Feasibility study of cold ironing from renewable sources in the Nordic region: case study: Port of Kapellskär in Stockholm

Aymen Abdaoui

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FEASIBILITY STUDY OF COLD IRONING FROM RENEWABLE SOURCES IN THE NORDIC REGION

Case Study: Port of Kapellskär in Stockholm

By

AYMEN ABDAOUI
Tunisia

A dissertation submitted to the World Maritime University in partial fulfilment of the requirements for the reward of the degree of

MASTER OF SCIENCE
in
MARITIME AFFAIRS
(MARITIME ENERGY MANAGEMENT)

2021
Declaration

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

(Signature): ....................................................

(Date): ............................................................

Supervised by: Dr. Fabio Ballini (Ph.D.)

Supervisor’s affiliation:

Maritime Energy Management Specialization

WORLD MARITIME UNIVERSITY
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Abstract

Title of Dissertation: Feasibility study of Cold Ironing from Renewable sources in the Nordic region: Port of Kapellskär in Stockholm as a Case Study.

Degree: Master of Science

Despite the fact that ships are one of the most efficient modes of transportation and play an important role in global trade, their emissions in ports are becoming increasingly problematic, particularly for NOx, SOx, and PM rather than CO2. While the amount of CO2 released by ships in ports accounts for a relatively tiny percentage of worldwide shipping CO2, the shipping industry is one of the biggest sources of air pollution in coastal regions, posing severe health and environmental risks. This study focuses on the feasibility of provision of Cold Ironing technology to address vessel emissions in the Port of Kapellskär, one of Stockholm’s Ports in Sweden.

The procedure of connecting ships to shore-side power rather than operating their Auxiliary Engines when at berths is known as Cold Ironing or Onshore Power Supply. This method is considered one of the effective processes not only to mitigate GHG emissions and air pollutants in the short-term, but also to get rid of vibrations and noise pollution at ports. Despite the fact that this technology has been accessible in several Nordic ports for over a decade, the uptake is delayed due to a number of issues.

After introducing this emerging concept and the legal framework of embracing and implementing Cold Ironing in the Nordic region and Sweden particularly, this paper presents a SWOT analysis based on interviews with Port Experts showing that the advantages and potential of implementing Cold Ironing at Stockholm Ports clearly exceed the issues and risks. However, supplying vessels with electricity from National Grids is considered as shifting the emissions from Ships at Port to another nearby area and the research to investigate this issue are few.

Therefore, this study comes to overcome this gap in the literature by developing and accessing a hybrid model that consists of supplying ships with shore side electricity from renewable sources rather than National grid. In order to show the concept in a realistic situation, 3 models have been investigated within the port of Kapellskär in Stockholm using HOMER and Crystal ball software. Next, a cost-effective analysis using real data and assumptions as well has been conducted taking in consideration 2 scenarios, whether 60% or 100% of ships calling the port are able to connect to OPS facilities.

Results of the simulations showed that the annual energy requirements of ships while at berths can be covered by installing three 660 kW Wind turbines representing the cost-effective solution taking the cost of emissions saving in consideration. With this configuration, the ships’ electricity demand exceeds the renewable energy production between June and September, thus, a costly battery storage system is not effective to off-set the variation in wind energy. In this way, significant emission reductions occur through a viable renewable energy solution ensuring a cleaner and healthier environment.

