already exists, which is not the case. Actions need to be taken right now to counter the slow modernization rate of the shipping industry while competitive zero-emission ocean-going vessels are developed. Batteries and hydrogen technologies are already used in zero-emission ferries and other types of ships. Indeed, the *Ampere* is the first full-electric car ferry and the *Viking Lady* is the first battery hybrid offshore ship in operation [64]. In Canada, the first all-electric ferries will service the Amherst Island and Wolfe Island in Ontario [65]. However, the same cannot be done with ocean-going ships.

The automotive industry's favorite energy sources to decarbonize the sector are electricity and hydrogen. It is, therefore, instinctive to think the same for the maritime industry. The Sandia National Laboratories published a paper [66] in which empirical approximations show the weight and space available in merchant ships if the internal combustion engine (ICE) was removed. The goal was to see if hydrogen or battery systems could fit in different types of ships. At this moment, none of the ocean-going ships could rely only on batteries or hydrogen in its gaseous state due to lack of space and available weight without compromising precious cargo capacity. All the space needed for access, cooling, maintainability, fire suppression, and containment are important compared to the theoretical space envisioned. While short sea shipping ships can store enough energy for short trips with batteries, hydrogen or both, ocean-going ships can sail many weeks at constant speed to cross the sea requiring an enormous energy storing capacity. Furthermore, hybrid hydrogen/battery systems could benefit zero emission oceangoing ships by improving the system ability to supply high loads while having important energy storage reserve. However, the energy storage reserve size of hydrogen or batteries will not be large enough in this case either to supply the ship's load during the entire sea crossing. According to Sandia, liquid hydrogen could be a good compromise. However, this technology is still not mature and competitive.

Also, the International Council on Clean Transportation (ICCT) report on zero-emission transportation [35] makes a fair comparison between battery, hydrogen, and ammonia systems. The document underlines the fact that none of these technologies are practical and economical for ocean-going ships at the moment, although continuing advances.

Biofuels are an attractive option since they can easily substitute existing residual and distillate fossil fuels without significant vessel design changes. It makes them one of the more favored options for the industry. However, technological advances for next generation biofuels and regulation modifications still need to be made. Also, biofuel production for the shipping industry would have major impacts on agriculture lands for early generation biofuels.

Therefore, all the options are on the table to attain IMO's goal to peak emissions as soon as possible and reduce global emissions. The first step toward decarbonization was determining the actual emissions of the maritime shipping sector and future trends. It has been done in the IMO GHG Studies [32], [33], [67], the United Nations Conference on Trade and Development (UNCTAD) Review of Maritime Transport 2019 [23], and other studies. Now, it is time to find and develop a suitable solution to achieve IMO's targets. In conclusion, three different kinds of measures can be taken to achieve the decarbonization: technological developments, alternative fuels and energy, and operational measures. The discussed data is based on the work of [68], [69], [70], [71].

3.4.1 Technological developments

Technological developments impact the ship itself and aim to enhance ship efficiency. Many technological developments can be implemented by now on many different ship types. Figure 3.2 presents the main ones along with their emission reduction potential.

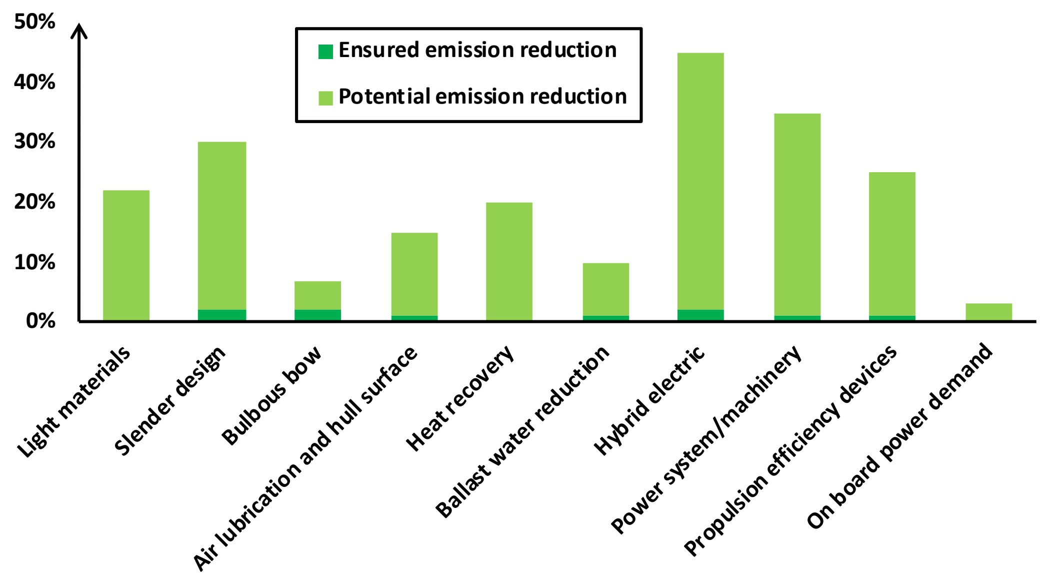

Figure 3.2: Potential of GHG reduction of technological developments

The Figure 3.2 has been created by aggregating the research results from the work of Winnes *et al.* [68], Halim *et al.* [69], Bouman *et al.* [70], and Serra and Fancello [71]. For each technology, development, energy or measure, the maximum and minimum value of their emission reduction have been taken. The smallest emission reduction value of all the studies is then identified by the "ensured emission reductions" and the maximum value is identified by "Potential emission reductions." Figure 3.3 and Figure 3.4 follow the same methodology and use the same references.

Noteworthy, is that of the range of emission reduction options presented in the foregoing papers are intended to be a broad view of the marine industry and, not all measures will be applicable to each type of ship. Many of these technologies are already widely implemented in the latest state-of-the-art ship designs so further efficiency gains can be very difficult to achieve. For retrofits to older ships there is usually significantly more scope for efficiency improvement. It is also essential to note that these proposed efficiency gains need to be viewed in the context of a specific ship-type, ship size, and trading pattern.

Lighter materials such as higher strength steel are already used as far as possible, within the limits of required fatigue criteria. Then, slender design can be utilized in certain ship-types where a loss of cargo carrying capacity can be accepted, within defined principal dimensions limited by ports or lock systems. A loss of cargo carrying capacity would actually increase the CO_2 emissions per transport work of cargo thus having a counterproductive effect on GHG emissions.

The latest designs for lower speed cargo ships such as bulkers and tankers are finding greater hydrodynamic efficiency without the use of a bulbous bow. For higher speed cargo vessels, modification of bulbous bow designs can improve efficiency in certain cases. Also, air lubrication is attractive for high speed, shallow draft vessels with relatively large areas of flat bottom. Ballast water reduction is applicable to certain vessel types engaged in frequent ballast voyages, however its relevance is minimal when assessing vessel types, such as tramping bulk carriers, which tend to avoid ballast voyages.

Next, waste heat recovery from main engines, auxiliary engines and even boilers, where some efficiency gains can be made is attracting more attention in the industry. Hybrid electric too is gaining momentum and has great potential currently for short-sea shipping where range is not a concern. However, the energy density of batteries for ocean-going ships is not yet sufficient to provide the necessary range.

With regards to power systems and machinery for main propulsion, there have been steady but incremental reductions in the fuel consumption per kWh over the years. Also, propulsion efficiency augmentation devices, such as pre-swirl stators or Mewis ducts forward of the propeller, or devices such as propeller boss cap fins, and rudder bulbs after the propeller, are under continual development using advanced computational fluid dynamics and generally present on all modern newbuildings.

Finally, advances in management of on-board propulsion power demand, by means of control systems for fuel consumption optimization are widely available, and the power demand of auxiliary electric consumers can be managed by installing more efficient modern items of equipment.

Technological developments are primarily available for new ships because the retrofit cost may overcome fuel consumption savings. Indeed, the possibility of a technological development to be viable for ships retrofit must be dealt with a case-by-case approach because of the wide variety of ship types, hull shape and so on. Although technology improves ship efficiency, more is required to achieve IMO's targets.

3.4.2 Alternative fuels and energy

Alternative fuels and energy represent all fuels, energy and materials that can substitute the fossil energy sources. The different measures are presented in Figure 3.3.

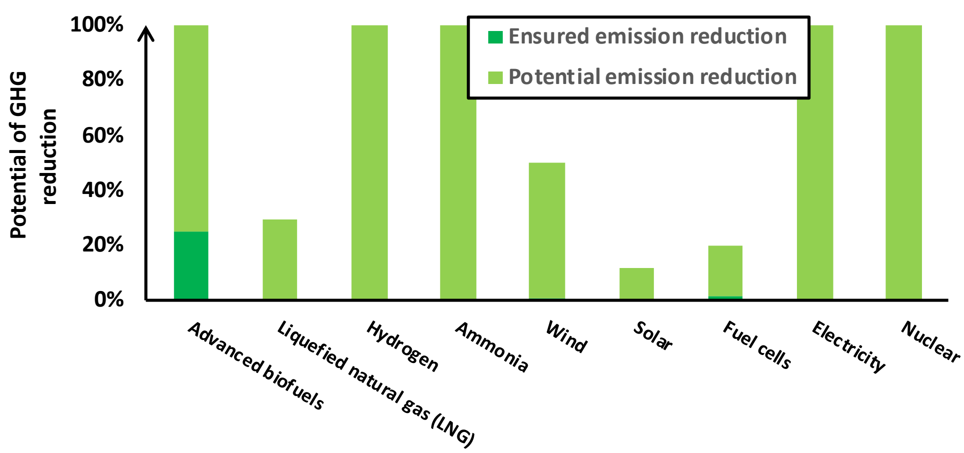

Figure 3.3: Potential GHG reduction of alternative fuels and energy

Advanced biofuels have high potential because of their carbon-neutral characteristics and very low air pollutant emissions. Most of all, they can be used on current vessel ICE. Advanced biofuels are separated in three categories: first, second, and third generation biofuels. First generation biofuels are made from crops such as soybean, palm, and rapeseed. The main downfall is that it will require a lot of agriculture land to produce first generation biofuels for the entire shipping fleet. It cannot be done currently without compromising world food supplies. Second generation biofuels are made from non-food crops like biomass and waste. Then, third generation biofuels are made of more sophisticated crops like algae. The second and third generation biofuels could be part of the solution because their production would not compromise world food supplies. However, they are still in a stage of development. Moreover, even if biofuels are technically compatible with marine standard ISO 8217, some biofuels are at risk of oxidation or degradation if stored for long periods. Therefore, further research is required to make biofuels a suitable option for widespread decarbonization of the sector.

LNG is currently one of the most mature available options for use in shipping. LNG reduces CO_2 emissions and nearly eliminate air pollutants such as SO_x and PM. However, methane emissions from LNG must be monitored carefully because of the "methane slip" problem [72]. Indeed, methane is a strong GHG, 34 times greater than CO_2 over one hundred years. LNG is a short-term solution but will not be enough to totally decarbonize the shipping industry.

Hydrogen is a gas that emits no GHG or air pollutants when consumed. It can be used with fuel cells to generate electricity or directly in ICE as a mixture with other fuels. The potential of hydrogen as a fuel for zero-emission ships is important, but many issues still persist. First, it is hard to store on-board. If it is stored in its gaseous state, it is voluminous: around 4 times the volume of current fuels [73]. If stored in its liquid state, it requires a pressure of 350 bars at 25 °C or a temperature of minus 252.9 °C at sea-level pressure. Since it is difficult and dangerous to attain, hydrogen storing strategies are lacking developments to gain the market. Also, the current infrastructure for hydrogen land storage and distribution is very limited. Finally, the creation of hydrogen is all but green at the moment. Because the hydrogen needs to be extracted from water by electrolysis, the process requires a large amount of energy which most of it comes from dirty energy. The process needs to use renewables to ensure hydrogen is a carbon-free solution. However, it should be mentioned that the gravimetric energy density of hydrogen (J/kg) is about 3 times more than conventional maritime fuels allowing more cargo to be carried for the same quantity of fuel [66].

Ammonia is a hydrogen carrier that can be used in the same way as hydrogen does. It is easier to store since it only requests 10 bars at 25 °C or minus 33.4 °C at sea-level pressure to keep it in its liquid state. However, the current available space for storage in ports and distribution infrastructure for hydrogen and ammonia are limited. Ammonia can be used in ICE as a mixture or in fuel cells and, its energetic density is better than hydrogen. But, like hydrogen, its generation and distribution are problematic. Nowadays, the ammonia is produced via the Haber-Bosch process and used for fertilizers. The process is highly energy intensive and uses 1% of the world energy [74]. Furthermore, the current production of ammonia cannot supply the future maritime sector. New ways to produce ammonia need to be implemented to make it more competitive and cleaner. Finally, ammonia-fueled combustion and oxidation turbines are possible technologies that could result in a zero-emission system for ships but they are still under development [75].

Electricity acts as an energy carrier that is controlled and transported by the help of power electronics. Various energy sources like wind, solar, fuel cells, generators, and nuclear reactor, generate electricity. It can then be accumulated with batteries, flywheels, thermal accumulators, etc. AC distribution systems presently dominate the world shipping fleet, but its DC counterpart has recently created enthusiasm in the R&D sector. It has been established that an average fuel savings of 6% can be achieved by converting an AC diesel-electric vessel to DC because of the wider range of operations it enables [76].

Solar and wind power can still be used nowadays to make substantial energy economies. Different ways to harvest the wind exist for ships: soft sails, rigid sails, wing sails, hull sails, towing kites, rotating cylinders and wind turbines [77]. Tilling *et al.* [78] found that an increase in fuel price could motivate the installation of wind-assisted propulsion and simulations showed fuel economies of 500 tons per year on a medium-range tanker. However, solar and wind power are unreliable because of their unpredictable nature. Also, they can only partially increase ship efficiency and partially diminish fuel consumption for ocean-going ships. Indeed, the proportion power demand for propulsion is high compared from the available energy from solar and wind. Still, it is a step ahead toward better efficiency and could help to recharge batteries when ships are in ports at no cost. A combination of wind and solar power can also optimize surface utilization. Nevertheless, new innovative ship designs are required to accommodate the usage of these types of renewable energy sources because they can take large amount of space on the ships to be effective.

Fuel cells use hydrogen or other fuels to generate electricity. The most popular and affordable technology is the proton exchange membrane fuel cells. It is also the most used in the automotive industry. Still, they are sensitive to impurities in the hydrogen or ammonia mixture and require complex water management systems. High-temperature fuel cells reduce their efficiency operation and pose safety concerns. Their main advantage is their ability to use high energy-dense fuels stored in large quantities in ships to achieve long distances compared to batteries.

Nowadays, the most viable batteries generally use Li-ion chemistry because of its good tradeoff between high specific energy and high specific power, as well as its market maturity. A sharp decrease in the Li-ion battery cost (~$100 US/kWh) has boosted its usage as a primary energy source in the automotive industry. Because of certification and safety of Li-ion maritime batteries, their cost is more expensive (~$400 US/kWh) [64]. The guidelines and rules are provided by the American Bureau of Shipping (ABS) [79], Bureau Veritas (BV) [80], Det Norske Veritas (DNV) [81] and Lloyd's Register (LR) [82]. The trend indicates that even low-cost batteries will arrive soon, which will open new applications for batteries. Nonetheless, their energetic density is reduced compared to conventional fuels, making them unreliable for long transoceanic distances. Li-ion batteries are more suited for short and high-power demands or for auxiliary systems [66]. Alternatively, the Solid-State Battery could overcome these issues if it becomes real in the future [83]. Despite their current drawback, batteries are still on the upfront of greener technologies because of their unique proprieties, i.e. [84]:

- Suit high-power and power-fluctuating applications
- Increase the “levels of autonomy” of the ship
- Enable by classification societies to be used as backup generators
- Limit the number of running generators (spinning reserve)
- Enhance dynamic performances
- Enable peak shaving
- Enable zero-emission operations

Considering, the ever-increasing electric load on the auxiliary system, more battery-powered energy storage systems will be part of the next generation of ships in the very near future. Indeed, Bach *et al.* [85] studied coastal maritime transportation in Norway and found that battery electric and hydrogen technologies had matured rapidly in the past years. Also, Pfeifer *et al.* study on zero emission ferry lines showed that battery ferries are the more economical to operate [86] which also underlines the great potential of batteries in shipping.

Finally, nuclear is also a possible avenue. However, many obstacles prevent nuclear from growing in the maritime sector, such as nuclear wastes, social acceptance, political acceptance, nuclear weapons creation, environmental catastrophes, safety, and operational cost.

3.4.3 Operational measures

Operational measures focus on the operation of ships and maritime transport systems. They relate to the manner ships are operated in terms of speed, destination, route, etc., but also how the world fleet is operated such as the fleet average size, the fleet average speed, and shore power availability. Figure 3.4 presents the main operational measures with their emission reduction potential.

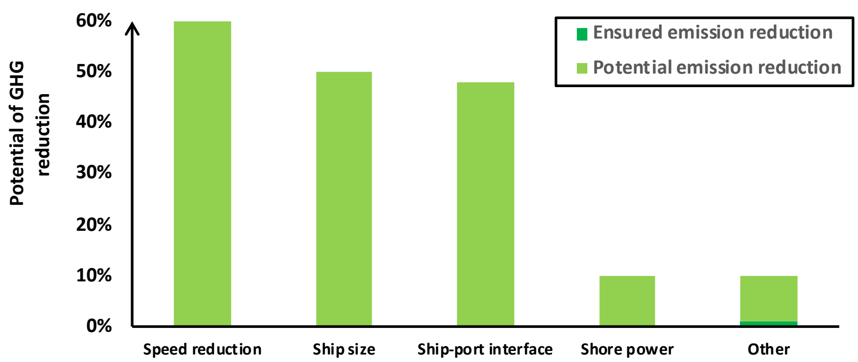

Figure 3.4: Potential of GHG reduction of operational measures

Vessel Speed reduction implies that more ships will need to enter service to sustain the same demand. Nevertheless, even if there are more ships on the sea, the emission reductions could be considerable. The “Transport and Environment” reports on slow steaming [87] showed that speed and engine power are closely related. The emission reduction will follow the speed reduction for the engine operating area comprised between 50% and 100% of maximum continuous rating (MCR). Beyond that operating point, engine specific fuel oil consumption (SFOC) might rise and overcome the benefits of speed reduction. Up to 19% of emission reduction can be achieved with a global fleet speed reduction of 10% and low abatement cost. This finding has been observed in other studies [88][89][90]. Indeed, this is the most popular short-time emission reduction solution.

The relation between ship size and ship efficiency in CO_2 per tons of cargo transported increases with the ship size. In other words, the bigger the ship is, the more efficient it will be. The relation explains why bigger and bigger ships are currently made. However, this relation is nonlinear. It is very advantageous at the beginning, but at some point, the curve flattens, requiring much larger ships to reach the same benefits. Also, not all ports can accommodate large ships. Nevertheless, in general substantial emission reduction can be achieved by increasing the global size of ships.

A low-cost measure is to enhance ship-port interface management. Presently, many ships still wait at anchorage or in ports for days and even weeks waiting their turn. This is ineffective as the ship DGS need to burn fuel to maintain the electrical load. T. Poulsen and Sampson's study [91] confirms the occurrence of idle or unproductive time for tankers. However, they also present the complexity of port call optimization. Shore power can also benefit from enhanced ship-port interface management because all berths cannot be equipped with shore power connections further increasing the complexity of berth allocation issues. Peng *et al.* propose a method for berth allocation to minimize CO_2 emissions and shore power cost [92]. Hence, managing the world fleet better would significantly reduce GHG emission and it is another option where the shipowners should focus their attention.

Shore power occurs when ships can power their electrical system with the shore electricity while in port and shut-down their auxiliary DGs. According to FEDNAV[2], handysize bulk carriers consume about 1.5 tons of diesel oil per day per ship at port, or more. Shore power can eliminate the emission of air polluters at ports which enhance the air quality and health for millions of people. Indeed, the biggest port generally lies in the biggest cities.

The GHG emission reduction capability of shore power is impressive mainly because the shore electricity is much more efficient than the one generated on-board. Even if the electricity is generated by coal plants on land, the total amount of GHG emissions will be less than the amount generated by the ship DGs locally. Figure 3.5 presents the average grid carbon intensity of major port states of the world with a focus on North America. It is shown that significant GHG emission

[2] Montreal-based **Fednav Limited** is Canada's largest ocean-going, dry-bulk, ship-owning and charting group.

reduction can be made by using shore electricity. Indeed, ship DGs has an average efficiency of 790 gCO_2/kWh, while most of the North Americans and European grids emit less than half of ship DG's emissions [93].

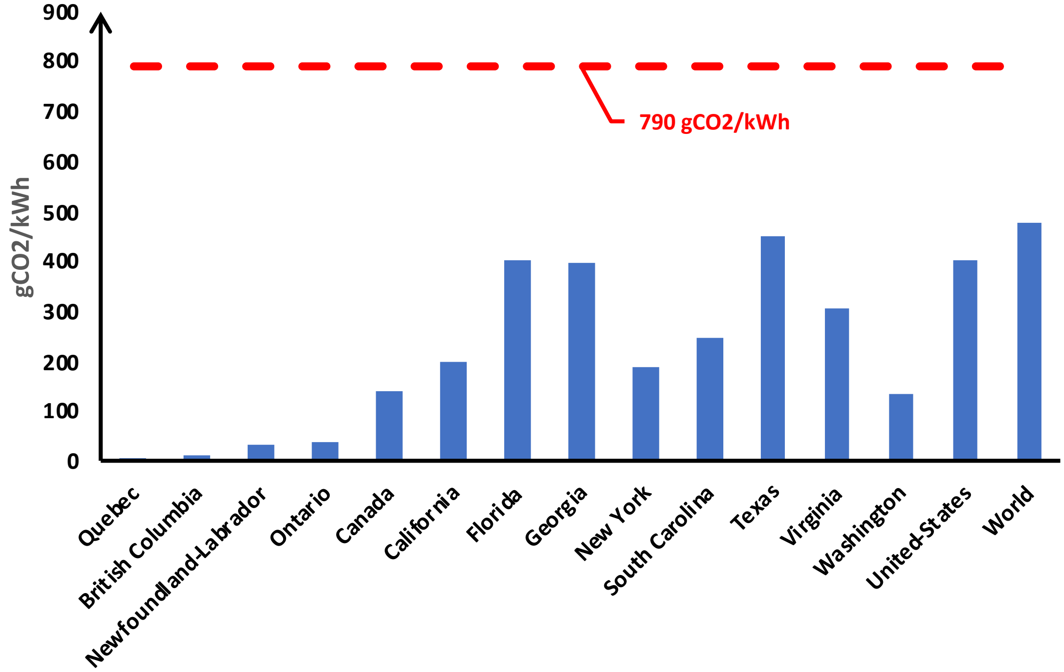

Figure 3.5: Carbon intensity of electricity generation across the world with a focus on North America

The Figure 3.5 uses the carbon intensity of multiple states, provinces, countries and regions over the world that have been collected in[49], [94] and [95] for years 2018-2019.

In a few provinces in Canada like Quebec, British Columbia, Newfoundland-Labrador and Ontario, most of the energy comes from renewables (hydro, wind, solar, nuclear, biomass, or geothermal) and is nearly carbon free. Since this clean energy is available onshore, the electricity needs to find its path to the vessels at berth.

A typical shore power installation, based on the international electrical standard "IEC/ISO/IEEE 80005: Utility connections in port," is presented in Figure 3.6. The specifications of the installation are given in Table 3.1. Indeed, IEC, ISO, and IEEE have launched the first world standard about electric connections in ports of shore to ship power supply. The electrical standard is split into three parts:

i. High voltage supply connection (HVSC). The standard expects to have practical applications on ships that require 1 MVA or more and high-voltage lines. It describes the HVSC system on board the ship and on the shore side, and how to supply the ship with electrical power from the shore installation.

ii. Data transmission between shore and ships. This standard specifies the interface description, addresses and data types to use when proceeding to voltage and frequency synchronization.

iii. Low voltage supply connection (LVSC). The standard expects to have practical applications for power demands of less than 1 MVA. It describes the LVSC system on board the ship and on the shore side, and how to supply the ship with electrical power from the shore installation.

Table 3.1: IEC/ISO/IEEE 80005 standards electrical summary

IEC/ISO/IEEE 80005	Part 1	Part 2	Part 3
Power	> 1 MVA	NA	< 1 MVA
Voltage	3.3 kV, 6.6 kV, 11.1 kV	NA	400 V, 440 V, 690 V
Plug	IEC 62613-2	Defined in standard	IEC 60309-1

The system is composed of the National Grid acting as the on-shore power source, an on-shore transformer used to lower the voltage of the grid, an optional on-shore frequency converter to adapt the gird frequency to the ship frequency, an on-shore connecting equipment, an on-board connector, an optional on-board transformer often used to further lower the voltage and an on-board control panel, as presented in Figure 3.6.

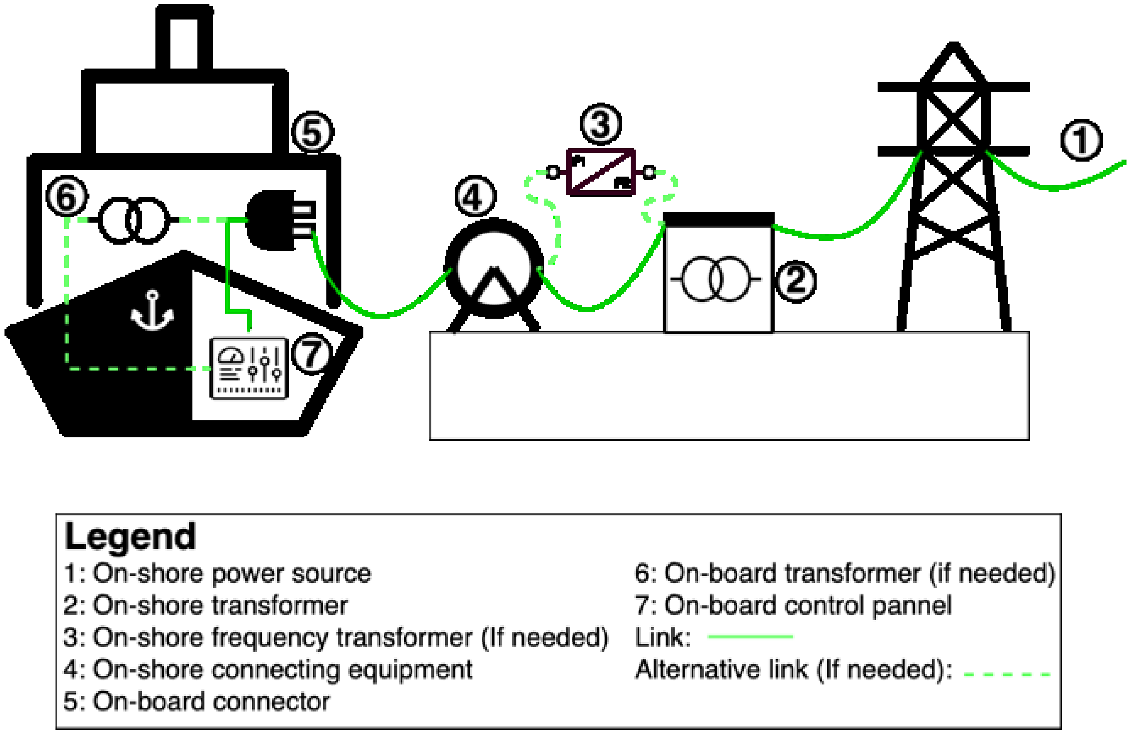

Figure 3.6: Shore power schematic and installation description

The port electrification topic has been well covered in the literature. Kumar *et al.* introduced the concept of the harbor area smart grid with distributed generation using batteries, renewables and the grid to supply ships loads with shore power [2]. Wang *et al.* proposed a method to electrify a port with renewables and energy storage devices considering shore power and electric dock cranes for containerships providing insights to policymakers and designers [96]. Rolán *et al.* study on the electrification of Barcelona port, Spain with 75% of the energy coming from wind turbines and 25% from solar panels showed positive results [1]. Then, Kotricla *et al.* electrified the port of a Greek Aegean island with four wind turbines of 1.5 MW and 5 MW of solar panels providing a considerable reduction of CO_2 and air pollutant emissions in ports [97]. Also, Gutierrez-Romero *et al.* carried a detailed investigation covering port calls, berth frequentation, in port emissions, shore power costs, port electrification with renewables, energy management and more for the port of Cartagena, Spain [3]. Finally, Ahamad *et al.* work on optimal sizing and performances of a port using shore power found that 75% of the energy production should come from renewables and 25% from the grid [98].

Then contributions on the energy management in ports are also present in the literature. Fang *et al.* propose a literature review on port microgrid and all-electric ships and proposed a control framework for the system [5]. Kanellos *et al.* used a multi-agent system to optimize power management in ports using shore power and achieved to reduce operational costs of 21.7% [99]. Du *et al.* propose a two-layer power supply method to address the problem of randomness arrival of ships in ports using shore power interfering with stability and economy of the grid [100]. The method was applied to a distributed generation system and achieved an error of less than 3% between scheduling supply and actual power supply. Next, a power management strategy for ports and an electrical analysis of shore power is presented by Feste *et al.* to reduce CO_2 emissions [101]. In [102], ship energy consumption is modelled with a machine learning method.

Other studies also focus on the financial and social aspects of shore power. Song and Hu looked at the construction and operation cost of shore power with an economic perspective on the grid electricity price [103]. They found that the increase of government subsidy rate will benefit all parties and that a minimum of 400 hours of berth utilization was required to make shore power viable in China. Then, Cao *et al.* made an economic analysis about ship shore power system cost which shows that long docking time and low electricity price reduce the return on investment (ROI) [104]. The shore power study in the port of Kaohsiung, Taiwan, acknowledges the environmental, financial and social benefits of shore power, and its high investment cost [105]. However, the analysis of the stakeholder's point of view showed that the actual political and economic climate would prevent shore power from being adopted. Also, Bellini and Bozze addressed the socioeconomic impact of harmful air emissions from cruise ships in ports by proposing a cost-benefit analysis of shore power [106]. In [107], Shwartz *et al.* pointed out that a lot of carbon emission reductions could be done at zero or negative cost and that 50% of emissions could be realized with profits.

3.4.4 Shore power as a first step toward shipping decarbonization

The IMO regulations like the EEDI, EEXI, CII are increasing the pressure on the shipping industry to invest in cleaner technologies. Electrification is also one of the key measures of green ports [108]. Furthermore, with an increasing number of DNV GL registered battery-powered ships and an ever-increasing electric power demand, it is evident that a trend on electrification of sea transportation is on its way. The electric power demand will always pose efficiency concerns and favor electric and shore power technologies to be installed on-board. Also, ships can use batteries for regenerative crane braking, zero-emission operations, backup power source, and optimization of auxiliary engines operation. [64]. All newly developed electric and hybrid ships will need shore power connections to recharge their batteries, enable zero-emission operations, gain fuel savings, and get access to low-cost energy.

Therefore, port electrification will happen in the near future. Shore power is a solid short-time investment since it can easily cut emissions in ports. At the same time, it is a long-term investment because it will enable the future electric and hybrid ships to recharge their batteries and access the low-cost shore electricity as well as allowing any shore power compliant ship to shut their DGs off while at berth. No matter the decarbonization pathway, shore power will play a key role by increasing ship efficiency, reducing emissions, and fuel consumption. The following section discusses the SWOT analysis of shore power.

3.5 SWOT analysis

The SWOT analysis is summarized in Figure 3.7 followed by a discussion of each strengths, weaknesses, opportunities and threats.

Internal factors	**Strengths**	**Weaknesses**
	• Technical feasibility • Standardized (IEEE) • New ships • Legislation • IMO, EU, EPA, China, etc. recommendation/regulation • Health • Weight	• Financial ○ Construction ○ Retrofits • Timescale • Need of government incentives • Ship non-standardization
External factors	**Opportunities**	**Threats**
	• Reductions ○ GHG ○ Air pollutants ○ Noise ○ Maintenance • Electric port (Future) • Subsidies • Reputation	• Political issues • Acceptance • Grid capacity
	• Oil cost • Electricity cost • ROI	

Figure 3.7: SWOT analysis of shore power

3.5.1 Strengths

The first advantage of shore power is its feasibility in the short term. Indeed, the Figure 3.6 details all the components required for a shore power system to take place. All these components are available on the market and already used in the shipping industry as much as in other sectors. Moreover, as presented in Section 3.2, shore power projects have taken place around the world for decades. While other technologies for shipping efficiency can be very popular, they tend not to be practically feasible yet, and their benefits can only be predicted.

When shore power was introduced, one of the main barriers for its wide adoption was the large differences in electrical requirements from one ship to another or from one country to another. Since no standards were guiding their design, ships using shore power were always using custom connections at specific berths and the system was not compatible with other ports. Even if it is not a problem for ferries always visiting the same berths, it is an issue for all ships travelling in different ports. Fortunately, the IEEE standard on shore power now covers high voltage and low voltage connections helping shore power facilities to become compatible with any ships [11][12].

Also, an important strength resides in the very low cost of making a newly built ship shore power compliant. Retrofit for existing ships is expensive [63] and might require to take the ship in dry-docking if important work needs to be done. However, the shore power equipment is easy to install when the ship is in the shipyard and can be amortized over a longer period.

Another strength of shore power is that more and more countries, states, ports, and international organizations are legislating or promoting its use. California has laws that force some ship types such as cruise ships and reefers to use shore power or an equivalent technology in port [44]. China has a new policy forcing ships equipped with shore power to use it in Chinese ports [109]. Then, many international organizations recommend shore power, such as the IMO MEPC.323(74) [110], the EU [111], and the EPA [112]. which has facilitated the technology expansion worldwide.

Finally, shore power considerably reduces air polluting emissions providing huge health benefits for the populations living near ports. In fact, air pollution was the prime motivator for shore power in California with the CARB regulation [44]. Indeed, Progiou *et al.* [52] found that anticipated damages from ship emissions in Piraeus Port affecting mainly health, but also crop losses and biodiversity loss reached 23.8M$ USD. Another study led by Ballini and Bozzo [106] demonstrated that external health cost benefits of covering 60% of the cruise ships power demand at Copenhagen Port could reach 3.35M$ USD per year. They concluded that external health costs would enable shore power facilities capital expenditure to balance in 12-13 years.

3.5.2 Weaknesses

As a drawback, shore power financial cost is a major concern, especially for ports because of all the construction costs that shore power installations engage. This is a conclusion that has been confirmed in many studies [107][105][113][114][115]. As an example, Tseng and Pilcher concluded that shore power cannot yet be economical without considering social benefits [79]. The retrofit cost is another problem for shipowners. Indeed, it can diminish profitability because of a too-long ROI.

Then, the timescale of such projects is also to consider. Such infrastructure requires important modifications to berths and docks, so the electric lines and electric facilities are installed properly. This task might require coordination and planning to limit the impact on the port's economic activities.

Next, the demand for governmental incentives to make shore power economical makes this technology dependent on legislation and policies. If no investment is made by governments into the electrification of ports in close alignment with the owners of the ships calling at these ports, the threat is that the current status quo remains. Indeed, the techno-economic analysis of Dai *et al.* [113] concludes that shore power may not be profitable without government investment and incentives or low electricity cost. Also, Innes and Monios [116] present a study of the electrification of Aberdeen Port with a ROI of 7 years. However, it would only take 3.5 years if the project was subsidized by the EU and if environmental benefits were considered.

The last drawback is that there exist a wide range of electrical systems in ships. Therefore, more power electronics are needed to adapt the electrical supply voltage and frequency to all ships. For example, the power demand in the port of cruise ships can go up to 10 MW and even more while small container ships might only require 300 kW. However, similar ship types tend to visit the same berths so the shore power connection can be made in consequence. Nevertheless, the ships internal grid voltage and frequency vary from where the ship has been designed and so does the voltage and frequency of the port grids around the world. A common example being the American grid working on 60 Hz while Europe uses 50 Hz.

3.5.3 Threats

External threats can also affect the likelihood of shore power to scale up, like political issues from governments or lobbies. While some of these threats might have slowed down shore power adoption in the past, the current trend on decarbonization is more likely to encourage shore power.

Public acceptance is also to be considered. A port can present great environmental benefits and still be rejected by the communities for many reasons like port or traffic expansion. For example, the "LNG Quebec" project [117] had the opportunity to supply a fuel worldwide which reduces CO_2 and air pollutant emissions greatly. However, other environmental issues of the project resulted in a strong public resistance and stopped the project from going forward.

Finally, a port's grid capacity and stability might not be strong enough to supply the entire ship's load since they have not been designed for that. Peak levelling technologies might be needed to lower power consumption during peak demand hours. A real-world example of this situation is the Port of Hueneme using 2 MWh Tesla batteries to store energy when the electricity demand is low and releasing it when the demand is high [118]. Indeed, the peak electricity demand is a main issue of electricity providers since the last decade. However, this threat could become an opportunity if the ships could supply the grid with their DGs or batteries inverting the flow of energy during peak hours or breakdowns. Also, for hybrid ships using batteries, they can be charged at night and provide power to the grid during peak hours.

3.5.4 Opportunities

The most important pros for shore power lie in its opportunities. Indeed, the reductions in GHG emissions, air pollutants, noise pollution in ports, and maintenance costs are important. Figure 3.5 of section 2.1.3 represents well this opportunity looking at GHG emissions. The carbon intensity of most states with access to sea or inland maritime routes is very low and enormous amounts of CO_2 emissions can be reduced by using shore side electricity instead of electricity generated by the onboard generators. The emission intensity of air polluters is not presented in this figure, but the same conclusion can be made because of the superior efficiency that large electricity generation plants have compared to the smaller DGS of ships. Moreover, noise reduction is also a great opportunity. Indeed, port noise has been demonstrated to have a negative impact on health [119] which is also recognized by the EU [120]. DGS are the main source of noise from ships in ports [121] and the use of shore power enables to shut all of them down.

Also, the port electrification will happen at some point in the future since ships will need to become more efficient due to the international regulations. With IMO's goal to diminish the total annual GHG emissions of 50% by 2050 and the CO_2 emission per transport work of 40% by 2030, more and more pressure will push shipowners and ports to invest in greener technologies. EEDI and EEXI do not integrate shore power in their calculation, but CII does by the fuel consumption of the auxiliary engines. As stated above in the strengths, countries, states, and international organizations are actively legislating or promoting the use of shore power. In this sense, port electrification will enable many new applications for hybrid and electric ships enabling them to recharge their batteries while connected to shore power.

Then, shore power is a great way to improve the reputation of sea transportation companies and ports by being green and sustainable to the public eyes. According to the Linder study, the firms public perception in the port sector can compete with economics [122]. As stated previously, the benefits of shore power on health and noise reduction of local populations are important. Plus, the GHG emission reductions that it enables are massive which also benefits a green and sustainable image to the public eyes.

Moreover, the high capital expenditure of shore power is a weakness, but for countries or states where subsidies are available, there could be a golden opportunity for shipowners and ports. Ports that benefit from subsidized shore power facilities have a competitive advantage over other ports by offering more services and benefiting from a more environmentally friendly image to the public eye. Also, shore side electricity tends to be less expensive than electricity generated with fuels enabling shipowners to reduce their operational expenditure with shore power.

Finally, oil cost, electricity cost, and ROI are external factors that can either be opportunities or threats. Oil cost and electricity cost affect operational expenditure by diminishing or augmenting the ROI. The ROI is a metric of paramount importance to ascertain the economic viability of shore power projects because of the economic viability insight it provides. High oil cost combined with low electricity cost and low-interest rate will significantly benefit shore power projects by shortening the ROI and diminish operational expenditure. However, low oil cost and high electricity cost will play in the opposite direction.

3.6 Current status of shore power

Since the first shore power facilities were built in the 2000s, an increasing quantity of ports are providing shore power services around the world. According to the World Port Climate Incentive, 28 ports were equipped with HVSC shore power facilities in 2017 [116] and are mainly concerning cruise ships and reefers. Also, the United States Environmental Protection Agency (EPA) made an in-depth analysis of shore power installations through the United States [112]. The report includes an analysis of 13 shore power ports in the US. According to the EPA, up to 69 berths among 10 ports are providing high-capacity shore power connections with HVSC standard for cruise ships, reefers, roll-on/roll-off ships, container ships and tankers. Then, 373 berths distributed among 6 ports are providing low-capacity connections. These berths are equipped with low voltage connections of 220-480 V and mainly concern fishing ships and tugs. However, none of these low voltage connections follow the LVSC standard.

A survey sent to the ports visited by Fednav's bulk carrier fleet in the St. Lawrence River and Great Lakes about shore power facilities enabled to enlarge EPA's work through North America. Out of the 10 ports that answered the survey, 6 are offering shore power services as presented in Figure 3.8. Based on EPA's work, the ports can be separated in two categories:

- High capacity shore power ports: Typically large cruise, container and reefer ships with internal voltage greater than 6.6 kV
- Low capacity shore power ports: Typically smaller ships with low voltage internal voltages smaller than 690 V

The survey showed that only 1 high capacity installation is available on the St. Lawrence River and Great Lakes. Indeed, cruise ships can connect to the HVSC system in Montreal Port since 2017. However, the lock system starting after Montreal limits the size of ships to 304 meters long. In consequence, no other high-capacity ports are observed mainly because international large ships requiring high capacity connections cannot reach the Great Lakes ports.

The rest of the installation totals 86 berths among the 6 low-capacity ports. These connections are low voltage connections and mainly used to provide power to ships wintering in port or other specific requests. However, none of these low voltage connections follow the LVSC standard.

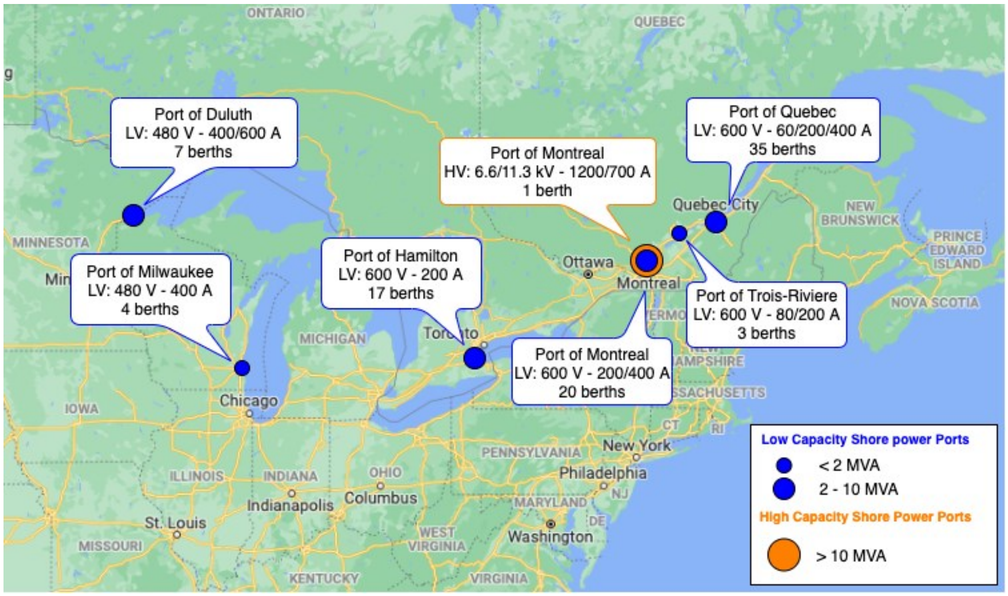

Figure 3.8: Current status of shore power along the maritime route of the St. Lawrence River and Great Lakes. (HV: high-voltage, LV: low-voltage)

While Port of Bergen in Norway provides LVSC connections till 2014 for commercial ships [123], there are not many ports in the world offering this alternative. Many berths are equipped with low voltage connections, but the voltage varies greatly from one port to another requiring the ships to adapt the voltage to their needs with an onboard transformer. Indeed, North American low voltage lines are 480 V and 600 V while low-voltage ships generally vary between 400 V, 440 V and 690 V. Till now, ports and berths visited by high voltage ships have been easier to electrify because these ships are generally larger and calls only in few ports making this option less complex and with a greater environmental potential. However, HVSC installations are very expensive. LVSC installation are much more economic but the berths where LVSC could be beneficial are visited by many different ships requiring an important quantity of ships to be LVSC compliant to justify the investment. On the other hand, shipowners have the same problem of not having enough ports LVSC compliant to justify the investment on their side.

3.6.1 Methods

The methods used to estimate the environmental performance of the IMO's main environmental indicators for the purpose of this paper are presented in this section. First, the energy efficiency designed indexes are presented followed by the carbon intensity index.

Energy efficiency indexes

The EEDI and the EEXI use the same equation in (3.1) presented in MEPC.203(62) [124] for EEDI and in MEPC(76)/WP.4 [39][38] for EEXI. It represents the efficiency of a ship in emissions of CO_2 per work done by the ship in tons of capacity multiplied by nautical miles. While the EEDI is only used for new ships, the EEXI is used for existing ships. Also, an important characteristic of these indexes is that they assume the ship is sailing at designed speed in deep water at a summer load draught. It also considers that the weather is calm with no wind and no waves.

$$\boldsymbol{EEDI} = \frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} C_{FME(i)} SFC_{ME(i)}\right) + \left(P_{AE} C_{FAE} SFC_{AE}{}^{*}\right) + \left(\left(\left(\prod_{j=1}^{M} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} P_{eff(i)}\right) C_{FAE} SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} P_{eff(i)}\, C_{FME} SFC_{ME}{}^{**}\right)\right)}{\mathrm{f_c} \cdot f_i \cdot Capacity \cdot V_{ref} \cdot f_w} \quad (3.1)$$

where, f_j is the correction factor for ship-specific design elements, M is the maximum number of design elements, nME is the number of main engines, P_{ME} is the main engine power at 75% MCR, C_{FME} is the main engine carbon factor, SFC_{ME} is the specific fuel consumption of the main engine, P_{AE} is the auxiliary engine power, C_{FAE} is the auxiliary engine carbon factor, SFC_{AE} is the specific fuel consumption of the auxiliary engines, nPTI is the number of shaft motors, P_{PTI} is the power of the shaft motors, f_{eff} is the availability factor of innovative energy efficiency technology, P_{eff} is the output of innovative mechanical energy efficiency technology, $neff$ is the number of innovative energy efficiency technology engines, f_c is the cubic capacity correction factor, f_i is the capacity factor, $Capacity$ is the capacity of the ship (deadweight for bulk carriers), V_{ref} is the designed ship speed, f_w is the weather factor.

Based on the EEDI and EEXI formula and behavior, shore power has no impact on its value. Indeed, this is because EEDI and EEXI are design indicators that look at the ship while at sea in perfect conditions. To the EEDI and EEXI point of view, shore power is seen as an operational measure and cannot influence the result of the design.

The reduction factor is the tool used by the IMO to regulate the efficiency ships needs to comply with. For example, EEDI Phase 1 for bulk carrier came into effect in 2015 with a 10% of EEDI reduction compared with 2008 baseline. Then the Phase 2 had a reduction factor of 20% in 2020 and Phase 3 a reduction factor of 30% for 2025. To determinate the 2008 EEDI reference line, equation (3.2) form section 3 of the MEPC.203(62) [124] document is used combined with the associated reference values:

$$EEDI_{ref} = a \times b^{-c} \tag{3.2}$$

where a is a variable parameter, b is the ship DWT and c is a variable parameter.

The EEXI will enter into force in 2023. For bulk carriers with a capacity above 20,000 DWT and below 200,000 DWT, the reduction factor is 20% as expressed in MEPC(75)/WP.3 [37][38]. Further phases of EEXI have not been established yet. Finally, the reference line for EEXI uses the EEDI reference line.

3.6.2 Carbon intensity index

CII is the carbon intensity index and is used to calculate how the ships are efficiently operated. Indeed, it calculates the real emissions of CO_2. At the beginning of CII negotiations, two indicators were considered for the CII: the EEOI, also called demand-based method by the IMO and the annual efficiency ratio (AER) also called the supply-based method. During MEPC(76), it was concluded that the AER would be used for CII.

The CII assesses the annual efficiency of a ship. It monitors ship carbon intensity and is more precise than EEDI because the index uses real fuel consumption data that can be found in the ship's logbook or other resources. The CII equation is presented in (3.3).

$$CII = \frac{\sum_i \sum_j FC_{ij} \times C_{Fj}}{DWT \times \sum_i D_i} \tag{3.3}$$

where i is the voyage number (the summation is over the total number of voyages in one year), j is fuel type, FC_{ij} is the mass of consumed fuel j and trip for trip i, C_{Fj} is the fuel mass to CO_2 mass conversion factor for fuel j, DWT is the deadweight and D_i is the distance sailed in nautical miles for trip i.

For CII, fuel consumption can be significantly reduced by shore power connection. It is considered in this document that the energy consumed in port by the auxiliary engines is completely replaced with shore side electricity.

Instead of using the 2008 reference line, CII is based on the 2019 reference line of the Fourth IMO GHG Study [32] and its parameters are available in MEPC(76)/WP.4 [39][38]. Indeed, the past IMO GHG studies did not present enough information to calculate the 2008 reference line accurately for CII like it is done for EEDI and EEXI. The reference line can be calculated in (3.4):

$$CII_{ref} = a \times capacity^{-c} \tag{3.4}$$

where *a* is a variable parameter, *capacity* is the ship DWT and *c* is a variable parameter. However, the *a* and *c* parameters are not the same as the parameters used in the EEDI reference line calculation.

Finally, the CII uses a quote to range the ships based on their CII performance as presented on Figure 3.9. To do so, ships will be rated from A to E, where A and B are ships performing better than the CII reduction factor, C is close to the reduction factor, D and E are above the reduction factor. Also, an incentive program is discussed to encourage ships that are performing better than the actual fleet average.

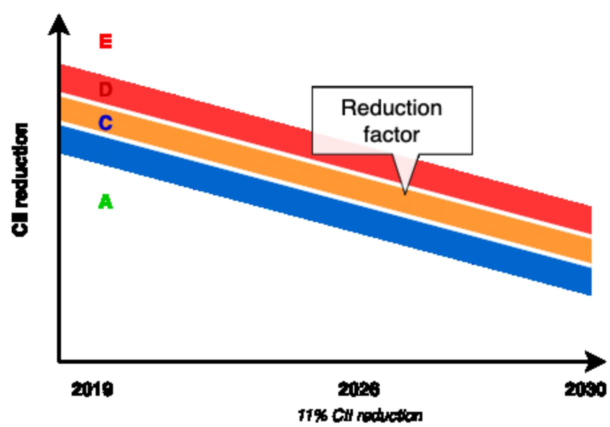

Figure 3.9: CII ratings

3.7 Vessel Case of study

To study the impact of shore power on the environmental indicators of a bulk carrier, we choose the Federal Baltic as a case study. Federal Baltic is a Laker owned and operated by Fednav and built in 2015 at Oshima shipyard in Japan. The vessel has a 34,564 DWT capacity in summer with six cargo holds and is equipped with four deck cranes of 35 ton each.

Figure 3.10: Federal Baltic [125]

To estimate the parameters of the ship to determine EEDI, EEXI and CII the methods of Section 3.6.1 have been used combined with different approximations that are presented in the following section.