KEY WORDS: Cold Ironing, Port of Kapellskär, Onshore Power Supply, emission reductions, National Grid, hybrid model, renewable energy, Wind turbines, Feasibility, Stockholm, battery storage system, Simulation, cost-effective, viable solution.
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<th>Definition</th>
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<tbody>
<tr>
<td>IMO</td>
<td>International Maritime Organization</td>
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<tr>
<td>WMU</td>
<td>World Maritime University</td>
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<tr>
<td>MARPOL</td>
<td>International Convention for the Prevention of Pollution from Ships</td>
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<tr>
<td>GHG</td>
<td>Green House Gases</td>
</tr>
<tr>
<td>CO2</td>
<td>Carbon Dioxide</td>
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<td>PM</td>
<td>Particulate Matters</td>
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<td>NOx</td>
<td>Nitrogen Oxides</td>
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<tr>
<td>SOx</td>
<td>Sulphur Oxides</td>
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<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
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<tr>
<td>SEEMP</td>
<td>Ship Energy Efficiency Management Plan</td>
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<tr>
<td>EEDI</td>
<td>Energy Efficiency Design Index</td>
</tr>
<tr>
<td>MEPC</td>
<td>Marine Environment Protection Committee</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>ECA</td>
<td>Emission Control Area</td>
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<tr>
<td>ISO</td>
<td>International Standards Organization</td>
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<tr>
<td>ME</td>
<td>Main Engine</td>
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<tr>
<td>AE</td>
<td>Auxiliary Engine</td>
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<tr>
<td>MGO</td>
<td>Marine Gas Oil</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
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<tr>
<td>AC</td>
<td>Alternative Current</td>
</tr>
<tr>
<td>CAPEX</td>
<td>Capital Expenditures</td>
</tr>
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<td>OPEX</td>
<td>Operational Expenditures</td>
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<tr>
<td>LCOE</td>
<td>Levelized Cost of Energy</td>
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<tr>
<td>kW</td>
<td>kilowatt</td>
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<tr>
<td>kWh</td>
<td>kilowatt hour</td>
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<tr>
<td>MW</td>
<td>Mega Watt</td>
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<tr>
<td>MWh</td>
<td>Megawatt hour</td>
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<tr>
<td>GW</td>
<td>Giga Watt</td>
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<tr>
<td>HOMER</td>
<td>Hybrid Optimization of Multiple Energy Resources</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<td>LCOE</td>
<td>Levelized Cost of Energy</td>
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<tr>
<td>NPC</td>
<td>Net Present Cost</td>
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<td>NPV</td>
<td>Net Present Value</td>
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<tr>
<td>IRR</td>
<td>Internal Rate of Return</td>
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<tr>
<td>PP</td>
<td>Payback Period</td>
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<tr>
<td>O&amp;M</td>
<td>Operations and Maintenance</td>
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<tr>
<td>RES</td>
<td>Renewable Energy System</td>
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<td>AMP</td>
<td>Alternative Maritime Power</td>
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<td>OPS</td>
<td>Onshore Power Supply</td>
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<td>CI</td>
<td>Cold Ironing</td>
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<td>EUR</td>
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Chapter I: Introduction

1.1. Background

One of the most controversial issues facing today’s world is global warming and there is a crying need to find urgent solutions to mitigate this issue by reducing the GHG emissions and air pollution more than anytime to ensure the planet sustainability in the future. Maritime industry which is observed as the backbone of the international trade, plays a crucial role in the facilitation of the global trade in the most cost-effective way and considered as the most energy-efficient mode of mass cargo transport, making an essential contribution to the international trade and being a key pillar of the development of a sustainable global economy (IMO, 2018). Although in term of emissions per ton-mile, maritime transport is seemingly one of the cleanest mode of transport, but meanwhile, international shipping securing more than 90% of the cargoes transported (Eibner, 2010), is not only considered as a major contributor for the global GHG emission with around 3% (Gu et al., 2019) which is equivalent to the total annual emissions of Germany, but a forecast of 50% to 250% increase is estimated due to the growth of the shipping sector by 2050 (Smith et al., 2014). Therefore, urgent measures had to be implemented to overcome the future challenges to decarbonize the shipping sector knowing that greenhouse gas emissions have to drop by 50% to 85% by 2050 compared with the current levels (Reay et al., 2007) in order to comply with the Paris agreement target. This international agreement, adopted in December 2015, aims to limit global warming by achieving a temperature stabilization within 2°C above pre-industrial levels and aim to limit it below 1.5°C in 2050 (Zhong et al., 2010). Although its massive contribution in the global trade, shipping sector has not been included in any international climate agreement. Yet, the International Maritime Organization IMO, as the United Nations’ body responsible for regulating maritime industry emissions, is expected to lead this process. After years of internal negotiations on how to develop a roadmap to the shipping sector in order to align with the goals of the Paris Agreement, the IMO has finally drafted a challenging
strategy in 2018 for the mitigation of GHG emissions by 50% by 2050 compared to 2008 and aiming for the decarbonization of the international shipping sector in the long-term (Serra & Fancello, 2020).