3.7.1 Indexes calculation

Considering the Federal Baltic case, the EEDI formula of (3.1) is simplified in (3.5) to facilitate the calculation of the estimated EEDI value. Indeed, the ship has one main engine, three DGS and do not use any innovative energy efficiency technology applicable to the EEDI equation.

$$EEDI' = \frac{\left(\prod_{j=1}^{M} f_j\right)\left(P_{ME(i)} C_{FME(i)} SFC_{ME(i)}\right) + \left(P_{AE} C_{FAE} SFC_{AE}\right)}{f_c \cdot f_i \cdot Capacity \cdot V_{ref}} \quad (3.5)$$

Following MEPC.1/Circ.866 [126] and data provided by Fednav considering ship sizes, capacity, design, speed, and so on. the remaining parameters have been determined in Table 3.2:

Table 3.2: Federal Baltic assumptions and sources for EEDI estimation

Parameter	Value	Assumption and reference
$Capacity$	34 564 ton	Fednav
P_{ME}	6050 kW	Fednav
C_{FME}	3.114 gCO_2/gFuel	MEPC.1/Circ.866 [126] (HFO)
SFC_{ME}	175 gFuel/kWh	Fourth IMO GHG study [32], Table 19, SSD main engine (HFO)
P_{AE}	302.5 kW	Simplified equation from [124]: $0.05 \times (MCR_{ME})$
C_{FAE}	3.206 gCO_2/gFuel	MEPC.1/Circ.866 [126] (MDO)
SFC_{AE}	195 gFuel/kWh	Fourth IMO GHG study [32], Table 19, Auxiliary engines (HFO)
f_c	1	Cubic factor from MEPC.1/Circ.866 [126]
f_i	1.005	Capacity factor, determined from Fednav data and from MEPC.1/Circ.866 [126]
V_{ref}	14.7 kt	Fednav
a	961.79	MEPC.203 (62) [124]
d	34 564 ton	Fednav
c	0.477	MEPC.203 (62) [124]
EEDI future reduction factor	30%	MEPC.203 (62), Phase 3 [124]
EEXI future reduction factor	20%	MEPC(76)/WP.4 [39][38]

The CII estimation has been determined based on fuel consumption analysis of the Federal Baltic during the year 2020. The details are presented in Table 3.3.

Table 3.3: Federal Baltic CII calculation assumptions and sources

Parameter	Value	Assumption and reference
DWT	34 564 ton	Fednav
D	56,467 nm	Fednav
C_{F1}	3.114 gCO_2/gFuel	MEPC.1/Circ.866 [126]
C_{F2}	3.206 gCO_2/gFuel	MEPC.1/Circ.866 [126]
FC_1	1970 tFuel	Fednav (estimate)
FC_2	1790 tFuel	Fednav (estimate)
$FC_{1_{In\ port}}$	34 tFuel	Fednav (estimate)
$FC_{2_{In\ port}}$	307 tFuel	Fednav (estimate)
a	4977	MEPC(76)/WP.4 [39][38]
$capacity$	34 564 ton	Fednav
c	0.626	MEPC(76)/WP.4 [39][38]
CII future reduction factor	11% (2026)	MEPC(76)/WP.4 [39][38]

To estimate the CII score of the ship while using shore power, we assume that the electric generation of the ship in port is supplied by the grid and that the fuel consumption during this period is eliminated. To do so, we subtract the estimated fuel consumption in port $FC_{In\ port}$ of the Federal Baltic for the two types of fuels in the CII calculation. For EEDI and EEXI, their calculation method prevents shore power to have an impact on their score. Therefore, their shore is kept still even if the ship uses shore power.

Finally, the results considering the calculation of EEDI, EEXI and CII and the shore power impacts on the indexes are presented in the next section.

3.7.2 Results

The measurements of the environmental indexes are presented in Table 3.4. Then, they are compared to their associated reference line and to the improved score if the ship was fitted with shore power. Finally, the next compliance is also presented. The "Next compliance" represents the next regulation the ship is facing regarding the IMO targets. It is available in Table 3.2 and Table 3.3. Figure 3.11 presents the results of Table 3.4 based on the percentage of improvement compared to the reference line. This metric is more relevant because the reduction factors of the IMO are expressed in percentages. Also, it enables to compare all indexes on the same base. Indeed, the goal is to investigate the impact of shore power on the main environmental indexes.

Table 3.4: Federal Baltic environmental indicator's results

Indicator	Unit	Score	Reference line	Shore power score	Next compliance
EEDI	gCO_2/ton*nm	5.21	6.58	5.21	4.60
EEXI	gCO_2/ton*nm	5.21	6.58	5.21	5.26
CII	gCO_2/ton*nm	6.17	7.17	5.61	6.39

For EEDI, EEXI and CII, the blue bar of Figure 3.11 represents the percentage of improvement based on the indexes particularly to 2008 reference line. Then, the green bar represents the percentage of improvements that shore power can provide to the indicator. Finally, the red line represents the improvement that the ship needs to attain to comply with the next regulation ahead. Indeed, to comply with EEDI phase 3, new bulk carriers must be 30% more efficient than they were in 2008.

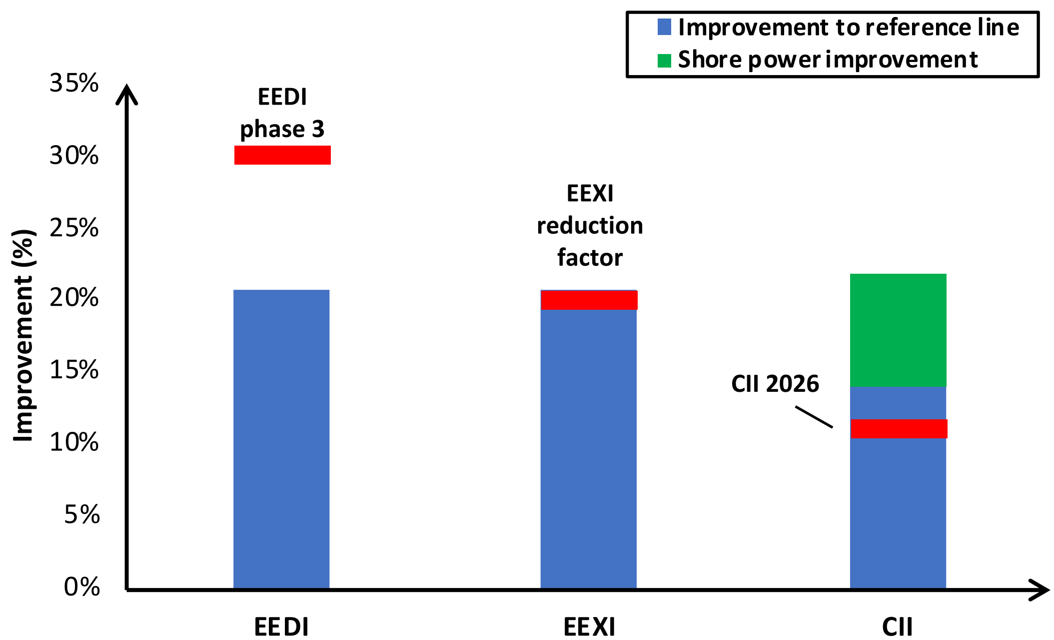

Figure 3.11: Federal Baltic environmental indicators shore power improvements

EEDI and EEXI indicators have improved compared to 2008 by 20.7% and comply with EEDI Phase 2 and EEXI reduction factor. Because no relevant modification has been made to the ship since its design, the EEXI and EEDI have not changed over time. Therefore, the operator of this ship will have to invest in efficiency devices, reduce its speed, augment its deadweight, or use efficient fuels if they want to comply with EEDI Phase 3 for new ships of the same design. Also, the reference line for EEDI and EEXI is the same because the IMO uses the same data sample to estimate the 2008 reference line for bulk carriers. Since the EEDI and EEXI are design indicators that look at the ship performances while at sea in perfect conditions, shore power does not have any impact on these indicators.

CII is analyzed for the year 2020 and shows that the ship complies with CII 2026 (11% reduction compared to the 2019 reference line) with 14% of improvement. Nevertheless, the usage of shore power shows even better results with an additional improvement of 7.8% resulting to a total of 21.8% of improvement. Since CII can vary a lot every year because of how the ship is operated, the use of shore power will play the role of a buffer enabling shipowners to have much more flexibility to operate the ship. Indeed, CII is an operational indicator and is dependent on how the ship is operated year after year. The score of one year does not grant the same score for the next year. Discussions at MEPC(76) suggest that further implementations of CII should be 22% of reduction in 2030 if the IMO wants to achieve its targets. Therefore, shore power could also help the Federal Baltic to comply with CII 2030. However, other measures will need to be taken to ensure the ship complies with CII 2030, because shore power alone will not be enough even if close. After all, no reduction factor has been set by the IMO so far for 2027 and onward. In this case, only assumptions can be made.

For CII, the addition of shore power enabled a 7.8% improvement to the score of the Federal Baltic enabling more flexibility in shipping operations. However, the EEDI and EEXI did not benefit from shore power. EEDI and EEXI are defined as energy efficiency designed indexes but apply only when the ship is sailing as it measures “transport work” not in port. Consequently, these regulations, which started in 2013 for EEDI, provide no incentive to reduce emissions in port. CII, which includes emissions in port, will enter into force in 2023. However, the issue of shore power is not addressed in priority, because for most ship types, the energy use in port is a very small fraction of the overall energy used. Furthermore, the Federal Baltic already complies with CII 2026, which is not a motivation to invest in shore power. For shore power to really take off, an increased focus on GHG emissions in port is required, that is a larger incentive than that expected to be provided by CII.

Two options to increase the priority of the "road map to shore power" under existing regulations are proposed. In Option 1, the regulation is modified to allow shore power to supply the auxiliary load of the ship during a certain portion of the time. For example, using data of the ship port calls, the in-port time can be evaluated for different ship types and used as a reference in the EEDI and EEXI formula (3.1) if shore power was fitted to the ship. In this case, the $Feff$ ratio of the auxiliary engine efficiency devices can equal the time in port vs. time at sea ratio considering the ship is always using shore power when in port. Then, by changing $Peff$ to equal PAE, the new energy efficiency indicators can be measured. Option 2 is to add a shore power parameter named F_{SP} at the end of the EEDI and EEXI formula (1) that benefits the EEDI and EEXI score of 10% reduction compared to the reference line if the ship is equipped with shore power. More precisely, this could be done by setting $F_{SP} = -\frac{EEDI_{ref}*(10)}{100}$. This option is more drastic but ensures that shore power is well promoted. Furthermore, a score bonus of 10% relates to what is already proposed by other environmental indicators such as ESI [41] and CSI [40] indexes that value shore power at 10-13% of their score.

The Figure 3.12 summarizes the two options impacts on EEDI and EEXI. In the case of the Federal Baltic, Fednav estimates that the ship was 25% of the time in port and led to a 1.2% of EEDI improvement for Option 1. However, another measure will need to be taken to comply with EEDI phase 3. On the other hand, Option 2 enables the Federal Baltic design to increase its EEDI score of 10% compared to its actual design and to become EEDI phase 3 compliant. In the Federal Baltic case, the EEXI is already compliant with the reduction factor. Nevertheless, shore power enabled its EEXI score to improve of 1.2% for option 1 and 10% for option 2. This augmentation could help other ships not complying with EEXI reduction factor to improve their score or even to comply depending on their situation.

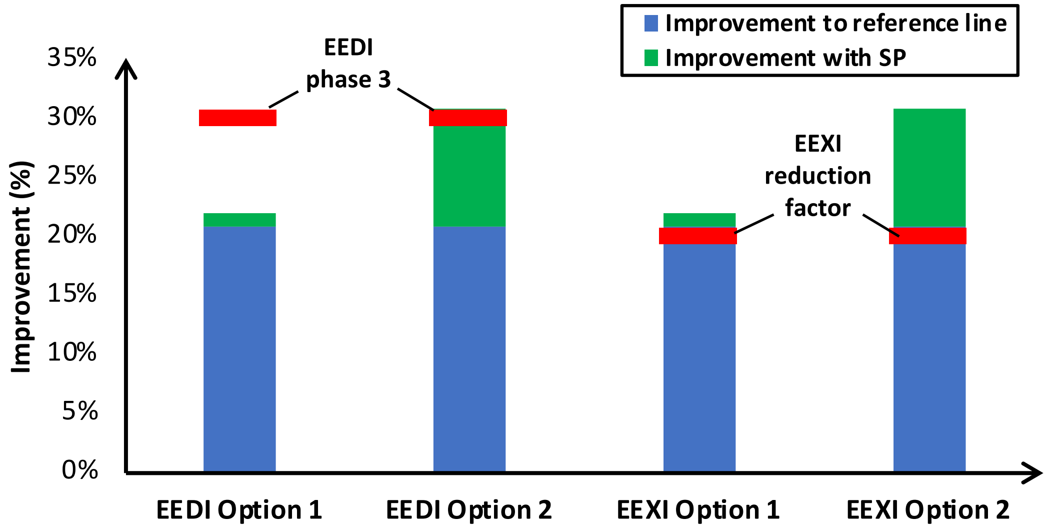

Figure 3.12: Impact of EEDI and EEXI regulation modification regarding shore power promotion

In the end, Option 1 has less impact than Option 2 but does not require any modification to the EEDI and EEXI equations. Plus, it better represents the ship efficiency benefits of shore power because it depends on the time in port ratio. It could be argued that shore power is not always available for ships in ports, but the EEDI and EEXI formula are design indexes and thus, do not concern the operation. In this sense, Option 1 respects better the actual equation behavior. Furthermore, this will motivate shipowners to invest in shore power systems which will also encourage ports to do the same. Indeed, since many ships will be shore power compliant, ports will try to be more competitive than others by offering better electricity prices.

3.8 Conclusion

To conclude, the pressure to lower the maritime industry carbon footprint is growing more challenging for shipowners, charterers, and ports. Three transition pathways are considered to predict which energy source will dominate in the future. Among all technological developments, alternative fuels and energy, and operational measures, shore power stands out as the next step toward green shipping. Shore power can eliminate GHG and air polluting emissions at port right now and across the world, it globally increases ship efficiency and it is a prime mover for the development of new maritime applications like hybridization and electrification. Furthermore, no other measures can reduce emissions as well while being a conservative investment in this uncertain technological future. Because of shore power strengths and opportunities, shore power should be adopted now on a large scale and across the world to lower GHG emissions and air polluters.

Then, the impact of shore power on EEDI, EEXI, and CII indexes has been assessed with a test case on the Federal Baltic and shows that the ship already complies with CII 2026. However, the addition of a shore power system has improved the CII indexes of 7.8% creating a buffer and giving ship operator flexibility in terms of shipping operation, ship speed, and so on. Shore power might also help the Federal Baltic to comply with further implementations of CII. Since EEDI and EEXI do not allow shore power devices in their calculation, two options have been proposed to modify the regulation. Option 1 enables the auxiliary system to be supplied for a specific ratio of the average in-port time based on the ship type. In the case of the Federal Baltic port calls data analysis, a 1.2% of EEDI and EEXI reduction is estimated. Option 2 is to add a fix parameter to the EEDI and EEXI formula reducing of 10% the score of the ship if equipped with shore power. This factor would enable similar ship design to comply with EEDI phase 3.

The methodology presented in this paper to measure the impact of shore power on bulk carriers can be applied to any types of ships e.g., cruise ships, containerships, tankers, Roll-on/Roll-off ships, and reefers. It is done by integrating Option 1 and Option 2 to EEDI and EEXI equations and the time in port ratio to the auxiliary fuel consumption. Indeed, the EEDI, EEXI, and CII calculations are well detailed and already categorize any type of ships of 500 DWT and more.

At the present time, the maritime industry possesses all the components to realize shore power installations and the benefits overcome largely the costs. Governments, industries, and academia must make a task force to develop a world network of shore power facilities. In comparison with the automotive industry, charging stations network is an important barrier, but the widespread expansion of the network enabled the industry to grow. It will be the same for the maritime industry with shore power.

Future work is required to address the high-level SWOT analysis of this paper in more details by investigating on the impacts of EEDI, EEXI and CII regulations on the world fleet emissions but that also integrates every point of the SWOT analysis. This would enable to gain better understanding of the shore power potential for shipping decarbonization.

CHAPTER 4

4 ENERGY AND POWER DEMAND AT BERTH

Following the shipping decarbonization and ship's electrical system literature reviews, this section assesses the measurement of the power demand of bulk carriers. Indeed, the data acquisition is required to perform a precise analysis of fuel consumption and CO_2 emissions in port. More precisely, it considers the power demand for the auxiliary system of a dry bulk carrier of the Fednav dry bulk carrier fleet.

The rest of this section is separated in three subsections. The first subsection details the process used to acquire the data and the main challenges encountered during the process. The second subsection presents the results of the load measurement and an analysis of the power demand in port. Finally, the last subsection explores the loading of the DGs in terms of efficiency.

4.1 Data acquisition

The measurement of data on a ship can be challenging. Indeed, dry bulk carriers implicated in the tramp trade have irregular schedules and, in most cases, they might only visit the same port once or twice a year. In addition, the recent COVID-19 pandemic has put the maritime industry on pressure limiting the access to the ships. In these circumstances, an automatic monitoring system had been selected to acquire the data. The system enables to log the data on a local computer that can subsequently be transferred to shore.

4.1.1 Monitoring and processing

The TERASAKI WATCH FREE SYSTEM is the software used on Fednav ships to monitor most of the auxiliary system sensors. The data is only accessible on a computer screen in the ship, but an update has been uploaded to the TERASAKI WATCH FREE SYSTEM so the data could be stored automatically on an "extension PC" connected with a wire to the system.

Each 10 minutes, the data present in the system temporary memory is saved into the extension PC in a .csv file with many different resolutions (1 d, 4 h, 1 h, 10 min, 1 min, 2 s, etc.). Then, the deputy fleet manager is responsible for uploading the data in a folder on a cloud-based platform.

The date included in the .csv file is at London time and local time. To know when the ship was in port, the date sand timings inscribed in the ship's statement of fact (SOF) are used. The SOF contains the exact berthing time under the name of "All fast to berth No.XX" or similar. However, the SOF do not always contain the leaving time of the ship from the port. Therefore, the voyager operation report is used to complete the information.

After the reception of the data, it is downloaded from the cloud-based platform to the computer that performs the analysis. Then, a script is executed in the MATLAB software. The script collects the load measurement of the diesel generators in kW with a resolution of 2 sec, extracts the date from the .csv file and associates a date to each data point. Since this work intends to measure the load demand of the ship in port, manual modifications are often required to adjust the in-port timing based on the observation of the data. Finally, different statistics and information can be determined from the data with another MATLAB script.

4.1.2 Challenges with the process

Sometimes, some issues with the ships' informatics or human-made mistakes can corrupt the data. As it can be seen in different load profiles of Figure 4.1, some data is missing or corrupted. In those cases, it is not possible or very complex to recover the data.

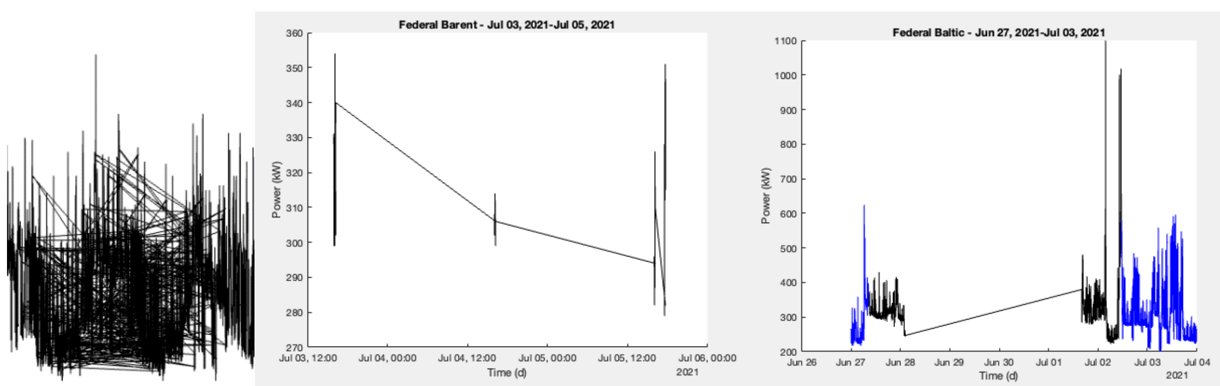

Figure 4.1: Corrupted data examples

Some issues still persist despite many issues have been addressed during the recording period. However, the quantity of corrupted data is not large enough to compromise the integrity of the global study.

Another challenge posed by this system is that it only provides the real power of the auxiliary system (kW) excluding apparent power (kVA) and reactive power (kvar). With all the inductive loads present on a ship, the value of the power factor (PF) is required to determine real current values flowing through the cables. To overcome this challenge, the operators of one of Fednav's bulk carriers have performed a measurement of the power factor in different situations:

- At sea: PF average = 0.8 with min max = 0.75 to 0.95
- At rest in port: PF average = 0.8 with no important fluctuations
- Loading/unloading in port: PF is fluctuating from 0.7 to 0.8

Therefore, the worst-case is a PF of 0.7 in loading/unloading conditions. While a PF of 0.8 is normally used in the maritime industry, the PF of 0.7 will be used as a reference to ensure the shore power studies really represent worst-case scenarios.

On-land factories generally install capacitive loads between their building and the grid to optimize the PF and lower their electricity bills. Since the bulk carriers have a lot of inductive loads (electric motors mainly), the same could be done with bulk carriers to reduce the increases of apparent power on the shore power connection.

In the next section, the acquired data is analyzed.

4.2 Power demand analysis in port

The load measurements investigated in this work considers the period between April 2021 and November 2021. Seven ships have been monitored following different starting dates:

- Federal Baltic since April 18th, 2021
- Federal Barents since July 5th, 2021
- Federal Caribou since July 14th, 2021
- Federal Frontier since August 10th, 2021
- Federal Fraser since September 18th, 2021
- Federal Franklin since September 19th, 2021
- Federal Freedom since October 7th, 2021

An example of a typical load profile is presented in Figure 4.2 where the Federal Baltic stayed 2 days in the Port of Manzanillo, Mexico. The power demand of the ship at berth is in blue while the rest is in black. Prior to the docking, the navigation load is quite small. Then, the very high load of ~900 kW represents the usage of the bow thrusters during docking operation. After that, the ship is at rest in port for ~1 day before starting loading operations. The crane power demand can be seen with a peak power demand of 601 kW. During its stay at Manzanillo, the Federal Baltic average power demand was 303 kW.

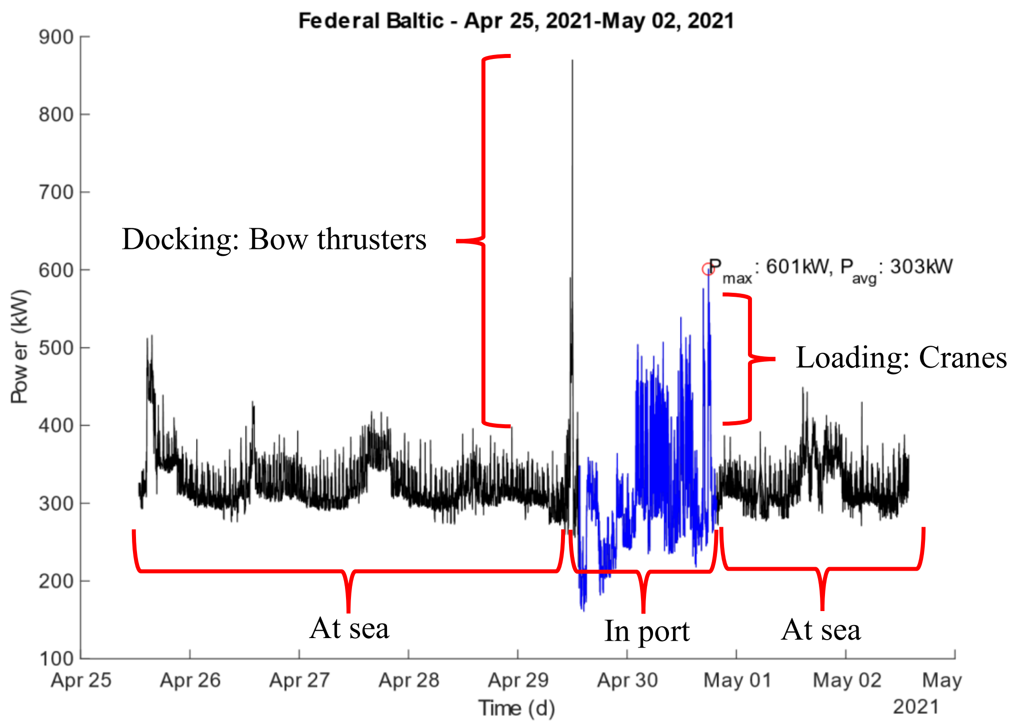

Figure 4.2: Load profile of the Federal Baltic in Port of Manzanillo. At sea (black), in port (blue)

While the Manzanillo port stay represent an average load consumption in port for loading operations, the Inchon stay on Figure 4.3 and Figure 4.4 is an example of a high-power demand in port. Indeed, the Federal Baltic did load a lot of cargo during nearly 10 days. During this stay, the ship had a peak load demand of 869 kW and a power demand of 337 kW on average. Figure 4.4 also presents a data corruption example. Indeed, the data was lost from the 15th of June 2021 to the 16th of June 2021.

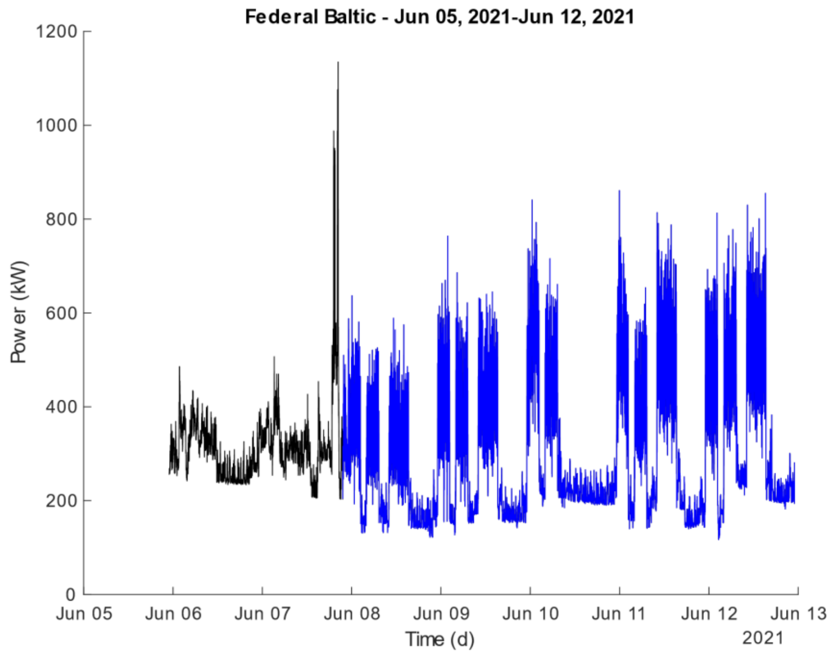

Figure 4.3: Load profile of the Federal Baltic in Port of Inchon (1). At sea (black), in port (blue)

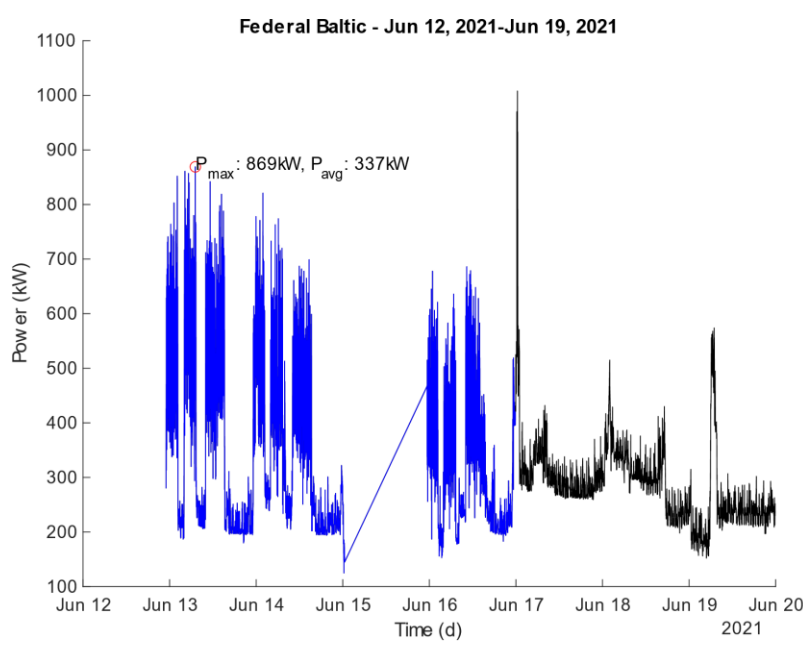

Figure 4.4: Load profile of the Federal Baltic in Port of Inchon (2). At sea (black), in port (blue)

Table 4.1 presents a summary of all the stay in port that occurred in Canada with the ship's average load consumption and peak power demand. The average power demand in Canada is 257 kW while in port with a maximum load demand of 1030 kW (1471 kVA, PF=0.7).

Since this work investigates the possibility of integrating a shore power connection to a dry bulk carrier, the maximum apparent power of a LVSC system is taken as a reference parameter for the analysis. Therefore, the peak power demands over 1 MVA are highlighted in red.

Table 4.1: Mean and peak load demand in port

Ship	Port	Operation	Number of days	Average power demand (kW)	Peak load (kW)	Peak PF=0.7 (kVA)
Federal Caribou	Sorel	Discharging	3.08	293	735	1050
Federal Caribou	Hamilton	Discharging	7.75	275	721	1030
Federal Caribou	Montreal	Bunkering	0.47	256	418	597
Federal Caribou	Baie-Comeau	Loading	2.77	253	795	1136
Federal Barents	Quebec	Discharging	2.86	304	829	1184
Federal Barents	Toronto	Discharging	7.18	183	529	756
Federal Baltic	Sorel	Discharging	7.80	333	676	966
Federal Barents	Montreal	Bunkering	0.72	183	350	500
Federal Caribou	St Catherine	Lock transit	0.22	420	885	1264
Federal Baltic	Oshawa	Discharging	8.98	236	932	1331
Federal Baltic	Thorold	Discharging	1.94	241	650	929
Federal Baltic	Hamilton	Loading	3.89	239	1030	1471
Federal Baltic	Quebec	Loading	1.31	162	357	510
Federal Franklin	Quebec	Discharging	2.86	226	698	997

Figure 4.5 visually presents all the power demands and time in port for every port stay for the period of the load measurement project. The left axis is the power, and the right axis is the time in port. In the left axis, the country where the port stay occurred is identified. The average power demand is green, the peak real power is blue and the peak apparent power with a PF of 0.7 is orange. Finally, the number of days in port is in grey.

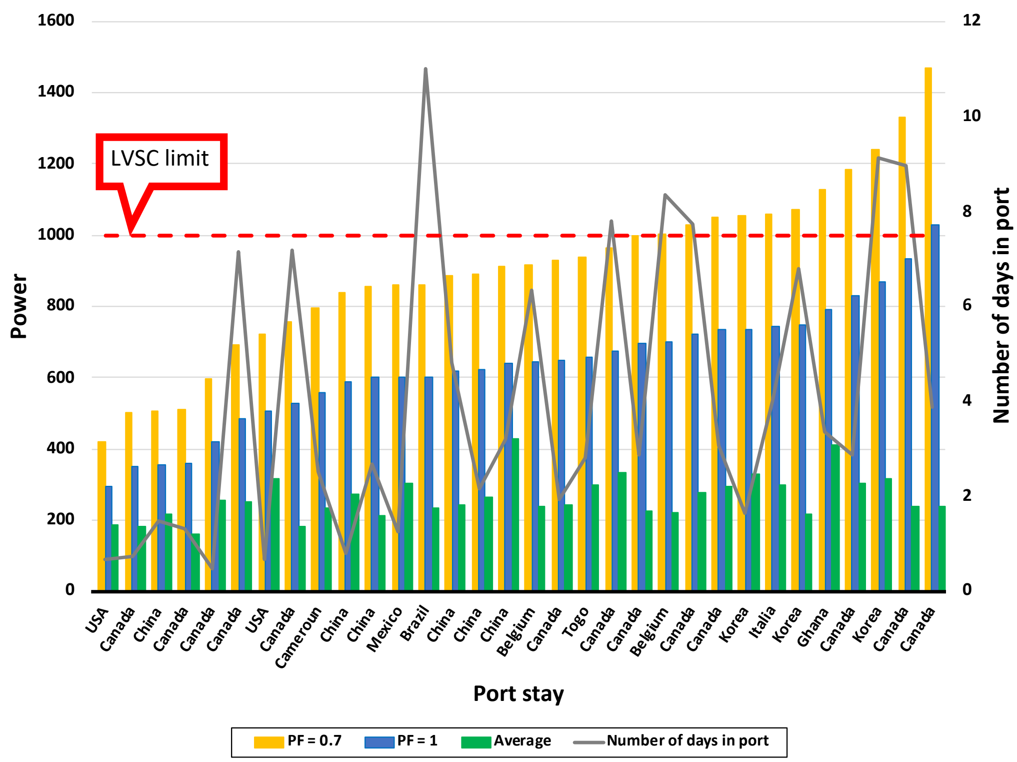

Figure 4.5: Port stay metrics sorted by peak auxiliary power consumption

The results show that the average power required by the ships at berth does not vary a lot, but the peak power demand does. Indeed, the maximum peak power was 1030 kW (1471 kVA, PF=0.7) for a discharging operation that happened at Hamilton Port in Canada by the Federal Caribou. However, the smallest peak is 294 kW (420 kVA, PF=0.7). Also, 11 port stay had peak power demand over 1 MVA.

Then, a statistical analysis of the peak power demands in port have been conducted over the entire data range. The results are presented in Table 4.2 and a focus on the peaks over 1 MVA enables to obtain more details on the peak's duration, occurrence, and power.

Table 4.2: Peak power demand analysis over the seven ships

Result	Value
Number of analyzed days	374 days
Number of analyzed days in port	137 days
Time in port	37%
Number of stay in port	32
Avg power in port	247 kW
Max power in port	1030 kW
Max apparent power in port (PF=0.7)	1471 VA
High power peaks (> 1 MVA)	
Number of stay in port with 0 high power peaks	21
Number of stay in port with at least 1 high power peak	11
Average number of peaks per stay for stays that have at least 1 peak	38
Average number of peaks per stay (overall)	10
Time per peak	
• Average	10.7 s
• Min	< 2 s
• Max	460 s
• Standard deviation	26.7 s

The peak power demand analysis shows that the high-power peaks are of small duration (average duration of 10.7 s with standard deviation of 26.7 s). Also, the results show that 21 of the 32 port stays have no high-power peaks. However, the stays in port that have high-power peaks also have many peaks (on average 38 high-power peaks for stays in port with at least one high-power peak).

Nevertheless, a close investigation with the shipowners and operators revealed that the peak power demands over 1 MVA can sometimes be caused by a minor displacement of the ship along its berth during the port stay. This operation can require the bow thrusters and many other equipment to be on standby and thus creating a high-power peak. Therefore, the peaks over 1 MVA should not affect the shore power operations if the ship uses a low voltage connection since the ship would not be connected in these circumstances. This issue has been considered for the uses of the load profiles in section 5, but should be more carefully addressed in future works with this data. The discussion following the peak power demand with the shipowners and the operators also revealed that the peak power demands could be decreased by modifying the operations of the auxiliary system to prevent all equipment to be used at the same time.

4.3 Diesel generator efficiency

While shore power can eliminate CO_2 emissions and fuel consumption in port, it is valuable to analyze the actual auxiliary system efficiency for comparison. When analyzing the DGs efficiency, it is required to look at the SFOC curve. This curve indicates how much fuel it takes to produce 1 kWh of energy. When a DG is used at low power, the SFOC tends to be very fuel consuming and inefficient. However, when used close to its maximum capacity, it is very efficient. Therefore, an efficient design would take the average power demand and size the system accordingly. However, ship designers need to make sure the DGs does not break down. In this case, the DGs are designed for worst-case scenarios. Yet, this tends to be very inefficient. Also, it is common practice to design the DG to be used at 80% load maximum which further diminish the efficiency [127].

The Table 4.3 presents the potential fuel consumption improvements that could be obtained by comparing the actual fuel consumption of the seven ships from which data was collected with the ideal fuel consumption of the system. This ideal fuel consumption is represented by the fictive case where the DGs would always operate at 80% load. While this case is impossible to attain with the current system, Table 4.3 presents the potential in fuel savings that an energy accumulation system combined with an energy management strategy can offer, and the potential improvements in fuel savings of shore power.

Table 4.3: Fuel consumption improvements if the diesel generators always work at 80% load operation point

Result	Value
Ideal fuel consumption improvement	
• Average	12.92 %
• Min	11.81 %
• Max	14.59 %
Ideal fuel consumption + shore power improvement	
• Average	39.13 %
• Min	32.52 %
• Max	49.42 %

Therefore, optimizing the system could lead to ~13% of fuel savings for the auxiliary system and ~40% of fuel savings by optimizing the system plus using shore power all time in port.

To explain in more details this analysis, Figure 4.6 presents a bar graph of the DG utilization in (% of time) for the three DG configurations (1 DG, 2 DG in parallel, 3 DG in parallel) for the Federal Baltic. Indeed, the load measurement data provided the information about whether the DGs were operated in parallel or not. Each bar is linked to its associated SFOC in the red curve. The SFOC is capped to 250 gFuel/kWh because the curve of reference supplied by the shipowners did not specify SFOC for DG loading smaller to 150 kW.

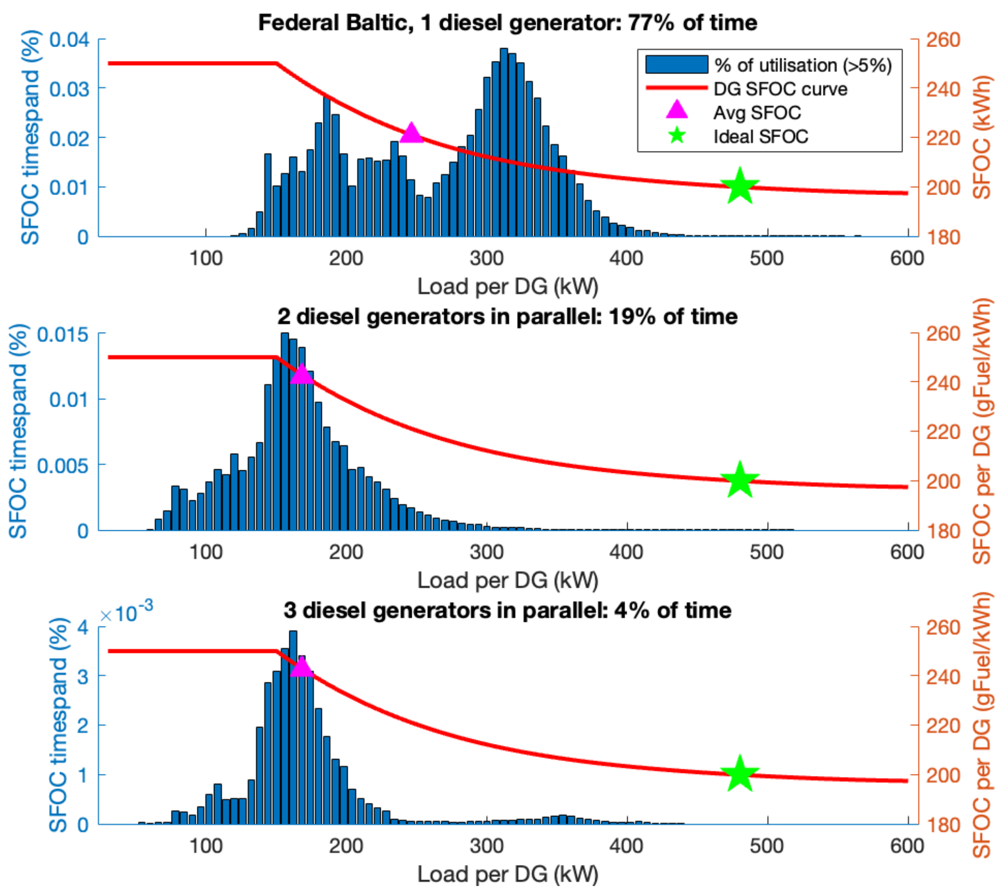

Figure 4.6: Federal Baltic, Bar graph of the DG utilization in (% of time) and SFOC curve

The results indicated that the ship is using one generator 77% of the time, two in parallel 19% of the time and three 4% of the time.

The magenta triangle of Figure 4.6 represents the average SFOC of the DG and the green star represent the ideal SFOC at 80% load of the DG (typical maximum operated power). The average SFOC (215 gFuel/kWh-1DG, 242 gFuel/kWh-2DG, 242 gFuel/kWh-3DG) is very far from the ideal SFOC in the three configurations of 200 gFuel/kWh. Indeed, most of the load supplied by two DGs in parallel could be supplied by only one DG, improving the SFOC. Also, nearly all the load supplied by the three DGs configuration could be supplied by two DG or even one DG. However, this is not practically feasible most of the time without an accumulator device such as a battery or super-capacitor bank because of the uncertainty in the instantaneous power demand or because of regulations requiring a certain amount of DGs to be operated at the same time for safety.

The same analysis can be done on Figure 4.7 with the DG utilization when the Federal Baltic is strictly in port. In this case, the DG loading is slightly better when the one DG is working, but in general the DGs are still very far from their maximum efficiency point.

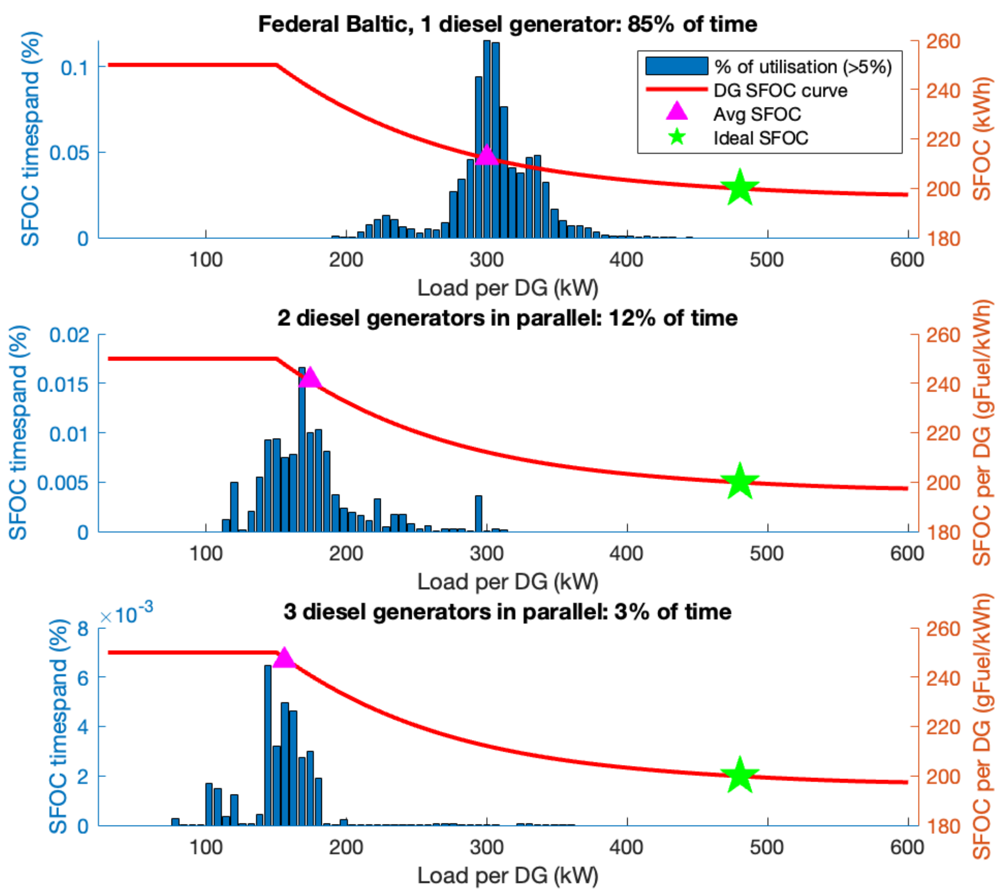

Figure 4.7: Federal Baltic, Bar graph of the DG utilization in (% of time) and SFOC curve for in-port operations

This analysis of the DGs loading highlighted the improvement that shore power can provide in terms of fuel consumption and how much inefficient DGs are operated on ships.

The next chapter presents the methodology to use to select a shore power system for ships. Indeed, many options can be used to supply ships with shore electricity, but different combinations of cost and CO_2 emissions can result from the use of the different methods. Therefore, a multi-objective approach is detailed in this chapter to provide good insights into the best solution for their ship. This chapter also discusses of the shore power system that would be best suited for a handysize bulk carrier of the St. Lawrence River and Great Lakes.

CHAPTER 5

5 MULTI-OBJECTIVE APPROACH FOR SHORE POWER DESIGN

Foreword

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Date of acceptance for submission: 25th of March 2022

State of acceptance: Submitted, under review.

Journal: Energy Conversion and Management – Elsevier journal

Reference: [14]

English title: Shore Operations Enhancement of Bulk Carriers based on a Multi-Objective Sizing Approach

French title: Amélioration des opérations à quai de vraquiers basé sur une approche multi-objective pour faire le dimensionnement du système

5.1 Abstract

The maritime industry is responsible for almost 3% of GHG emissions worldwide and this figure is expected to grow due to market expansion. The IMO aims to lower GHG emissions by 50% and improve ship efficiency by 70% compared to the 2008 baseline. While shipowners are having more difficulties to comply with new policies, shore power is gaining attention. This paper develops a multi-objective approach to select and size a multi-source shore power system for bulk carriers to minimize CAPEX and CO_2 emissions of the auxiliary system. This approach is versatile, considering most of the possible shore power source systems in a single model for real scenarios. The methodology is used in a case study of a bulk carrier with three different load profiles. A

technical-economic analysis evaluates the payback period, return on investment (ROI), operational expenditure (OPEX) and total savings of the selected solutions. Results show that the emissions of the auxiliary power generation system can be reduced by 100% for the typical power demand scenario with an investment of 323 k$ USD and a payback period of 15 years reduced to 6 years if 50% of the initial capital is subsidized.

Keywords: Multi-objective optimization, Bulk carrier, Shore power, Marine Battery, Ship

5.2 Introduction

Climate change has become a major concern for the world future. The international maritime transport sector represented by the IMO wants to reduce GHG from shipping. The IMO has fixed goals to reduce the total annual GHG emissions by at least 50% by 2050 compared to the 2008 baseline, and to reduce the CO_2 emission per ton-nautical miles of the international fleet by 40% in 2030 and 70% in 2050. However, business as usual scenarios predict that GHG emissions will continue to increase because of the shipping market expansion. With 2.89% of the global GHG emissions coming from the maritime industry [32], strong actions are needed to achieve the IMO's goals.

To limit emissions, the IMO has adopted the EEDI to regulate new ships efficiency and pave the way to zero-emission ships. Nevertheless, this measure has no impact on the current ship fleet that will continue to emit GHG in the atmosphere during decades. To tackle this issue, the IMO has introduced the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Index (CII) during the 75th session of the Marine Environment Protection Committee (MEPC) [36]. The pressure on the shipping industry to reduce current and future emissions of the international fleet is huge and shipowners without a plan to reduce their emissions will face important economic penalties.

Three sets of measures are considered to decarbonize the industry: technological, fuels and energy, and operational measures [69] [70] [128]. While only the fuel and energy measures can lead to zero-emission ships, some technologies are not fully mature yet to be used to decarbonize the international fleet. In the interim, technological measures and operational measures are key drivers of the new and existing ships emission reduction efforts. Shore power, also known as cold ironing

(CI), alternative marine power (AMP), shore-side electricity (SSE), shore-to-ship (SSP) or onshore power supply (OPS), is an operational measure that started to get more attention in the last decade. The process reduces the ship emissions in ports by turning the ship engines off while supplying the ship with the energy available onshore. Indeed, according to Dalsøren *et al.* [45], 5% of fuel consumption from ships happens when they are at berth. The International Council on Clean Transportation (ICCT) conducted a thorough study showing that, on average, 9.2% of the ships CO_2 emissions happen while ships are at berth [129]. In addition to the environmental impact of carbon emissions, shipping-related emissions have a huge impact on human health [130]. However, due to many barriers such as technical challenges [131], lack of standardization, high CAPEX [105][113], high-power demand in the microgrid during charging and discharging process, the technology is taking time to expand.

In the last decade, three main shore power standards were developed:

1. IEC/ISO/IEEE 80005-1 [11] is the High Voltage Supply Connection (HVSC) shore power standard, which is used for high-power transfer or high-voltage situations. HVSC standard covers shore power connections of 1 MVA or more with typical voltages of 3.3 kV, 6.6 kV and 11.1 kV at 50 Hz or 60 Hz.
2. IEC/ISO/IEEE 80005-2 [27] is intended to standardize data communication for monitoring and control in shore power systems.
3. IEC/ISO/IEEE 80005-3 [12] is the Low Voltage Supply Connection (LVSC) shore power draft standard, and finds practical applications for shore power connections of less than 1 MVA, with typical voltages of 400 V, 440 V or 690 V at 50 Hz or 60 Hz. The draft standard includes a table with the recommended number of cables to put in parallel for a safe connection based on the voltage and the expected apparent power. The cable size is also provided with a value of 185 mm^2 for a maximum current of ~350 A per cable [17]. However, the cable size guideline might get withdrawn from the upcoming official version of the standard to promote innovative cable designs.

Unfortunately, the investment cost for such systems is a major issue for shipowners and ports, especially for HVSC systems. Indeed, they are required by the IMO to reduce their carbon intensity, but no profitable solutions seem to exist to reduce emissions in ports. While the LVSC draft standard can provide an economic shore power connection for ship owners and ports, the standard limits the power to 1 MVA. Nevertheless, it could be possible to augment the maximum power of a low voltage connection up to 2 MVA with 5 cables of 690 V, while respecting the maximum number of cables, the maximum current per cable, and the voltage of the LVSC draft standard. Whereas this option would require upgrading the safety components to allow such a charge and to violate the 1 MVA limit of the LVSC standard, it is an option that could lead to more affordable shore power systems for ships requiring apparent power slightly over 1 MVA. Since the current formulation of the standard forbids this operation, we do not investigate it further in the paper.

A lot of work has been conducted to decarbonize and optimize zero-emission ships. Ross et al. [132] studied the possibility of zero-emission ships by combining high-temperature superconductivity, battery storage and shore power on a container ship at Rotterdam Port. Letefat *et al.* [6] used the improved sine cosine algorithm (ISCA) to optimize the CAPEX and the OPEX of a ferry boat including fuel cells, batteries and shore power. With this model, a 2% reduction of design cost was achieved compared to the actual system, and 2.4% of operational cost reduction compared with a rule-based method presented in the literature. Homme and Trovão [9] studied a hybrid excursion boat to enable zero-emission maneuvers using the Energetic Macroscopic Representation (EMR) formalism. The proposed system (which is composed of an ICE, batteries, supercapacitors and shore power) was able to reduce emissions by 20%. Yu *et al.* [29] developed a multi-objective approach based on the non-dominated sorting genetic algorithm (NSGA-II) to plan the retrofit of a fleet to use shore side electricity. The objective was to optimize the payback period and environmental benefits at the same time. With a test case on the containerships at the Dalian Port (China), it was concluded that an average of four years of payback time would be required per ship for an environmental benefit of 128 million $USD. Auxiliary drives, energy storage and shore power were analyzed by Sciberras *et al.* [43] to assess the potential environmental benefits and energy consumption enhancements. Using a HVSC shore power system on a roll-on/roll-off (RoRo) ship and a real load profile, the highest environmental performance was reached when the ship was using shore power and batteries as much as possible and recharging batteries, with shore power giving a reduction of 2.1% in fuel consumption. However, the system required a cost increase of 0.74% compared to the current baseline. Ritari *et al.* [133] did a similar study to retrofit a battery-powered passenger ferry that travels between Finland and Sweden supplying the ship in port with an HVSC shore power system. Using a mixed integer linear programming (MILP) optimization model solved with the GUROBI solver [134], the authors found that the installation of a battery was economically feasible. The results indicated that a battery can economically replace the emergency generators and enhance the overall system efficiency. However, CO_2 emissions were not reduced as much as expected and the investment cost of the shore power system was not taken into consideration. Al-Falahi *et al.* [135] proposed a DC integrated-electric architecture for a ferry with a battery optimizing the fuel consumption and recharging the battery at sea to augment the load of the DGs which further increased their efficiency. A 7.48% of fuel consumption improvement was achieved compared to the current fuel consumption with the grey wolf optimization technique. However, the study does not consider the recharge of the battery in port with shore power. Zhu *et al.* [31] developed a multi-objective model considering GHG emissions, design cost and operational cost. The hybrid electric ship design combining a battery and the diesel generators (DG) was optimized using the NSGA-II algorithm. Then, a rule-based energy management strategy (EMS) was used to determine operation parameters. The study presented a test case of a tugboat using hardware in the loop (HIL) techniques and proved that 15% fuel economy, 14% GHG emission reduction and 12% life cycle cost could be achieved in comparison with the real application. Nevertheless, the authors supposed that shore power was available in the port and its integration cost was not included in the design. In [30], Wu and Bucknall used a similar approach and developed a very complete model that simultaneously minimized average cost and the global warming potential of a fuel cell battery hybrid ship. The model was separated in two layers. The inner layer solved the best power split problem with a deterministic dynamic programming (DDP) algorithm for each combination of fuel cell and battery capacity. The outer layer used the NSGA-II algorithm to find the Pareto optimal front, which consisted of the non-dominated solutions (feasible solutions for which no improvement is simultaneously possible in all objective functions, i.e., to improve one objective function value it is necessary to accept degrading at least another objective function value). The model was tested with a coastal ferry between Denmark and the UK, showing that a minimum of 65% of global warming potential could be reduced. However, the work does not integrate shore power investment cost and design for the ship. Kim *et al.* [136] used a different approach proposing a battery-super capacitor-DG design for a handysize bulk carrier considering the high-power demand during harbor modes.

Some papers assessed the port decarbonization and electrification perspectives as Acciaro *et al.* [137], Fang *et al.* [5] and Notteboom *et al.* [138], considering environmental, economic, technological, social and policy aspects. Gutierrez-Romero *et al.* [3] carried out a well-detailed investigation covering port calls, berth utilization, in port emissions, shore power costs, port electrification with renewables, energy management for the port of Cartagena, Spain. Pfeifer *et al.* [86] studied the best scenarios to fully decarbonize smart islands considering shipping as an opportunity. While the shore power integration to port has been well covered with detailed literature reviews, discussions, and case studies, it is not the same for the ship side. Few papers presented detailed models with encouraging results, but in general they did not cover the CAPEX aspects of the shore power system or did not present all the different available shore power technologies. Since CAPEX is the major barrier to shore power, a study presenting a clear vision of the different shore power solutions for ships detailing their investment cost and emission reduction capability to comply with the IMO's goals is of major interest.

This paper expands the work done in [13] and aims to develop a methodology to select and size a multi-source shore power system for bulk carriers. A multi-objective approach is developed to guide the decision maker through the optimization process to find balanced solutions displaying the trade-offs between minimizing CO_2 emissions and CAPEX. Based on this analysis, the decision maker can assess good compromise solutions to suit its financial and environmental goals associated with different load diagrams. The proposed methodology has the advantage to be adaptable to a wide range of situations since it considers most of the possible shore power systems in a single model. The proposed methodology is well suited to offer decision support in selecting the different energy sources and size shore power system while reducing GHG emissions. Also, a technical-economic analysis provides insights about the long-term economic viability of shore power projects and investigates the sensitivity of the main parameters on the results.

The paper is divided in five sections. The introduction and literature review are presented in section 1. Section 2 presents the mathematical modelling of the different systems, the objective functions, constraints, and multi-objective approach used to obtain the solutions. Section 3 discusses the results of three load demand scenarios. Section 5.6 details the technical-economic study. Finally, section 5.7 concludes with the main findings and suggestions for further research.

5.3 Model

The proposed methodology which sizes a shore power system based on the minimization of CO_2 emissions and CAPEX is presented in this section. Figure 5.1 describes the overall methodology. First, the ship load profile in port and shore power cost estimations are taken as inputs. Then, the model computes the solutions and discriminates the unfeasible solutions, e.g. solutions that cannot supply the required energy and the peak power demand. Finally, the solutions are evaluated based on the scalarization process using the Chebyshev metric described in section 5.3.5. This step enables to outputs the non-dominated solutions and to display the Pareto front with CO_2 emissions and CAPEX of each non-dominated solution.

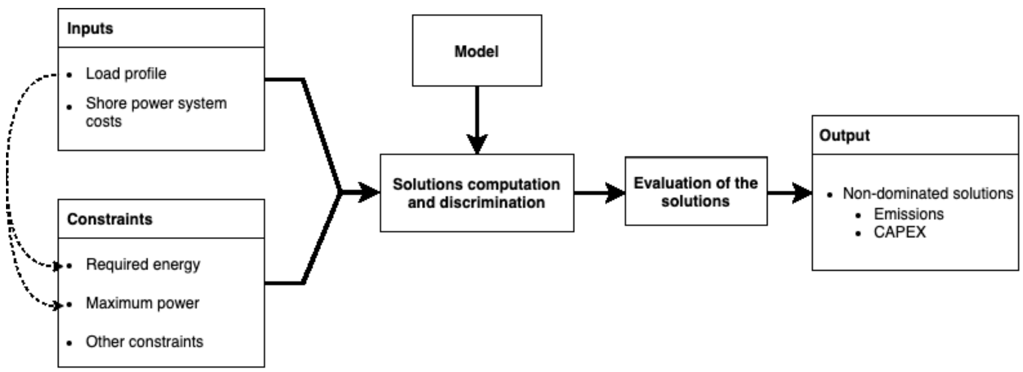


Figure 5.1: Methodology overview

Figure 5.2 displays the desired multi-source system, with the DGs being the prime auxiliary energy source on most ships worldwide. The shore power connection is divided into three systems: the HVSC, the LVSC and the dry-docking supply connection (DDSC). The DDSC is aimed to supply the ship while in dry-docking for low-power applications [139]. Since dry-docking connection is common for oceangoing ships, minor changes to the design could provide considerable amount of energy to the ship at low cost while in port. The implementation of DDSC is based on the LVSC standard; however, DDSC implies a modification to the current design while LVSC is a new system. Oceangoing ships behave differently from ferries or RoRo ships since they do not require a quick connection to shore power. Indeed, ferry docking is limited in time and needs automatic connection systems to optimize their charging time [140]. However, bulk carriers can stay in ports during many days and the shore power connection time is not a limitation. In this case, the cabling management system is less complex and expensive. Lastly, batteries can be used to store energy on ships. Nonetheless, batteries need to get through a process of certification to be installed on ships. The guidelines and rules for the so-called marine batteries are provided by different organizations like the American Bureau of Shipping (ABS) [79], Bureau Veritas (BV) [80], Det Norske Veritas (DNV) [81], and Lloyd's register (LR) [82].

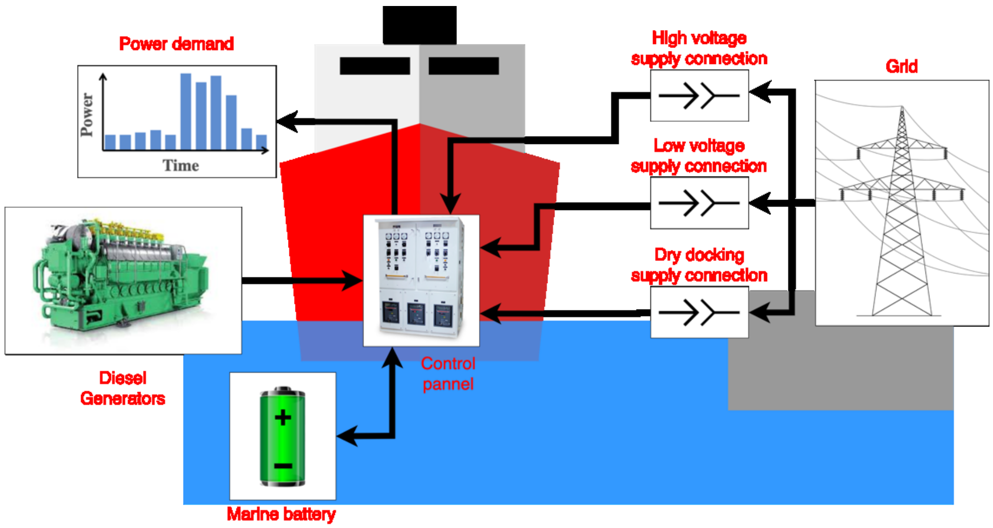


Figure 5.2: Energy sources map

The next sections introduce the decision variables used to size the different energy sources.

5.3.1 Decision variables

First, let us define the set of energy sources used in this model: $S = \{G, H, L, D, B\}$ for the DGs, the HVSC, the LVSC, the DDSC and the marine battery, respectively. Since each energy source characteristics do not influence costs and emissions in the same way, they require different types of decision variables:

- The decision variable x_G is used to determine the share of energy supplied by the DGs: $0 \leq x_G \leq 1$. We consider that the ship is already equipped with DGs either for new designs or retrofits. Therefore, the DGs rated apparent power is constant. However, the amount of energy they supply can vary, which is directly related to the system CO_2 emissions.
- The decision variable $w_H \in \{0,1\}$ determines if the HVSC system is used or not.
- The HVSC system is sized in function of its maximum apparent power because only this variable impacts the investment cost. The decision variable x_H determines the HVSC rated apparent power $0 \leq x_H \leq M w_H$ with $M = 1$.

- The decision variable $w_L \in \{0,1\}$ determines if the LVSC system is used or not.
- The LVSC system is sized in function of its maximum apparent power because only this variable impacts the investment cost. The decision variable x_L determines the LVSC rated apparent power: $0 \leq x_L \leq Mw_L$.
- The DDSC system is also sized in apparent power, but at a constant value. The DDSC system rated power depends on the internal dry-docking breaker capacity and ships AC bus voltage. Therefore, it is considered that the system can be used on not. This design choice is represented by the decision variable $w_D \in \{0,1\}$.
- The decision variable $w_B \in \{0,1\}$ determines if the marine battery system is used or not.
- The marine battery is sized in energy because the investment cost of batteries is highly dependent on their capacity. The decision variable x_B determines the share of energy supplied by the marine battery: $0 \leq x_B \leq Mw_B$.

5.3.2 Energy sources

In this section, the energy sources are modeled based on their maximum rated apparent power, supplied energy, CO_2 emissions, and investment cost. The CO_2 emissions associated with grid supply and battery fabrication are not considered because the focus is on reducing the emissions coming from the ship exclusively. A detailed life cycle impact assessment of different shipboard equipment such as DG operation and metallic scrap disposal, battery chemical impact, shore power transformer disposal, and other is presented in [141].

Diesel generators

The DGs system maximum apparent power is determined in (5.1) and is based on the rated apparent power of each DG on the ship. DGs are normally not loaded at more than 80% load [127] and they are connected in parallel in situations where more than 80% of their rated apparent power is required or may be required.

$$Smax_G = \sum_{j=1}^{N_{Gen}} G_{RP_j} \tag{5.1}$$

where $Smax_G$ is the maximum rated apparent power of the DGs power generation system [kVA], N_{Gen} is the number of DG in parallel, j is the DG identifier and G_{RP_j} is the apparent rated apparent power of the DG j [kVA].

The total energy supplied by all the DGs is presented in (5.2) and the relation between the DGs maximum apparent power and supplied energy is included in constraint (5.20) of section 5.3.3:

$$Q_G = x_G Q_{tot} \tag{5.2}$$

where Q_G is the energy supplied by the DGs [kWh] and Q_{tot} is the total energy required by the ship at berth [kWh].

A typical DG specific fuel oil consumption (SFOC) curve is given in Figure 5.3. In the maritime industry, most DGs are designed to rotate at a certain speed that determine the frequency of the main bus (50 Hz or 60 Hz). An automatic voltage regulator monitors the output voltage of the DG and adjusts the governor of the diesel engine so it can match the load. While DGs most efficient operating point is around 80%-100% load, they are rarely used at their optimal point to ensure enough power is available to supply any peak load.

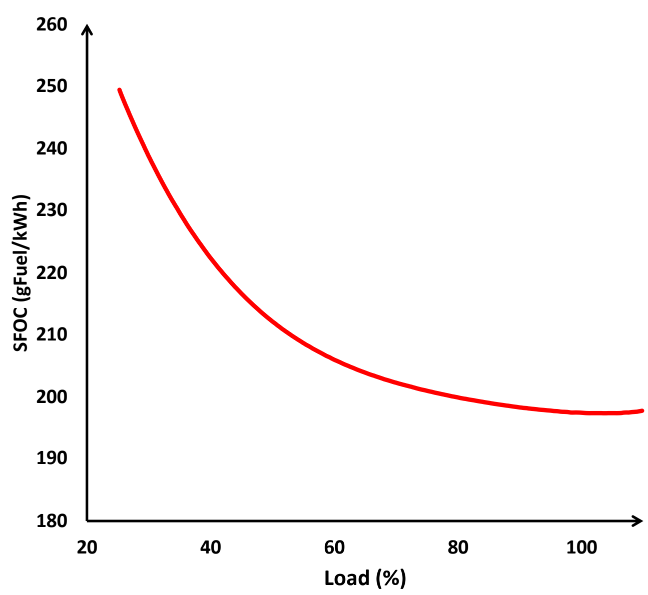


Figure 5.3: Typical SFOC curve for a single DG of a bulk carrier

To calculate CO_2 emission of the auxiliary power generation system adequately, the average SFOC is used. Indeed, a dynamic SFOC value following the curve of Figure 5.3 requires an EMS which is not the focus of this study.

The total amount of CO_2 emission of the DGs is calculated in (5.3) and is a simplified version of the formulation presented by Dalsøren *et al.* in [45]. Also, only the emissions from the ship docked in port are considered. Emissions from the grid or emitted during docking and undocking operations or full life cycle impact assessment are not considered.

$$CO_2 = Q_G \cdot SFC \cdot CF_{MDO} \tag{5.3}$$

where CO_2 is the average quantity of carbon dioxide emissions [tCO_2], SFC is the specific fuel consumption coefficient of the DG [tFuel/kWh] and CF_{MDO} is the carbon factor coefficient for marine diesel oil (MDO) [tCO2/tFuel].

Since the DGs are essential for the ship and do not require any changes to ship design, their CAPEX, $Cost_G$, is considered null.

$$Cost_G = 0 \tag{5.4}$$

High Voltage Supply Connection

The HVSC system supplies electricity via a shore connection and a cabling management system with electricity coming from the grid. The apparent rated power of the HVSC system is modeled in (5.5).

$$Smax_H = x_H Smax_{ship} \tag{5.5}$$

where $Smax_H$ is the designed HVSC system maximum apparent power [kVA] and $Smax_{ship}$ is the maximum apparent power of the load profile (given in Section 5.5.1) [kVA].

Then, it is considered that the HVSC energy source is used at maximum capacity if the system is installed to reduce CO_2 emissions. Therefore, the energy Q_H of the HVSC [kWh] depends on the load profile as presented in (5.6):

$$Q_H = \sum_{i=1}^{I} P_{i_H}\,\delta_i \text{ with } P_{i_H} = \begin{cases} PF \cdot Smax_H\,, & for\ P_i \geq PF \cdot Smax_H \\ P_i\,, & for\ P_i < PF \cdot Smax_H \end{cases} \tag{5.6}$$

where I is the interval length of P_i, P_i is the power of the load profile at time step i, P_{i_H} is the power delivered by the HVSC source at time step i, δ_i is the time step length and PF is the security power factor.

The cost of the HVSC system $Cost_H$ is presented in (5.7) in [$]:

$$Cost_H = a_H Smax_H + b_H w_H \tag{5.7}$$

where a_H and b_H are coefficients used to estimate HVSC system cost given in Table 5.2.

Low Voltage Supply Connection

The LVSC system supplies electricity to the ship like the HVSC system. However, it is limited in power by the LVSC IEEE draft standard maximum apparent power $Smax_{LVSC} = 1$ MVA as presented in (5.8).

$$Smax_L = x_L Smax_{LVSC} \tag{5.8}$$

where $Smax_L$ is the designed LVSC system maximum apparent power [kVA].

It is considered that the LVSC energy source is used at maximum capacity if the system is installed to reduce CO_2 emissions. Therefore, the energy Q_L of the LVSC [kWh] depends on the load profile as presented in (5.9):

$$Q_L = \sum_{i=1}^{I} P_{i_L}\,\delta_i \text{ with } P_{i_L} = \begin{cases} PF \cdot Smax_L\,, & for\ P_i \geq PF \cdot Smax_L \\ P_i\,, & for\ P_i < PF \cdot Smax_L \end{cases} \tag{5.9}$$

where P_{i_L} is the power delivered by the LVSC source at time step i.

The cost of the LVSC system $Cost_L$ is presented in (5.10) in [$]:

$$Cost_L = a_L Smax_L + b_L w_L \tag{5.10}$$

where a_L and b_L are coefficients used to estimate LVSC system cost given in Table 5.2.

Dry-docking supply connection

The power of the DDSC system rated power is limited by the ship dry-docking breaker maximum current $Imax_D$ [kA] and the ship's internal voltage V_{ship} [kV]. Therefore, there can be only one value of rated power for the DDSC system as presented in expression (5.11).

$$Smax_D = w_D \cdot \sqrt{3}\, V_{ship}\, Imax_D \tag{5.11}$$

where $Smax_D$ is the DDSC system maximum apparent power in [kVA].

Like HVSC and LVSC, DDSC energy source is used at maximum capacity if the system is installed to reduce CO_2 emissions. Therefore, the energy Q_D of the DDSC [kWh] depends on the load profile as presented in (5.12):

$$Q_D = w_D \sum_{i=1}^{I} P_{i_D}\, \delta_i \text{ } with \text{ } P_{i_D} = \begin{cases} PF \cdot Smax_D\,, & for\ P_i \geq PF \cdot Smax_D \\ P_i\,, & for\ P_i < PF \cdot Smax_D \end{cases} \tag{5.12}$$

where P_{i_D} is the power delivered by the DDSC source at time step i.

The cost of the DDSC system $Cost_D$ is presented in (5.13) in [$]:

$$Cost_D = w_D b_D \tag{5.13}$$

where b_D is the coefficient used to estimate DDSC system cost given in Table 5.2.

Since the DDSC system has a constant maximum power by design, the cost equation has no variation coefficient. Indeed, the DDSC system is intended to only supply the ship when it is in dry docking. Only minor modifications to the ship system are required to make it usable for shore power applications but its rated power cannot be improved. Therefore, the relation with the cost is binary.

Marine battery

Marine batteries can be used to store energy supplied by the grid using the shore power connections and do peak levelling. It is considered that the battery is full and recharged on shore with shore electricity or at sea. Also, the battery size is determined based on a maximum battery size Q_{Bmax} [kWh], which is determined by the decision maker and represents the maximum battery size that can be physically installed on the ship. The energy supplied by the batteries is determined in (5.14):

$$Q_B = x_B Q_{Bmax} Bat_{range} \tag{5.14}$$

where Q_B is the energy supplied by the marine batteries [kWh] and Bat_{range} is the operating range of the battery.

To limit batteries premature aging due to full discharge of the cells, a battery operating range is applied to the required capacity ranging from:

$$Bat_{range} = SOC_{max} - SOC_{min} \tag{5.15}$$

where SOC_{max} is the maximum allowable state-of-charge of the battery and SOC_{min} is the minimum allowable state-of-charge of the battery (given in Section 5.5.1).

The maximum power delivered by the battery is based on the battery capacity, the battery energy density Bat_{ED} [Wh/kg], the battery power density Bat_{PD} [W/kg] and the battery range $Batt_{range}$. Its power calculation is made dynamically since it is dependent on the battery capacity. The maximum power of the marine battery is presented in (5.16):

$$Smax_B = Q_B \times \frac{Bat_{PD}}{Bat_{ED}} \times \frac{1}{PF} \tag{5.16}$$

where $Smax_B$ is the maximum power that can be delivered by the battery [kVA].

The cost of the battery $Cost_B$ [$] is equal to the required battery capacity multiplied by the variable battery cost a_B [$/kWh] plus the fixed battery cost b_B [$] (given in Section 5.5.1) and presented in (5.17):

$$Cost_B = a_B \frac{Q_B}{Bat_{range}} + b_B w_B \tag{5.17}$$

5.3.3 Constraints

This section presents the constraints of the model that are used to eliminate the unfeasible solutions.

The system needs to be able to supply all the energy required by the ship at berth calculated from the load profile. This is done by aggregating the energy supplied by each source as presented in (5.18):

$$\sum_{s \in S} Q_s \geq Q_{tot} \tag{5.18}$$

The system must also be able to supply the highest load of the load profile. By aggregating the maximum apparent power of every energy source in use, the maximum apparent power of the system is determined (5.19):

$$\sum_{s \in S} Smax_s \geq Smax_{ship} \tag{5.19}$$

Another energy related constraint is the maximum energy that can be supplied by the all the DGs. The model makes the energy supplied by all the DGs vary with the decision variable x_G to make the CO_2 emissions vary. Nevertheless, constraint (5.20) limits the amount of energy that the DGs can supply.

$$Q_G = \sum_{i=1}^{I} P_{i_G}\, \delta_i \; with \; P_{i_G} = \begin{cases} PF \cdot Smax_G\,, & for\; P_i \geq PF \cdot Smax_G \\ P_i\,, & for\; P_i < PF \cdot Smax_G \end{cases} \tag{5.20}$$

where P_{i_G} is the power delivered by the DG source at time step i.

Finally, the equation (5.21) is a constraint preventing the system to be supplied by more than one type of shore power connection (HVSC, LVSC or DDSC). Indeed, it is not practically interesting for the crew, for the designers and for the operators to manage different types of shore power connections for one ship. Therefore, if more than one system is used, the sum will be greater than 1 and the algorithm will discard the solution.

$$w_H + w_L + w_D \leq 1 \tag{5.21}$$

5.3.4 Objective functions

The two objectives are to minimize CO_2 emissions of the ship while at berth (5.22) and to minimize the CAPEX in [$] of the system (5.23).

$$minimize\; CO_2(x_G) = SFC \cdot CF_{MDO}\, x_G Q_{tot} \tag{5.22}$$

$$minimize\ CAPEX\left(x_{\{G,H,L,B\}}\ , w_B\right) = \sum_{s \in S} Cost_s \tag{5.23}$$

Engineering and installation fees are out of the scope of this paper, but they should be estimated for real CAPEX estimations. Also, it is considered that the methodology primarily applies to new ship designs since its integration is easier and more profitable. However, it can also be applied to ship retrofitting.

The resulting model is a multi-objective mixed integer non-linear programming problem (MOMINLP) and requires MINLP algorithms to be solved. While some equations of the model can be linearized, equations (5.6) and (5.9) cannot because their relationship with the load profile is not linear.

Because the model presents most of its optimal solutions in the extreme values allowed for its decision variables, an exhaustive search has been performed. The scalarization technique is used to combine the objective functions and is presented in the next section.

5.3.5 Scalarization of the objective functions

The sizing multi-objective problem aims to find a combination of energy sources that minimize both objective functions. However, a solution minimizing simultaneously both economic and environmental objective functions do not exist because of their conflicting nature. A scalarization technique can be used to compute non-dominated solutions.

Several scalarizing techniques exist to compute the non-dominated solutions defining the Pareto front, including e-constraint technique, the weighted sum (WS) technique and the reference point techniques [142]. We have used the reference point technique aiming to compute a compromise non-dominated solution that minimizes a distance function to a reference point, in our case the ideal point *I'*, considering the weighted Chebyshev metric (just the largest difference in all dimensions to the reference point counts) and a normalized function based on the nadir point *N'*. The reference point *I'* is set at the origin because it would be the ideal solution (eliminates emissions at zero cost), which is not attainable. The distance function is presented in (5.26). The consideration of weights λ_k associated with each objective function f_k enables to scan the entire Pareto front. Also, the normalization of the objectives prevents one objective to be advantaged over another due to the different measurement scales. Indeed, different objective functions can have values with different magnitude and the weighting would not be consistent. The Chebyshev metric enables to find non-convex Pareto fronts.

First, the two objectives are normalized by dividing the results by their highest possible value N':

$$f_1 = \frac{CO_2(x_G)}{N'_{f_1}} \tag{5.24}$$

$$f_2 = \frac{CAPEX\left(x_{\{G,H,L,B\}}, w_B\right)}{N'_{f_2}} \tag{5.25}$$

Then, the Chebyshev metric equation is presented with the normalized functions of (5.24) and (5.25):

$$L_\infty^\lambda = \max(\lambda_k|f_1 - z_1|, (1-\lambda_k)|f_2 - z_2|), \qquad 0 \le \lambda_k \le 1 \tag{5.26}$$

where z_1 and z_2 are the normalized ideal points of f_1 and f_2 respectively.

The study also compares the results provided by the Chebyshev metric with a WS approach and with a reference-point technique considering the minimization of the Manhattan metric (sum of all differences in each dimension to the reference point), as presented in (5.27) and (5.28).

$$Weighted\ sum = \lambda_k f_1 + (1-\lambda_k) f_2, \qquad 0 \le \lambda_k \le 1 \tag{5.27}$$

$$L_1^\lambda = \lambda_k|f_1 - z_1| + (1-\lambda_k)|f_2 - z_2|, \qquad 0 \le \lambda_k \le 1 \tag{5.28}$$

Finally, the multi-objective model is completed by gathering the scalarizing functions and the physical constraints of Section 5.3.3:

$$\begin{gathered} \min f_1 \\ min\ f_2 \end{gathered} \tag{5.29}$$

$s.t.$ (5.18), (5.19), (5.20), and (5.21) are satisfied.

The exhaustive methodology used to compute the Pareto front based on the scalarizing techniques is presented in the following section.

5.4 Methodology

As presented in Figure 5.4, the first step of the methodology is to analyze the ship's load profile by measuring the maximum power needed by the auxiliary system and the total energy used per stay in port. These parameters are needed to size the different energy sources. Then, solutions are generated by testing every combination of w_D and $x_{\{G,H,L,B\}}$. A step of 0.01 is used for the sizing of the DGs ($x_{\{G\}}$), 0.005 for the battery ($x_{\{B\}}$) and of 0.1 for the sources designed in rated power ($x_{\{H,L\}}$). The step resolution of $x_{\{G,H,L,B\}}$, is selected to obtain a well-distributed Pareto front and have a complete representation. For each combination, the feasibility is evaluated. If a solution is feasible, the CAPEX and CO_2 emissions of this solution are calculated. If not, the algorithm generates another solution. At the end of the loop, the set of feasible solutions is sent to the scalarization process.

Then, the algorithm finds the *I'* and *N'* points so the feasible scalarizing functions can be normalized. A second loop starts to generate every combination of weights λ_k to measure the WS, the L_∞^λ and the L_1^λ. A step of $d_{\lambda_k}$of 0.0005 is selected to find all non-dominated solutions. For each weight combinations, the result that minimizes the WS, the L_∞^λ or the L_1^λ is output to the Pareto front. When every combination is measured, the Pareto front is presented to the decision maker so it can be further analyzed, namely regarding the assessment of the trade-offs between the objective functions.

Based on this model, three scenarios using estimated load profiles from a bulk carrier operation at berth have been estimated in the next section.

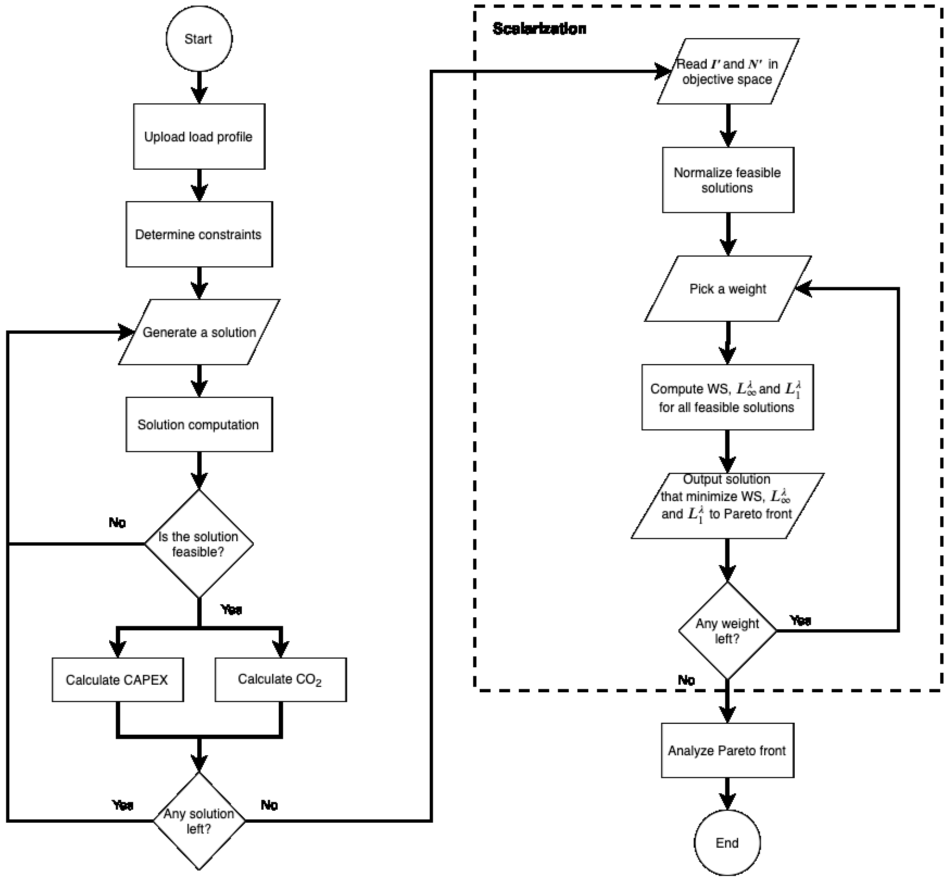


Figure 5.4: Flowchart of the methodology

5.5 Results and discussions

5.5.1 Studied Bulk Carrier

The ship under study is the Federal Baltic bulk carrier of Fednav. This ship has been selected because it well represents the next generation of international Lakers that will sail on the Saint-Lawrence River and Great Lakes area in terms of shape and load. It is a 1C ice class (light ice conditions) dry bulk carrier of handysize with a capacity of 34,564 dead weight tonnage (DWT) built in Oshima shipyard in Japan. Equipped with four deck cranes of 35 t, the ship can load and unload its cargo without the need of shore cranes, but the load on the DGs greatly increases when the cranes are in operation. To supply the auxiliary demand, the crew operates three DGs of 750 kVA each of which can be synchronized in parallel to supply loads until 2.25 MVA. International Lakers are a special type of bulk carrier, because of their special design specifically made to fit in the St. Lawrence Seaway lock system. During a typical journey, the ship stops in many ports to load and unload cargo.

Figure 5.5: Federal Baltic[3]

Based on data provided by Fednav Inc., three load profiles have been estimated. Figure 5.6 represents a typical load profile of the ship in loading and discharging operations, while Figure 5.7 represents a high-power load profile and Figure 5.8 a low power load profile of the ship at rest in port. A resolution of 2 s is used for the load profiles instead of a more standard average on 10 minutes because important information lies in the peak power demands.

In the load profile A of Figure 5.6, the ship is in loading and discharging operations requiring a maximum apparent power of 1230 kVA and 7.74 MWh of energy for 24 hours. However, loading/discharging operations can last days of continuous work. The auxiliary system supplies the

[3] https://www.fednav.com/en/federal-baltic-0

hydraulics of the deck cranes, which are the highest load of the system when the ship is docked. To load/unload cargo, the crane operator needs to do multiple actions explaining the high fluctuation on the load profile: pick up the load, bring the load up (hoisting), turn over (slewing), adjust the jib (luffing), and lower the load. Also, not all four cranes are operated together at the same time. Although this may happen, only one crane is normally used at a given time. At the same moment, the auxiliary system also supplies the hotel load, which corresponds to lightning, deck equipment, engine room machinery, cooking, laundry, ventilation, air conditioning, etc.

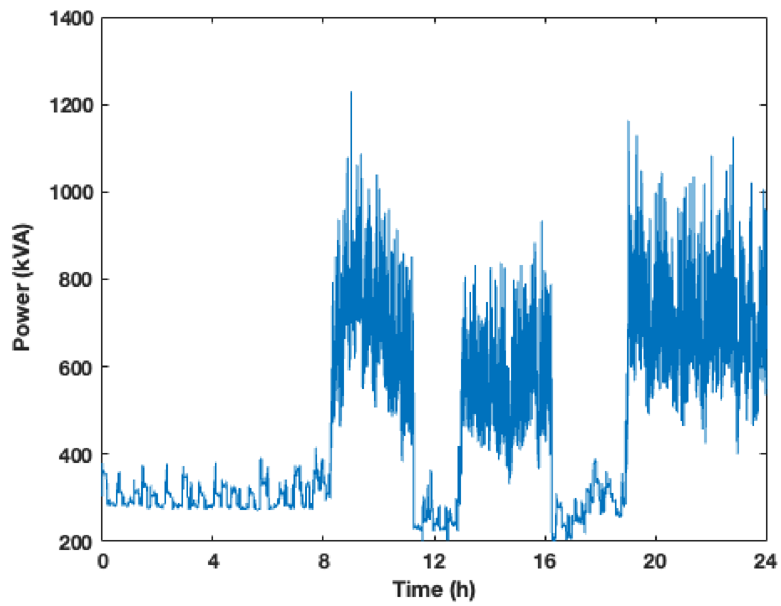


Figure 5.6: Load profile Scenario A

The load profile B of Figure 5.7 is a high-power load profile requiring a maximum power of 2023 kVA and 18.4 MWh of energy for a period of five days. In this case, the three DGs of the auxiliary system are used near their maximum capacity. However, this load profile is a fictive one because it would require operating the ship in a way that is not practical. It is obtained by multiplying with a factor of 3 the load profile of Scenario C. The factor of 3 is used to match the maximum power of the load profile with the combined maximum power of the Federal Baltic DGs. Therefore, we can investigate a case where the ship would be used at a maximum load capacity.

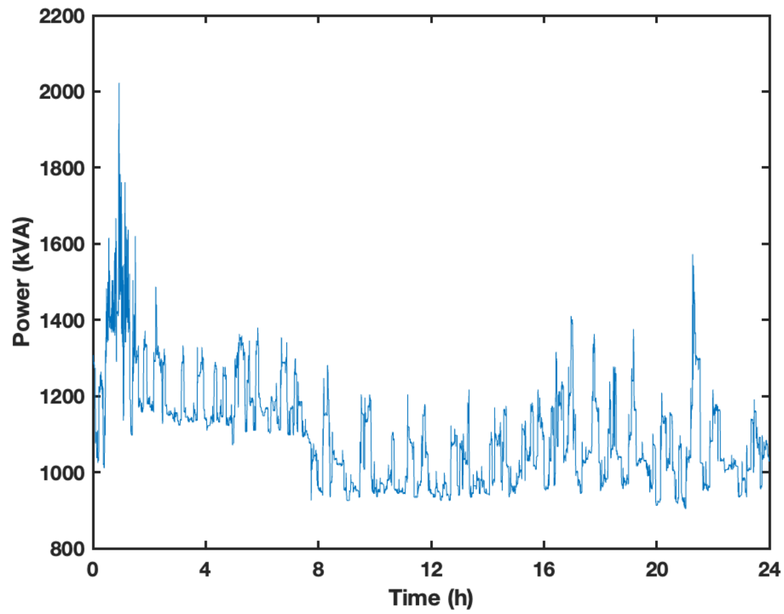


Figure 5.7: Load profile Scenario B

The third load profile analyzed in this study is the estimation of the ship's load when at rest in the port. As presented in Figure 5.8, the Federal Baltic auxiliary system supplies the hotel load for six days with a maximum apparent power of 674 kVA and 6.14 MWh.

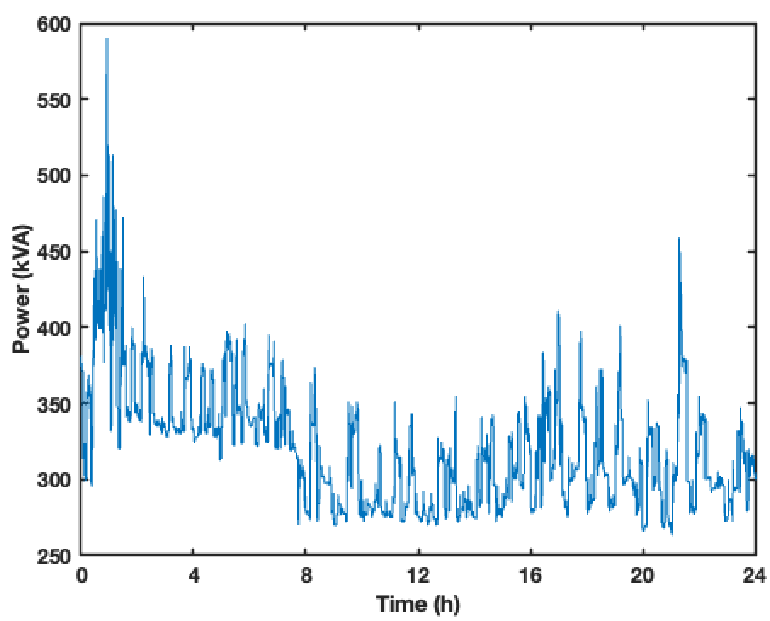


Figure 5.8: Load profile Scenario C

The parameters concerning shore power system costs have been obtained by using the shore power cost estimation tool from the World Port Sustainability Program (WPSP) [143] in Table 5.1 with few estimations to complete the table. It is considered that the cabling management system is onboard the ship, but it could also be provided by the port which would further decrease the initial capital of the system.

Table 5.1: World Port Sustainability Program shore power cost data and estimations

	WPSP data		Estimation from WPSP data		
	RORO, 1.5 MVA (HVSC)	CONTAINER, 7 MVA (HVSC)	300 kVA (LVSC)	1 MVA (LVSC)	300 kVA (DDSC)
Transformer ($USD)	238,000$	357,000$	NA	NA	NA
Main switchboard, control panel ($USD)	119,000$	119,000$	59,500$ (*estimation*)	119,000$	20,000$ (*estimation*)
Cabling ($USD)	3,570$	3,570$	3,570$	3,570$	NA
Cable reel system ($USD)	180,880$	180, 880$	180, 880$	180, 880$	180, 880$
Total ($USD)	541,450$	660,450$	243,950$	303,450$	200,000$

Table 5.2 presents the parameters used to supply the model. Measurements on the Federal Baltic have shown that the power factor is on average 0.7 when the ship is loading or discharging cargo with its deck cranes. Therefore, the value of 0.7 is used as a worst-case scenario instead of a typical value of 0.8 for the maritime industry. Also, the battery parameters follow the state of the art of marine batteries for bulk carriers. The DNV GL study on electrical energy storage for ships pointed out the relevant battery technologies to use depending on the ship type [144]. Nickel manganese cobalt oxide, lithium iron phosphate (LFP) or lithium titanate oxide were suggested by DNV GL as the best and most secure battery technology for bulk carriers. Taking Li-ion as the main battery type, the average energy density and power density value for Li-ion battery systems has been calculated based on the work of Stenzel *et al.* [145].

Table 5.2: System parameters.

Parameters	Values		Source
Ship (Federal Baltic)			
DG rated power	G_{RP}	750 kVA	Fednav
Number of DGs	N_{Gen}	3	Fednav
DG worst SFC	SFC_{wrst}	250 gFuel/kWh	Fednav
DG best SFC	SFC_{bst}	197 gFuel/kWh	Fednav
Shore power systems			
HVSC base cost	b_H	$509,000	Table 5.1
HVSC cost variation	a_H	$21.64/kVA	Table 5.1
LVSC base cost	b_L	$218,450	Table 5.1
LVSC cost variation	a_L	$85/kVA	Table 5.1
DDSC base cost	b_D	$200,000	Table 5.1
Security power factor	PF	0.7	Fednav
Ship AC bus voltage	V_{ship}	440 V	Fednav
Maximum current capacity of DDSC	$Imax_D$	400 A	Fednav
Marine battery base cost	b_B	$3570	Table 5.1
Marine battery cost variation	a_B	$400/kWh	[140]
Maximum battery state of charge	SOC_{max}	90%	Typical for battery sizing
Minimum battery state of charge	SOC_{min}	20%	
Battery maximum size	Q_{Bmax}	500 kWh	Fednav
Battery energy density	$Batt_{ED}$	43 Wh/kg	[145]
Battery power density	$Batt_{PD}$	167 W/kg	[145]

5.5.2 Results

The following section presents the multi-objective analysis for each scenario. The Pareto front consisting of the non-dominated solutions is displayed. Each of its solutions is identified on the graph by a number. Each solution is associated with an uncertainty based on the maximum and minimum SFOC value of the DG, which is represented by black vertical line. When there is no change to the current design of the ship, there is no extra CAPEX investment to make, but the emissions are at their maximum because the DGs are used at maximum capacity. For the analysis of load profiles, A, B and C, this solution is referred to as the *current* solution and is denoted as solution 1 on the Pareto front. Finally, we also present bar graphs of the CAPEX, energy repartition and available apparent power of each solution to support the analysis of the Pareto front and give more insights on the non-dominated solutions.

Scenario A

The first scenario using load profile A is a typical load profile for the Federal Baltic in port with loading and discharging operations. Figure 5.9 presents the Pareto front computed for this load profile. The weighted Chebyshev metric is used to compute the Pareto optimal solutions and its results are compared with the ones of WS and the weighted Manhattan metric. We can see that the solution lying on the convex hull of the Pareto optimal front are found by every technique, but only the Chebyshev metric can find solutions located in the interior of the convex hull of the Pareto front.

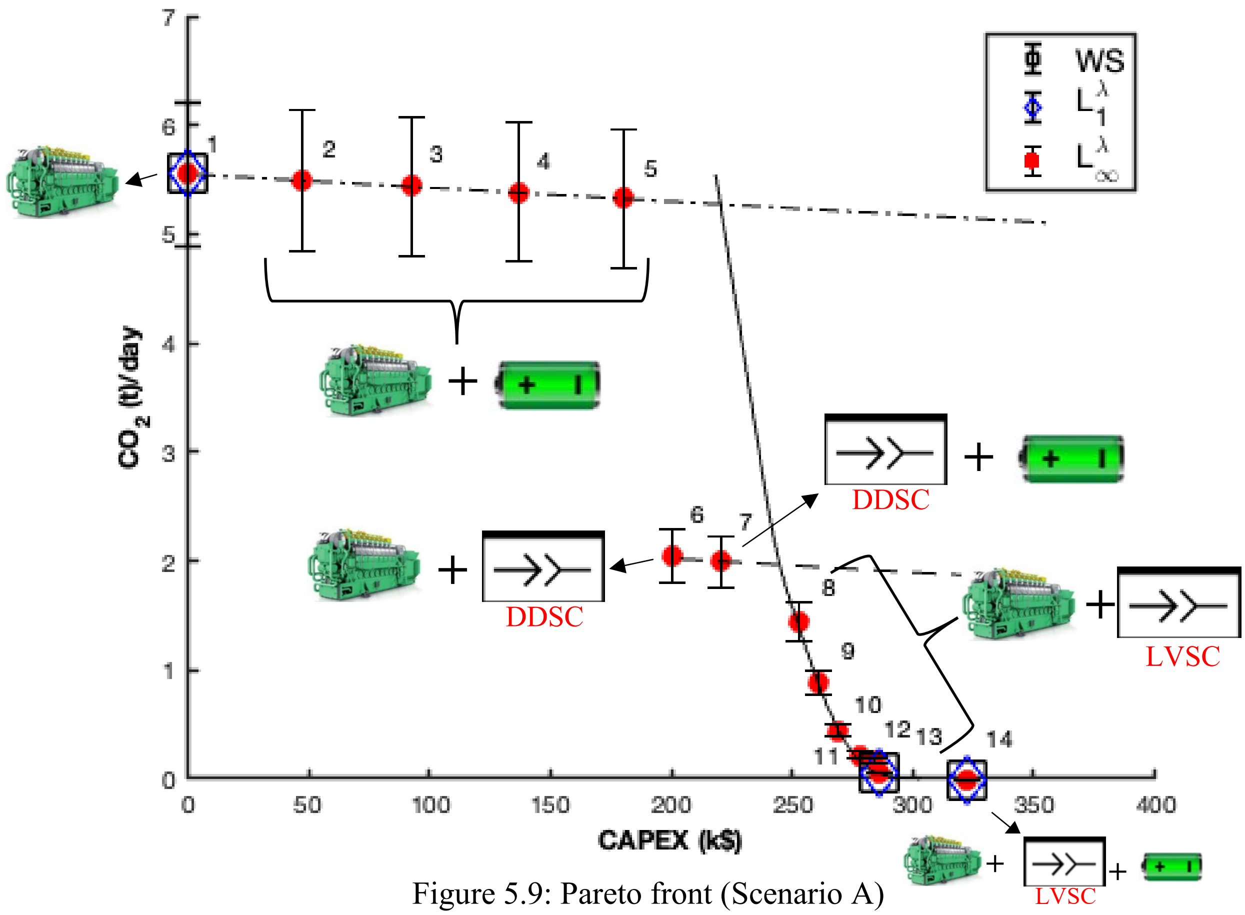


Figure 5.9: Pareto front (Scenario A)

The solution 1 (current solution) of the Pareto front is the point where only the DGs are used to supply the ship ($x_G = 1$). This is the solution with the highest CO_2 emissions with 5.55 t CO_2/day $\pm$ 0.66 t CO_2. If the crew operated the DGs at their most efficient point all the time, they could emit only 4.89 t CO_2 per day. However, this scenario is hard to attain for the crew because of the fluctuating power during loading and discharging operation.

Then, the next points are a combination of the DGs and a battery as presented in Figure 5.11 (a) for solutions 2 to 5 ($x_G = \{0.99, 0.98, 0.97, 0.96\}$, $x_B = \{0.220, 0.445, 0.665, 0.885\}$). At solution 6, the emissions drop considerably ($x_G = 0.37, w_D = 1$). This is because the increased cost of the battery meets the minimum cost of the DDSC system as presented in Figure 5.10. With an investment of 200 k$, the DDSC can supply far more energy than the batteries for less investment and take down emissions to 2.05 t of CO_2/day e.g., a 63% emission reduction per day if we subtract the emissions of solution 6 to the emissions of the current solution.

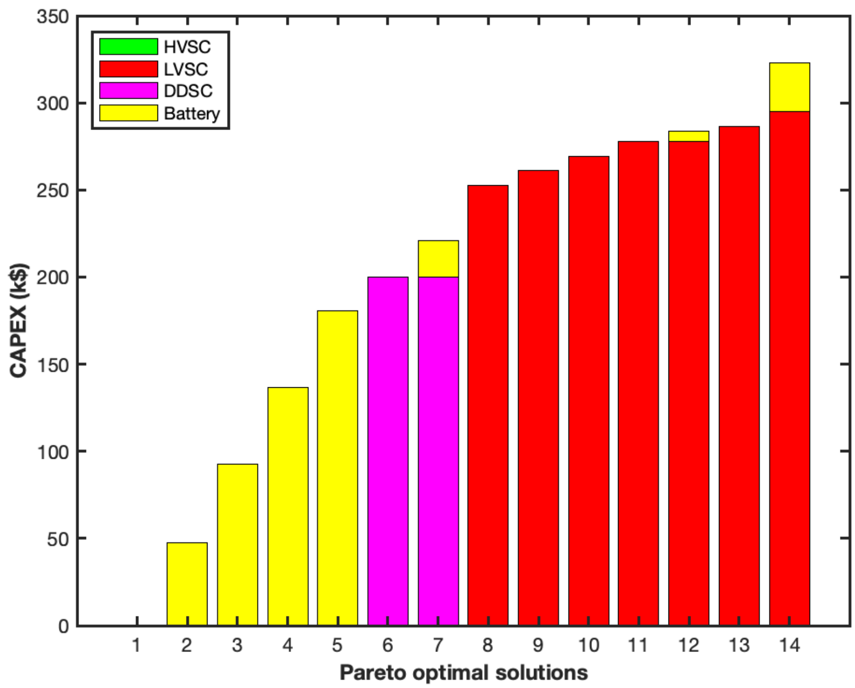
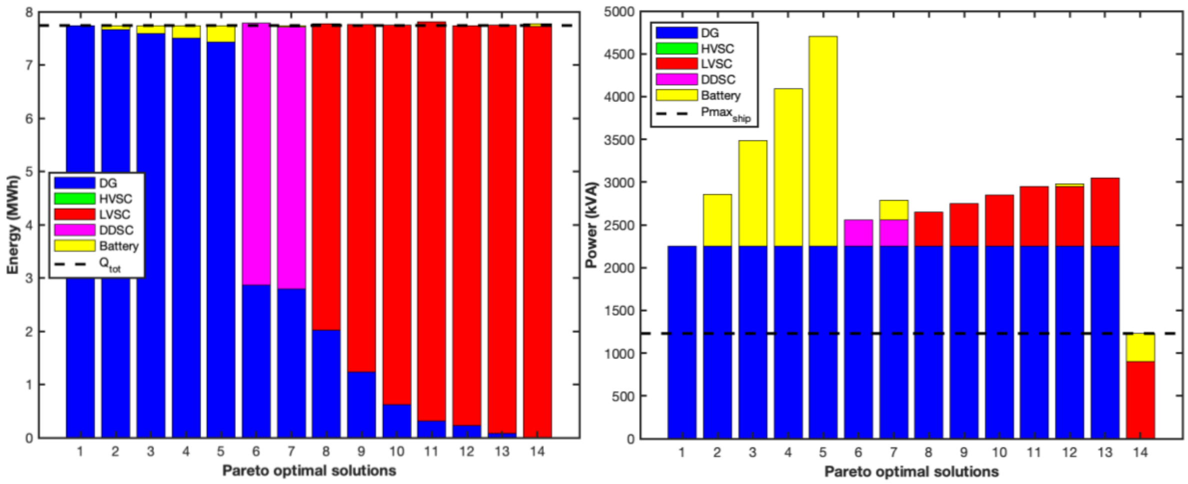


Figure 5.10: CAPEX of the Pareto optimal solutions (Scenario A)

However, solution 6 still requires the DGs to operate in order to provide enough power during high-power demand as seen in Figure 5.11 (b). Solution 7 represents combinations of the DGs, the DDSC system and a battery ($x_G = 0.36, w_D = 1,\ x_B = 0.085$). In solutions 8 to 13, the LVSC system maximum power is increasing reaching $x_G = 0.01,\ x_L = 0.8$. Yet, the DGs still need to be used to fill the power gap. Finally, solution 14 uses the LVSC and a battery of 60 kWh ($x_L = 0.9, x_B = 0.120$) resulting in 0 t of CO_2/day at a cost of 323 k$. It should be noted that solution 14 does not have a LVSC system designed at maximum rated apparent power. Since the cost per kVA of the LVSC system is slightly higher than the cost per kVA of the battery, it is more affordable to have a bigger battery. Indeed, a very small amount of energy is needed to supply the high-power peaks of the load profile. Figure 5.11 a) displays how much energy is supplied by each source to supply the demand for all the non-dominated solutions and Figure 5.11 b) presents the available maximum power. For all solutions except solution 14, the DGs need to be used to supply enough energy, enough power or both. Even if the HVSC system is used for peak power demands greater than 1 MVA, this solution is dominated by solution 12 because it is too expensive compared with a combination of a battery and the LVSC system.



a) Supplied energy repartition b) Available apparent power

Figure 5.11: Supplied energy repartition and the available apparent power for the different energy sources for the Pareto optimal solutions (Scenario A)

For this load profile, the battery is very helpful because it enables a more affordable system even if the LVSC system is not powerful enough to supply the peak load demands. Indeed, the Federal Baltic load profile in port is characterized by the use of the cranes which are engaging high, but very short, power demands and the battery is well suited to supply this high demand at lower price. Also, the use of the DDSC system along with the DGs offers a CO_2 reduction of 63% compared to solution 1, while being less expensive. Finally, if the decision maker is more focused on eliminating emissions, the LVSC system combined with a 60 kWh battery presents the most interesting solution at 323 k$.

Scenario B

The Scenario B analyzes the high-power load profile B of Figure 5.7 to ascertain what system is the most adequate if the ship is operated at maximum power. The Pareto front of Figure 5.12

presents the results of the analysis. The Pareto front is composed of different regions with convex and non-convex shapes. We see that the WS and Manhattan metric only found the solutions 1, 12 and 17 defining the convex hull. The other solutions were computed using the Chebyshev metric giving a well-distributed Pareto front.

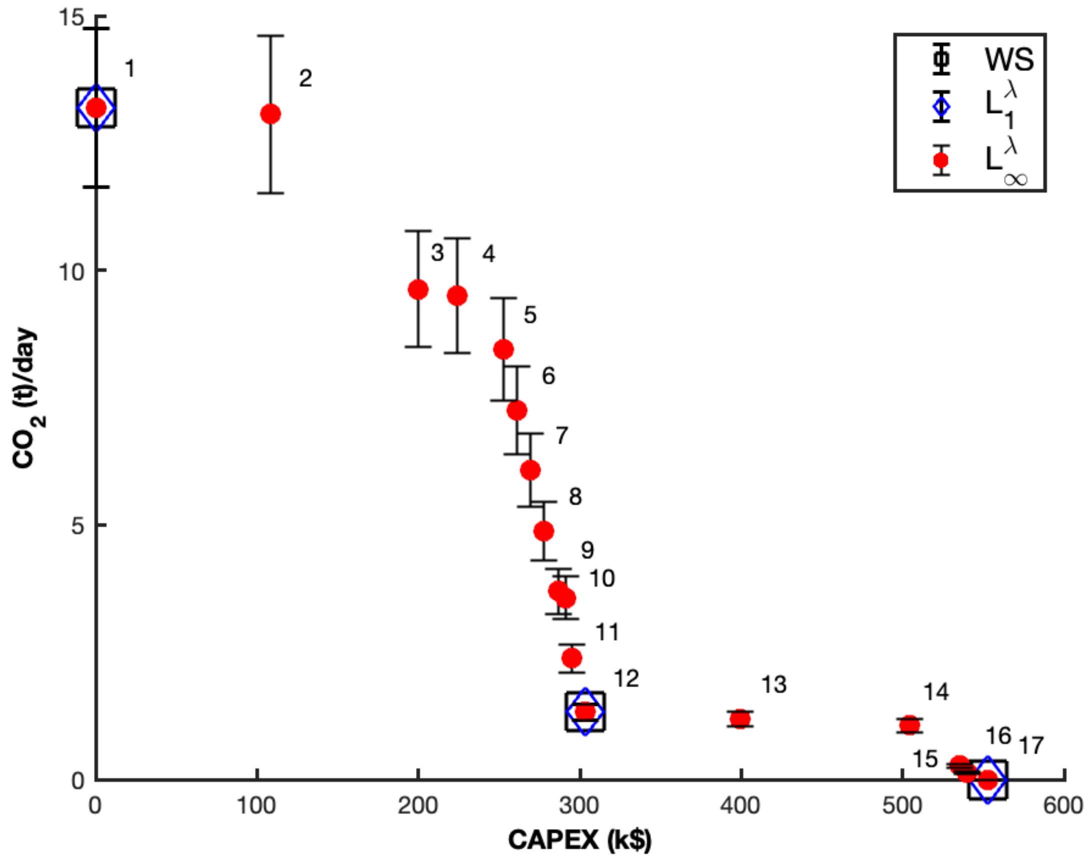


Figure 5.12: Pareto front (Scenario B)

This Pareto front shape is different from the previous Pareto front of Scenario A because the peak power demand and total energy required by the load profile are much higher.

Solution 1 represents the case where only the DGs are operated and is the current solution ($x_G = 1$) with 13.2 t CO_2 per day. Solutions 2 represents combinations of the DGs and batteries ($x_G = 0.99, x_B = 0.525$). In solution 3, the increased cost of the battery meets the cost of the DDSC system as presented in Figure 5.13 at a cost of 200 k$ and 9.6 t CO_2/day ($x_G = 0.73, w_D = 1$). At this point, a drop of approximately 27% in CO_2 emissions is obtained compared to the current solution. Solution 4 is a combination of the DGs, the DDSC system and a battery ($x_G = 0.72, w_D =$

$1, x_B = 0.1$). Right after, the increased cost of the battery meets the LVSC cost curve for solutions 5 to 12 ($x_G = \{0.64, 0.55, 0.46, 0.37, 0.28, 0.27, 0.18, 0.1\}$, $x_L = \{0.4, 0.5, 0.6, 0.7, 0.8, 0.8, 0.9, 1\}$). Solution 10 also has a small battery ($x_B = 0.005$).

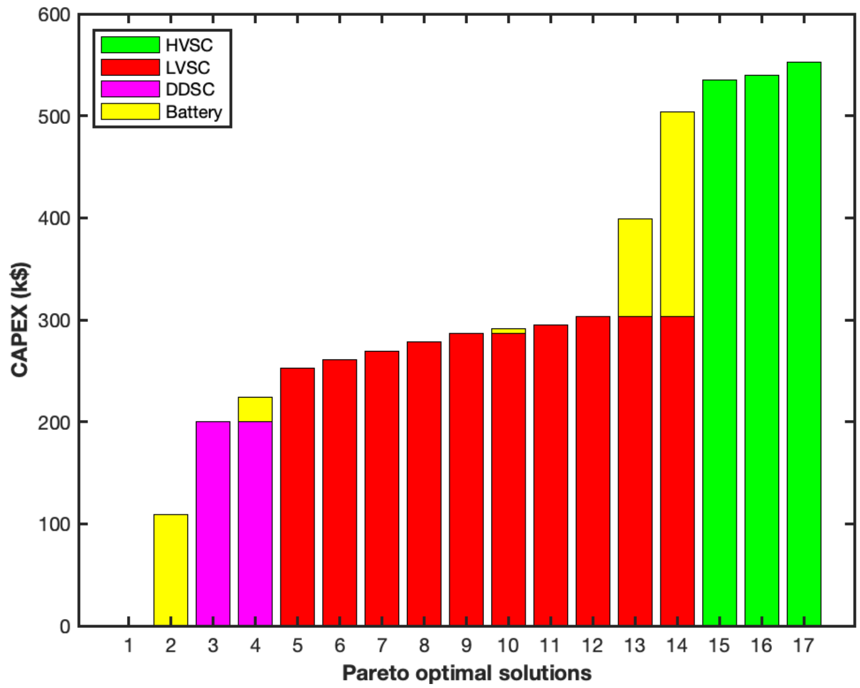
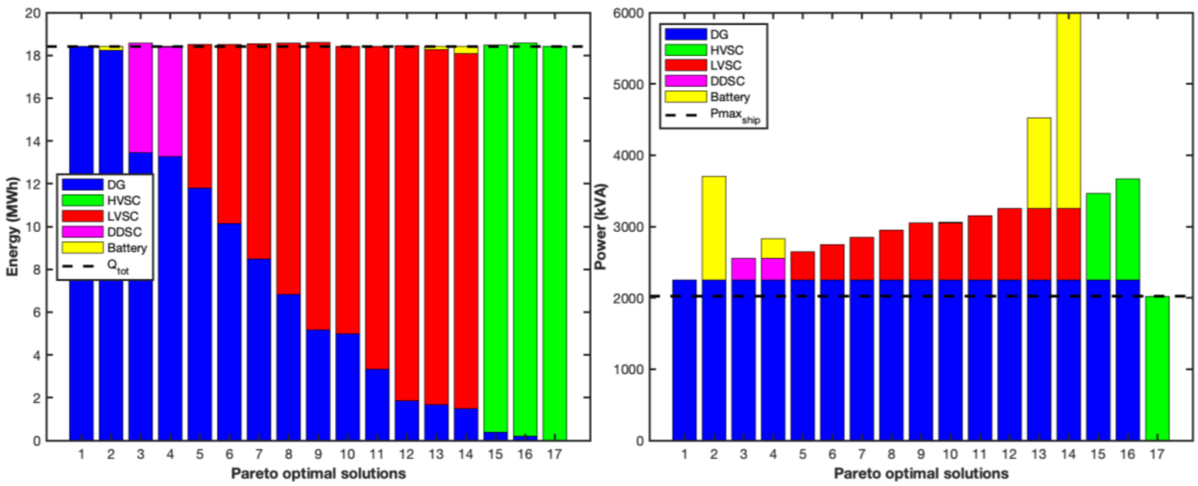


Figure 5.13: CAPEX repartition between the different energy sources for the Pareto optimal solutions (Scenario B)

At solution 12, the maximum design power of the LVSC system is reached ($x_L = 1$). This solution presents a 90% emission drop compared to the current solution with only 1.3 t CO_2 emitted per day and a cost of 303 k$. Solutions 13 and 14 are a combination of the DGs, the LVSC system and batteries ($x_G = \{0.09, 0.08\}, x_L = 1, x_B = \{0.46, 0.985\}$). At solution 15, the increased battery cost reaches the HVSC cost curve. Solutions 15 and 16 represent combinations of the HVSC system and the DGs ($x_G = \{0.02, 0.01\}, x_H = \{0.6, 0.7\}$). Finally, in solution 17, $x_H = 1$ and the HVSC system is strong enough to supply the entire load eliminating the DGs emissions at a cost of 553 k$.



a) Supplied energy repartition b) Available apparent power

Figure 5.14: Supplied energy repartition and the available apparent power for the different energy sources for the Pareto optimal solutions (Scenario B)

For load profile B, the battery is not useful because the load profile requires a lot of energy at high-power and the battery cannot supply both economically. Its energy cost is too high compared to the other energy sources. If the maximum power of the DDSC or the LVSC system was close enough to $Smax_{ship}$, a battery could provide the extra power and become useful. However, it is not the case.

In this scenario, the decision maker should focus only on three different solutions (3, 12 and 17), because the other solutions do not present interesting benefits in terms of emissions for the corresponding cost increase. Solution 3 considers the installation of a DDSC system to reduce the emissions in 27% compared to solution 1 at a relatively low cost of 200 k\$. Solution 12 uses a LVSC system on the ship that can reach up to 90% of emission reduction compared to solution 1 at a cost of 303 k\$. The only option eliminating emissions of the DGs completely for the load profile B is a HVSC system of 2023 kVA at cost of 553 k\$ in solution 17.

Scenario C

Scenario C considers the case where the Federal Baltic ship is at rest in port. In this situation, the system is optimized for low-power applications, but could still be used to provide energy in port for higher-power demands if the DGs provides the balance of power.

In this case, solution 1 is the current solution ($x_G = 1$) with 4.4 t CO_2 per day ±0.52 t CO_2. Solutions 2 to 6 are combinations of the DGs and a battery ($x_G = \{0.99, 0.98 \ldots 0.95\}, x_B = \{0.165, 0.33 \ldots 0.82\}$).

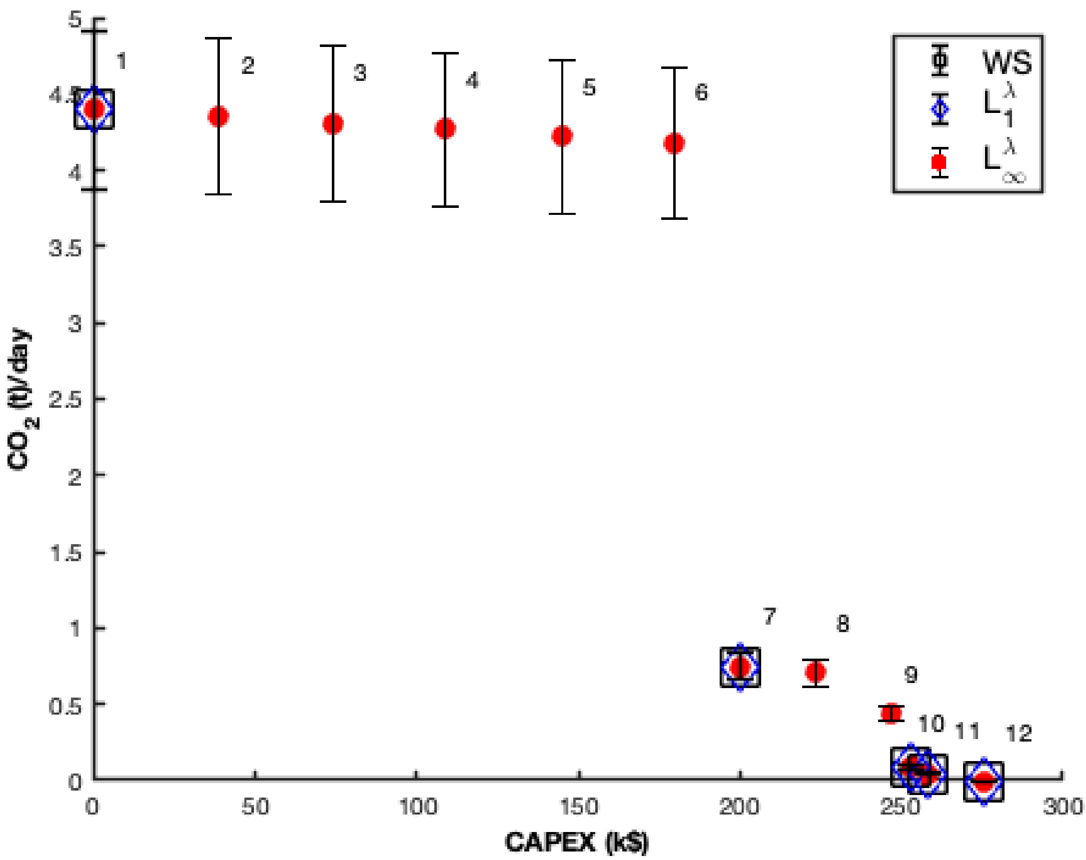


Figure 5.15: Pareto front (Scenario C)

As presented in Figure 5.16, the cost of the battery meets the DDSC cost at 200 k$, and solution 7 consists of a combination of the DDSC system and DGs energy supply ($x_G = 0.08, w_D = 1$). This leads to approximately 92% of CO_2 emission reduction compared to solution 1 where only the DGs supply the load with only 0.35 t CO_2 emissions per day. However, the DDSC system is not powerful enough to supply the entire load on its own even when the ship is at rest. The maximum required apparent power is 674 kVA while the DDSC system is limited to 305 kVA. Solutions 8 and 9 are combinations of the DDSC system, DGs and a battery ($x_G = \{0.07, 0.06\}, w_D = 1, x_B = \{0.035, 0.195\}$). In solution 10, the increased cost of the battery meets the LVSC cost curve ($x_G = 0.02, x_L = 0.6$). The LVSC maximum power augments in solution 11 ($x_G = 0.01, x_L = 0.7$).

Finally, solution 12 provides a LVSC system strong enough ($x_L = 1$) to eliminate the DGs emissions of load profile C at a cost of 267 k$.

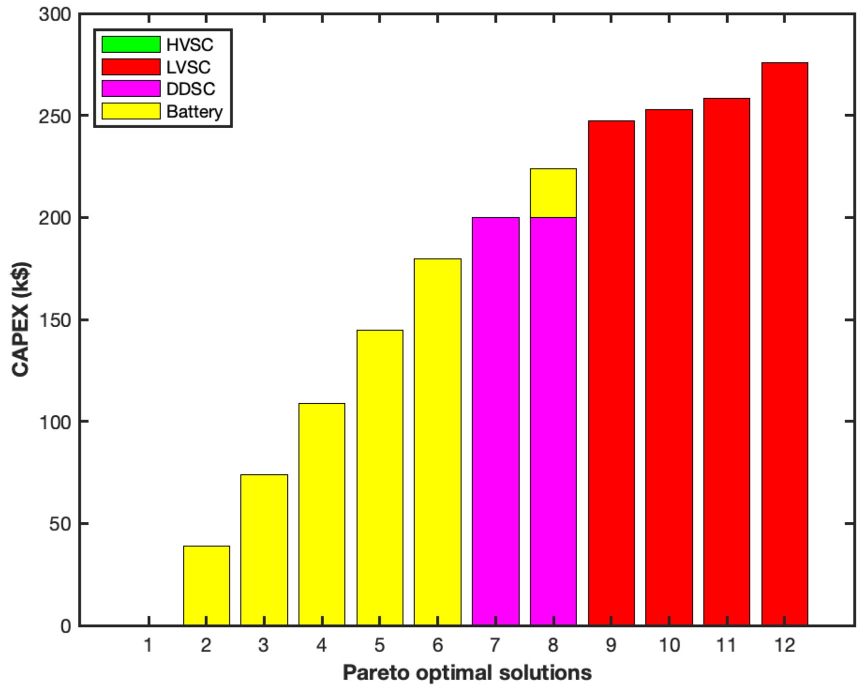
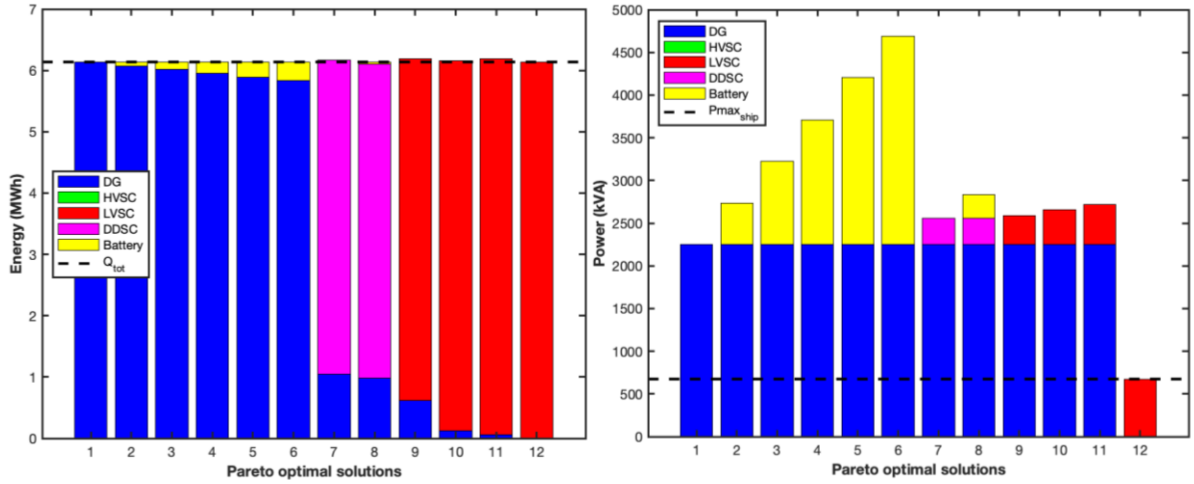


Figure 5.16: CAPEX of the Pareto optimal solutions (Scenario C)

Figure 5.17 a) shows that the addition of a 1043 kWh battery to the DDSC system would have been sufficient to fill the energy and power gaps and eliminate DGs emissions. However, this solution is not presented because the cost of such a battery is too high, and the solution is not a non-dominated solution.



a) Supplied energy repartition

b) Available apparent power

Figure 5.17: Supplied energy repartition in and available apparent power for the different energy sources for the Pareto optimal solutions (Scenario C)

The load profiles A, B and C are characterized by their high peak power demand due to the action of the cranes during loading and discharging operations. In the case of Scenario B, the battery was found to be very useful to supply high-power demands when the LVSC system could not supply the peak load while not having to invest in a HVSC system. However, the battery also revealed of being expensive sources of energy storing small amount of energy. Therefore, hybrid systems are necessary for the use of batteries.

The analysis of the three scenarios enables assessing the trade-offs to select a non-dominated solution that can be recommended for new shore power design of the Federal Baltic including the decision maker's preferences in the decision support process. The results show that the LVSC system combined with a battery of 60 kWh is an interesting trade-off when the goal is to find an economic solution that can reduce CO_2 emissions the most. Indeed, this combination can reduce emissions compared to the current solution of 100%, 90% and 100% for scenario A, B, and C, respectively at a cost of 323 k$. However, the installation of the DDSC system is also interesting because it enables to reduce emissions in comparison to the current solution of 63%, 27%, and 92% for scenario A, B, and C, respectively, at a low CAPEX value of 200 k$. Finally, if the decision maker wants to eliminate emissions of the DGs in port for any given scenario, it is recommended to invest in a HVSC system at a cost of 553 k$.

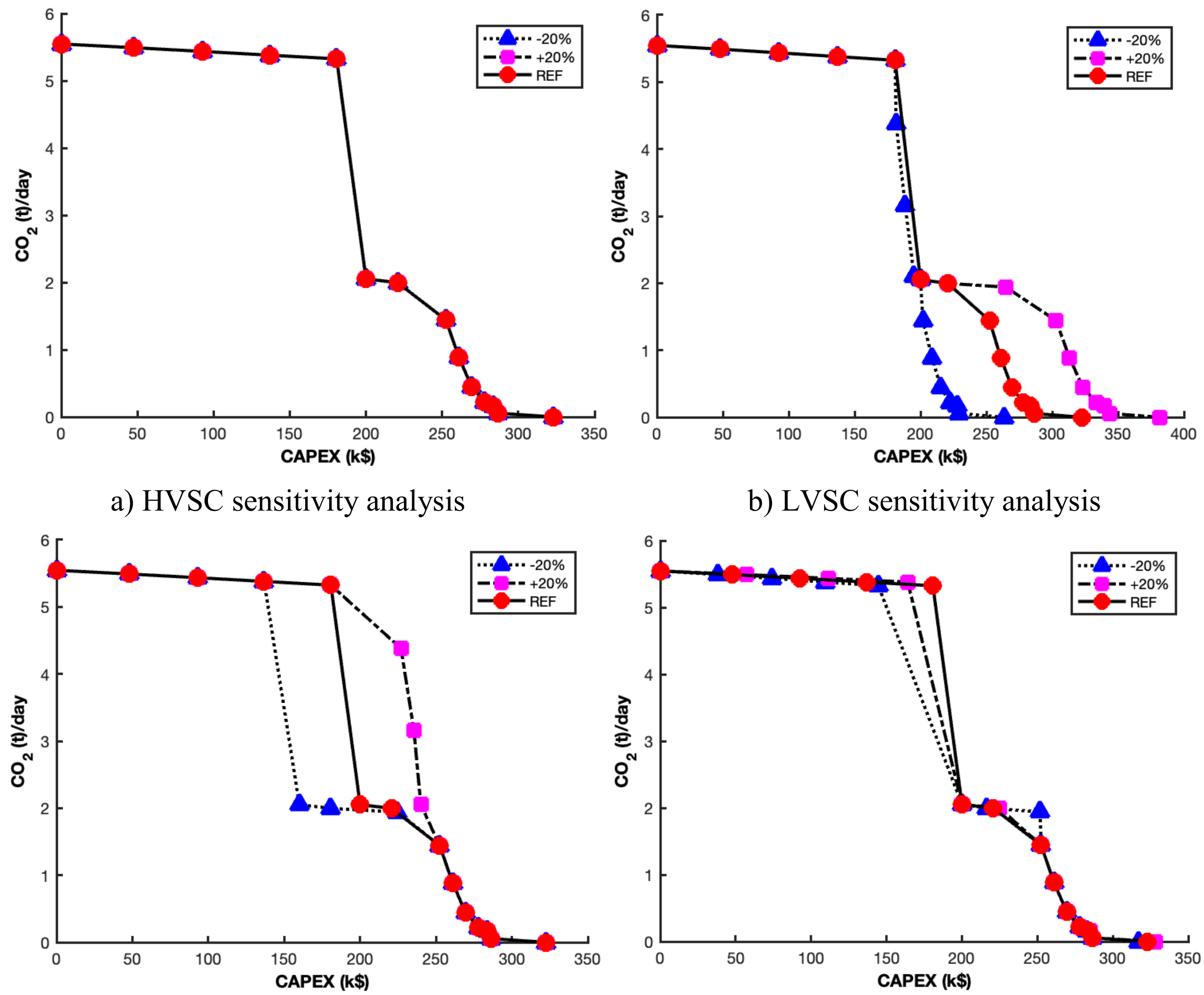
It must be noted that the value of 60 kWh for the battery is a good starting point for further investigations. Indeed, simulations and proper engineering analysis are required to confirm this value for real world industrial applications.

5.6 Technical-economic analysis

In the first subsection of the technical-economic analysis, we investigate the economic sensitivity of the model presented in Section 5.3. Then, the second subsection investigates the long-term economic viability of each solution from the Scenario A. This subsection ends with a further sensitivity analysis evaluating the variation of the economic performance indicators.

5.6.1 Sensitivity analysis of the model

To investigate the sensitivity of the model, a variation of ±20% is applied directly to the cost function of equations (5.8), (5.10), (5.13), (5.17) for the HVSC, LVSC, DDSC, and battery systems, respectively, for the Scenario A solutions. The impact of this cost variation for each system is individually presented in Figure 5.18.



a) HVSC sensitivity analysis

b) LVSC sensitivity analysis

c) DDSC sensitivity analysis

d) Battery sensitivity analysis

Figure 5.18: Sensitivity analysis on the Pareto front of Scenario A

Based on Figure 5.18 a), the sensitivity analysis shows that a variation of +20% or -20% on the cost of the HVSC did not affect much the shape of the Pareto front. Even if a variation of -20% was applied to the HVSC cost, it was not enough for it to appear as a solution on the Pareto front. However, the impact is significant for the LVSC and DDSC sensitivity tests. Indeed, a variation of -20% on the cost of the LVSC system was enough to equal the cost of the DDSC system for the same investment cost and design. The general observation is that a variation in the cost parameters of the shore power systems is proportionally related to the final cost of the system after design.

5.6.2 Long-term economic analysis

The technical-economic analysis evaluates the long-term viability of the different solutions of Scenario A by analyzing key financial indicators: the payback period, the ROI, the OPEX, and the cumulative savings ($Savings_{tot}$). The technical-economic analysis is based on the work of [136], which also presents a detailed technical-economic analysis.

Equation (5.30) presents the ROI:

$$ROI_p = \frac{Savings_{tot_p} - CAPEX_{ini_p}}{CAPEX_{ini_p}} \times 100\% \tag{5.30}$$

where p is the non-dominated solution identification from Scenario A with $p \in P = \{0,1,2 \ldots 12\}$ and $CAPEX_{ini_p}$ is the initial investment for solution p.

Equation (5.31) presents the OPEX. The daily OPEX is multiplied by the annual time in port set to 25% of the year, which is a typical time in port for Fednav bulk carriers.

$$OPEX_p = (FC_p \times Cost_{fuel} - EC_p \times Cost_{elec}) \times time\ in\ port \tag{5.31}$$

where FC is the fuel consumption [t/day], $Cost_{fuel}$ is the cost of fuel [$/tFuel], EC is the electric energy consumption [kWh/day], $Cost_{elec}$ is the cost of electricity [$/kWh] and $time\ in\ port$ is the number of days the ship is in port per year.

Equation (5.32) presents the total saving formula using the annual savings ($Saving_{annual_p}$). To ensure that the financial indicators are representative of the current value of money in time, all the calculations are based on the net present value (NPV) and a project lifespan N_{Ship} of 20 years. Other studies concerning maritime projects have used different interest rates: 8% in [146], 7% in [147], and 3.25% in [148]. In this study, the yearly interest rate i is set to 6%.

$$Savings_{tot_p} = \sum_{n=1}^{N_{Ship}} \frac{Saving_{annual_S}}{(1+i)^n} \tag{5.32}$$

where n is the year.

The annual savings of each solution are the current cost of the system minus the fuel cost and the electricity costs. To consider battery aging, the annual savings consider the replacement cost of the battery every 10 years [149]. Also, the average value of fuel consumption for each solution is used in this study not considering the uncertainty to simplify the calculation. Moreover, the cost of maintenance is not taken into account.

$$\begin{aligned} Savings_{annual} &= \left(FC_{actual} \times Cost_{fuel} - FC_p \times Cost_{fuel} - EC_p \times Cost_{fuel}\right) \\ &\times time\ in\ port \end{aligned} \tag{5.33}$$

where FC_{actual} is the current fuel consumption [tFuel/day].

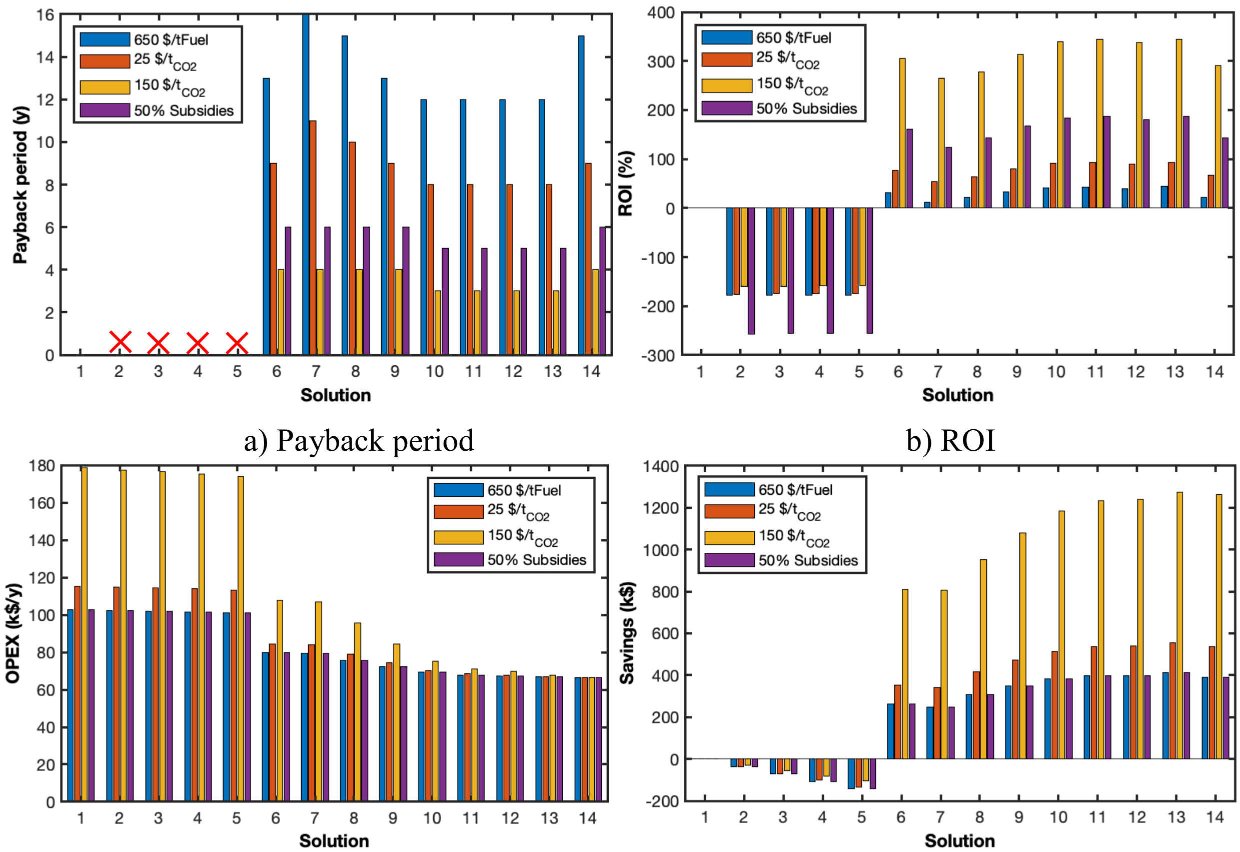
Finally, the payback period is determined at the year n from equation (5.32) that the cumulative savings equal the initial capital investment.

Since different environmental measures are discussed by the IMO or by local governments across the world regarding shipping decarbonization, the technical-economic study compares the reference Scenario A to the following cases:

- A carbon tax of 25$ per ton of CO_2
- A carbon tax of 150$ per ton of CO_2
- The investment cost or CAPEX is subsidized of 50%

Indeed, a carbon emission tax should benefit shore power projects because it will indirectly increase the cost of oil and make the electricity from shore more economic. The literature has shown that shore power projects need to be subsidized to be economic [13].

For our study, an average oil cost of 650 $/t of fuel provided by Fednav is used. This cost is based on an average of 2021 bunker prices for the oil cost in the St. Lawrence River. The cost of electricity considering the power cost and taxes is based on the Canadian average for June 2021 at 0.092$/kWh [150]. The results are presented in Figure 5.19.



a) Payback period

b) ROI

c) OPEX

d) Total savings after 20 years

Figure 5.19: Long-term economic analysis of the solutions

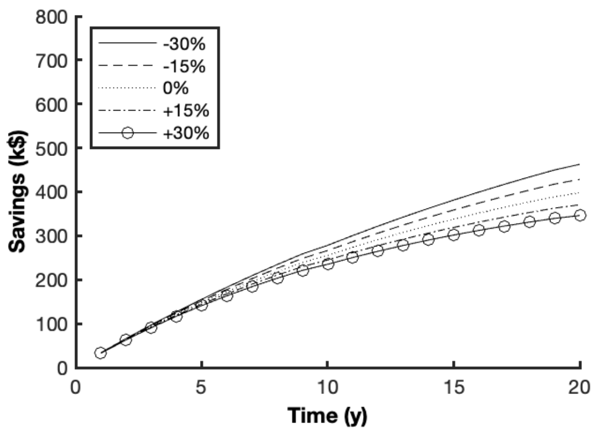
Firstly, the reference case with an oil cost of 650$/t of fuel is analyzed. Figure 5.19 a) shows that the payback period of the current solution is null (equal to zero). The payback period of not investing in a project in scene as instantaneous in this model. The ROI and total savings are also equal to zero for the same reason. The OPEX of the current solution is 103 k$. Solutions 2, 3, 4 and 5 were unable to repay the initial capital investment in 20 years as shown by the red "x" on Figure 5.19 a). Therefore, these solutions can be classified as uneconomical.

Solution 6 is the DDSC system combined with the DG. It has a payback period of 13 years, a ROI of 30.9%, an OPEX of 79.8 k$ and a total saving of 262 k$. Even if the OPEX of solution 7 is slightly smaller than the one of solution 6, its other performance indicators are less profitable. Solutions 8 to 13 use a combination of the LVSC system and the DG, with the exception of solution 12 which also uses a battery. The more the LVSC system can supply energy, the more the payback period, ROI, the OPEX and total savings improve. Solution 13 has a payback period of 12 years, a

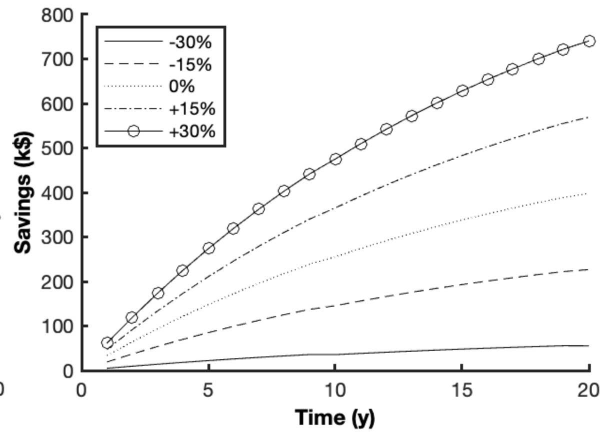
ROI of 43.6%, an OPEX of 66.8 k$ and total savings of 411 k$. Solution 14 using the LVSC system with a battery has a payback period of 15 years, a ROI of 27.9%, an OPEX of 66.4 k$ and total savings of 391 k$. This makes solution 13 the most advantageous solution after 20 years. Indeed, it presents the best trade-off in terms of CAPEX and OPEX because it can use mostly the electricity from shore, which is more affordable, but at the same time keeping a smaller CAPEX that improves its payback period.

Looking at the cases of the carbon taxes and governmental aid, the 150$/t$CO_2$ carbon tax is the measure that benefited shore power projects the most, thus making solutions using shore electricity with the DDSC or LVSC system being paid in 4 years or less. Comparing the 50% subsidy and the 25$/t$CO_2$ carbon tax, it is the subsidy that is more advantageous despite having smaller total savings. Indeed, the reduction of the investment cost enables to get return on investment more quickly and to improve the ROI ratio greatly.

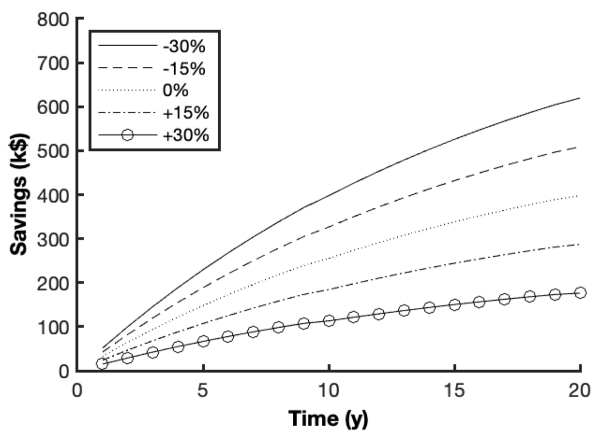
Lastly, the technical-economic analysis explores a second sensitivity analysis for the interest rate, fuel cost, electricity cost, and the time in port parameters. A variation of -30%, -15%, 0%, +15% and +30% is applied to each parameter and the resulting impact on the total savings is presented in Figure 5.20. The total savings graph presents the cumulative savings as a function of the year for 20 years. Also, the sensitivity analysis only investigates the solution 14 of the Pareto front, which combines the LVSC system with a battery.



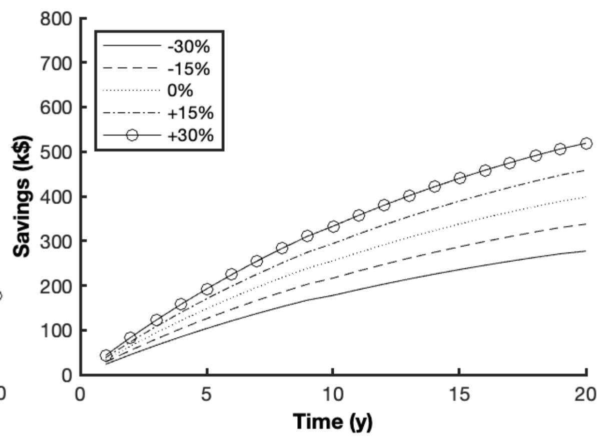
a) Interest rate



b) Fuel cost



c) Electricity cost



d) Time in port

Figure 5.20: Sensitivity analysis on the total savings

The outlook of the sensitivity analysis shows that the fuel cost and the electricity cost are the two parameters that influence the long-term economic viability the most. After 20 years, the -30% variation on fuel cost impacted the total savings by 342 k$, an 85% decrease. Nevertheless, a +30% variation improved the final total savings of 85%. The irregularities appearing on the cumulative savings graphs are caused by the replacement cost of the batteries every 10 years. Electricity cost showed variations of 55.6% in the final total savings for ±30% variation. In general, the rise of the fuel cost and time in port as well as the decrease in electricity cost and the interest rate improved the economic performance indicators because more benefits could be generated by the system.

In summary, the technical-economic analysis offers insights about the economic viability of the different solutions in the future. While the solutions using only the battery combined with the DG were not profitable, all the solutions using energy from the DDSC or LVSC systems obtained a return of investment after 12 to 16 years with ROI going up to 43.6%, OPEX of 79.8 k$ to 66.4 k$, and total savings after 20 years of 411 k$ in the best cases. When a carbon tax was applied to the analysis or a subsidy, the economic viability was much improved. For instance, solution 14 obtained a payback period of 6 years and a ROI of 142% when the project was subsidized in 50%. The OPEX and the final total savings were not impacted. This result is similar to other studies about shore power in the literature by the fact that a governmental help or a carbon tax is required to make shore power competitive [113], [116].

5.7 Conclusion

This paper presents a multi-objective approach methodology to size a shore power system aiming to reduce carbon dioxide emissions and capital expenditure. The model integrates multiple shore power connection methods, DGs and marine batteries to analyze the best system sizing for any load profile. The methodology proposed in this study is adaptable to a wide range of situations.

The analysis of three scenarios of the Federal Baltic bulk carrier led to the result that emissions can be totally reduced in port for ships using deck cranes with the addition of a LVSC system combined with a battery of 60 kWh. Based on the interpretation of the 2018 emission inventory report of the Quebec province in Canada [151], we find that a light car emitted on average of 3.1 tCO_2 per year. Therefore, an investment of 323 k$ would be equivalent to take ~650 cars off the road per day per ship in a city like Quebec or Montreal visited by the Federal Baltic. This solution has a payback period of 15 years and a ROI of 27.9%. However, it could get a payback in 6 years and a ROI of 142% if the investment cost is subsidized by 50%. Also, the LVSC system includes a cable reel system that accounts for roughly half of its total cost. Yet, this piece of equipment could be provided by the port further reducing the payback period for the ship owners.

Overall the three scenarios, the DDSC and LVSC sources seem to provide the most advantageous options for the Federal Baltic load profiles because they can reduce the emissions of the ship with a smaller CAPEX. The HVSC could supply any load but is very expensive and is only interesting if the ship is operated at maximum auxiliary power. This case is unlikely to happen in real operating profiles. However, in the case of large bulk carriers, large containerships, cruise ships or other large ships that require very high-power demands, LVSC, DDSC or battery will not be able to supply the entire ship load. In these situations, the HVSC system becomes the most economic option. Also, the study showed that marine batteries revealed to be very useful sources of power to supply the peak load demands. However, it is a poor source of energy since the marine battery overall capacity cost is too expensive compared to the HVSC and LVSC cost. Looking at IMO regulation, LVSC and DDSC systems have a very high potential of significantly reducing CO_2 emissions at low CAPEX. These systems are an interesting decarbonization measures and can pave the way for new hybrid ship designs in the short and medium term.

Further work is envisaged to include more energy sources into the system analysis like hydrogen or biofuels. Also, the mathematical model could be combined with an EMS to determine the real emissions, operational costs and return on investment time. This can be done using a rule-based EMS, but also with a lower layer that could optimize operational costs and emissions at the same time. Finally, the battery can improve the loading of the DG using an optimized EMS and thus lower CO_2 emissions further than the average presented in this paper for a low investment.

CHAPTER 6

6 SUMMARY

In conclusion, the impact of in-port emissions is important, but the path to decarbonization of the maritime industry is not clear. Indeed, a significant amount of CO_2 is emitted while ships are loading and unloading cargo or resting in ports which contributes significantly to climate changes. Also, large populations lie in direct contact with air pollutant gas coming from these ships impacting their quality of life and health. Finally, the IMO unprecedented environmental regulations are increasing the pressure on the maritime industry to diminish its carbon footprint. However, it is still not clear what will be the solution for the future since many possibilities seem to stand out as the best solution.

Throughout this work, we reinforced the importance of shore power as the next step toward maritime decarbonization and provided a clear methodology to design shore power systems for bulk carriers and other types of ships. The methodology tested on a dry bulk carrier sailing through the St. Lawrence River and Great Lakes has demonstrated that a low voltage connection combined with a marine battery was able to eliminate the emissions from the ship at berth while requiring the smallest initial capital investment for the shipowners.

The first step of this research was to evaluate the potential of shore power compared to other measures envisioned to decarbonize the shipping industry and to propose a clear road map to lower the maritime sector's emissions. The literature review has shown that most green technologies and measures are either not technologically mature enough or they present environmental concerns when implemented on a large scale. Furthermore, the SWOT analysis of shore power clearly highlights the great potential of shore power for: an emission reduction measure, its technological maturity, its standardization, and its beneficial impact on health. Also, the study of the impact of shore power on environmental indicators of the IMO has shown how interesting shore power can be for shipowners. The test case on the Federal Baltic achieved a reduction of 7.8% on CII.

Nonetheless, the literature review also underlined that the main concern for the wide adoption of shore power is the high CAPEX of shore power installations and a long payback period. To minimize this issue, a multi-objective method has been proposed to help shipowners to select and size shore power systems by presenting the best trade-offs between the CAPEX and CO_2 emissions on a Pareto front. The model has the advantage of uniting most of the available sources for shore power applications. Indeed, low voltage connections are not well covered in the literature, and this is one of the only works clearly detailing low voltage connections for ships shore power connections. Three load profiles were studied to test the model: a real typical load profile, a fictive high power load profile, and a real low power load profile. The Chebyshev metric enabled to find the non-dominated solutions for each load profile. The LVSC system combined with a 60 kWh marine battery stood out as the most economical solution that could eliminate emissions completely in port with a CAPEX of 323 k$ and a reduction of 5.5 ton CO_2 per day in port. Nonetheless, the CAPEX for shipowners could be reduced by nearly half if the cable management system was supplied by the port instead. The following technical-economic study estimated a payback period of 15 years that could be reduced to 6 years if the project was subsidized at 50%.

Since shore power has the potential to reduce CO_2 emission by the equivalent of 650 light cars per day per ship in port, there is no doubt about the relevance of this work for the energetic transition. While the carbon intensity of electricity generation can lower the overall efficiency of shore power, the electricity generated in the states and provinces along the St. Lawrence River and great Lakes maritime routes have a small carbon intensity factor. It is particularly the case with the electric network of Quebec which has a grid ~99% emission free thanks to hydropower. On top of that, the operational cost of shore power would be better than the current cost of electricity generation on ships since Quebec's cost of electricity is very small. Therefore, shore power is an emission-reduction measure that can be implemented by now along the St. Lawrence River and Great Lakes maritime route with a huge potential.

Future work needs to be done to ensure shore power takes off on the right foot on the St. Lawrence River and Great Lakes maritime route. A multi-criteria analysis of the electrification of ports and ships considering each ship sailing the maritime route, and which berth they call is required. The analysis should integrate a massive data collection using shipowners and ports data, and possibly automatic identification system (AIS) data combined to a wider study of CAPEX and OPEX. Also, the issue of berth availability and power availability in ports should be addressed by proposing a methodology for the optimal routing of ships. The energy management in ports considering the incertitude of ship's arrival may also complement this study.

CONCLUSION

En conclusion, l'impact des émissions dans les ports par la marine marchande est majeur, mais le chemin pour décarboner cette industrie n'est pas encore bien défini. En effet, une quantité importante de CO_2 est émise par les navires lorsqu'ils chargent et déchargent de la marchandise ou lorsqu'ils sont au repos au port ce qui aggrave les impacts des changements climatiques. De plus, de grandes populations sont en contact direct avec les émissions nocives provenant des navires au port, ce qui diminue leur qualité de vie et leur santé. Finalement, les nouvelles régulations internationales de l'OMI sont sans précédent et augmentent la pression sur l'industrie maritime pour qu'elle diminue son empreinte écologique. Cependant, il n'est pas encore établi quelle solution sera utilisée dans le futur pour décarboner l'industrie puisqu'aucune technologie ne semble se démarquer.

Cette recherche renforce l'importance de l'alimentation à quai comme la prochaine étape vers la décarbonation de l'industrie maritime et apporte une méthodologie claire pour sélectionner et dimensionner des systèmes d'alimentation à quai pour des vraquiers ou d'autres types de navires. La méthode est testée sur un vraquier sec navigant dans le Saint-Laurent et les Grands Lacs. Elle a montré qu'une connexion basse tension combinée à une batterie marine était capable d'éliminer les émissions du navire à quai tout en étant la solution qui demande le plus petit investissement pour éliminer les émissions.

La première étape de la recherche était d'évaluer le potentiel de l'alimentation à quai comparativement aux autres mesures disponibles pour décarboner l'industrie maritime et de proposer une route claire à suivre pour réduire les émissions du secteur. La revue de la littérature a montré que la plupart des technologies et mesures vertes ne sont pas assez matures ou bien comportent des enjeux environnementaux s'ils sont déployés à grande échelle. De plus, l'analyse FFOM de l'alimentation à quai souligne clairement le potentiel de l'alimentation à quai pour : sa capacité à diminuer les émissions, sa maturité technologique, sa standardisation et ses bénéfices sur la santé. De surcroit, l'étude de l'impact environnemental de l'alimentation à quai sur les indices environnementaux de l'OMI a montré à quel point cette mesure pouvait être intéressante pour les armateurs. L'étude de cas d'un vraquier sec a démontré qu'une réduction de l'IIC de 7,8% était envisageable si le navire utilisait l'alimentation à quai en tout temps au port.

Néanmoins, la revue de littérature souligne aussi que l'enjeu majeur pour l'adoption globale de l'alimentation à quai dans le monde est l'investissement initial élevé des projets et la longue période de retour sur l'investissement. Dans le but de minimiser ce problème, une approche multi objectif a été proposée dans ce travail pour aider les armateurs à sélectionner et à dimensionner un système d'alimentation à quai. Cette méthode présente aux décideurs les meilleurs compromis en termes d'investissement et d'émission de CO_2 sur un front de Pareto. Le modèle a l'avantage d'unir la majorité des sources d'alimentation à quai. En effet, les connexions basse tension ne sont pas bien couvertes dans la littérature et c'est un des seuls travaux qui détaille clairement les connexions en basse tension. Trois profils de demande énergétique sont étudiés pour tester le modèle : un profile réel typique, un profile fictif de haute demande de puissance et un profil réel de basse demande de puissance. La distance de Chebyshev a permis de trouver les solutions non dominées pour chaque profil de demande énergétique. La connexion basse tension combinée à une batterie marine de 60 kWh s'est démarquée comme étant la solution la plus économique pouvant éliminer les émissions au port avec un investissement initial de 323 k$ et une réduction de 5,5 tonnes de CO_2 par jour par navire. Néanmoins, l'investissement initial pour les armateurs peut être réduit de moitié si le système de gestion des câbles est installé sur le quai plutôt que sur le navire. L'analyse technico-économique montre que la période de retour sur l'investissement pour la solution original est de 15 ans, mais qu'elle pourrait être réduite à 6 ans si le projet était subventionné à 50%.

Puisque l'alimentation à quai a le potentiel de réduire les émissions de CO_2 par l'équivalent de minimum 650 voitures légères par jour par navire au port, il n'y a pas de doute sur la pertinence de ce projet pour la transition énergétique. Alors que l'intensité de carbone de la génération d'électricité peut diminuer l'efficacité de l'alimentation à quai, l'électricité produite dans les régions bordant les berges du Saint-Laurent et des Grands Lacs possède un facteur d'émission de carbone très petit. C'est particulièrement le cas pour le réseau électrique du Québec qui est à ~99% sans émissions grâce à l'hydro-électricité. En plus, le coût opérationnel de l'alimentation à quai serait plus bas que le coût de production d'électricité par les génératrices au diesel des navires puisque l'électricité du Québec est très abordable. Donc, l'alimentation à quai est une mesure de diminution des GES qui peut être implémentée dès maintenant sur la route commerciale du Saint-Laurent et des Grands Lacs qui a un immense potentiel.

Des travaux futurs devraient être entrepris pour s'assurer que l'alimentation à quai prenne bel et bien son envol sur la route commerciale du Saint-Laurent et des Grands Lacs. Une analyse multicritère de l'électrification des ports et des navires considérant chaque navire navigant sur la route commerciale et chaque quai qui est visité est requise. L'analyse devrait intégrer une collecte de donnée massive utilisant des données des armateurs et de système d'identification automatique (SIA) combiné à une étude plus détaillée des capitaux initiaux et coûts opérationnels. Aussi, l'enjeu de la disponibilité des quais électrifiés et de la disponibilité de la puissance au port devrait être adressé en proposant une méthodologie pour optimiser les déplacements des navires. L'étude de la gestion de l'énergie dans les ports considérant l'arrivée incertaine de navire dans les ports pourrait aussi complémenter cette étude.

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