In addition, and as a special agency of the United Nations, the IMO by developing this roadmap is aiming to contribute in achieving the U.N Sustainable Development Goals by 2030 especially the goal number 7 “affordable and clean energy” by becoming more energy-efficient as well as shifting to new technologies and clean energy sources and number 13 “climate change” by improving regulations and incentives to tackle GHG and air pollutants emissions (R. B. Johnston, 2016).

According to (Bichou & Gray, 2005), ports which are defined as an important economic asset for the region they are located, can range from only a small quay for berthing a ship to a massive scale center with terminals and a cluster of industries and a variety of services. The main role that ports play differentiate from country to other based on geographical, political and economic perspectives. For instance, in Singapore, ports are considered as a vital trading hub concept for the country, while in the USA, ports represent one of the five pillars of the maritime transportation system (MTS). However, in Japan, ports consist of industrial development zones, trading centers and energy supply areas. Despite the fact that ports which are a complex and dynamic entities generate an important socio-economic development and benefits, almost all their activities are a major contributor for greenhouse gas emissions and air pollution which are negatively affecting the environmental and ecological systems in addition to the social life of local communities (Azarkamand et al., 2020). Furthermore, the on-going worldwide development trends resulting from the growth of the global trade and the significant increase of the ship size as well as the need to modernize the infrastructure and the port facilities are imposing the need for new investments in ports. Although those infrastructure development opportunities are beneficial from the economic perspective, but no one can deny the negative externalities largely affecting the social and environmental systems (Schipper et al., 2017).

(Vallega, 2001) highlights the important role that ports are playing in the global industry and states that 14 from the 20 most economically leading and most competitive cities in the world are port cities in addition to the fact that those coastal cities are highly populated and generally their population exceeds million people. However, Ports and terminals playing an essential role in the global supply chain industry, are significantly contributing to air pollution and a large amount of this pollution resulted essentially from ship emissions at berth (Chen,
Zheng, et al., 2019) which constitute a major problem in relation to impacts on human health. It is estimated in this context that 12% of the total health effects in Europe are due to air pollution from shipping traffic (Brandt et al., 2013) especially SOx, NOx and PM giving rise to a wide range of effects on human health and well-being namely increasing the frequency of bronchitis, respiratory distress, lung cancer and asthma (Merk, 2014). According to a study carried out by (Corbett et al., 2007), shipping-related Particulates Matter emissions from ship activities contribute approximately to 60,000 deaths annually at a global scale and this huge impact is mostly concentrated in coastal regions on major trade routes. Although it can be argued that the geospatial distribution of GHG emissions from shipping activities is not of high interest due to the global effect of consequent climate change, no one can deny the regional and local effects of SOx, NOx and Particulate matters emitted from ships at berth, near coastal areas or even when they are emitted in the atmosphere at ten of miles away from cities and ports. Besides, it is estimated by the European Commission that emissions from ships can reach the amount of land based emissions in the European Union in the common years if no preventive actions were urgently taken (European Union, 2013).

The significance of air pollution from ships at berth is widely recognized and studies have shown that Northern Europe and Nordic countries are among the highly affected regions by emissions resulting from shipping activities occurring close to coastal areas (Dalsøren et al., 2009). Therefore, an increasing focus on harmful effects from ship emissions specifically in the Nordic countries gained more interest and a growing public attention to these effects has led to a rise in political awareness about air pollution from ship-port interface (Tourism, 2020). Hence, it is essential to control and limit air pollution and GHG emissions from shipping activities with resort to abatement technologies available.

Numerous measures had been introduced recently to reduce GHG emissions and air pollution from ships at port. Liquefied Natural Gas LNG used as a fuel for ships represent one of the most attractive alternatives to tackle this issue. Large part of vessel sailing within North and Baltic sea had resort to use LNG as fuel in order to comply with the specific international maritime regulation especially NOx and SOx limit knowing that the combustion of LNG result in low amount of NOx compared to HFO and MDO as well as almost no SOx and PM emissions. Besides, various exhaust gas purification system has been largely installed onboard ships in addition to the use of LNG namely the use of scrubbers to limit the amount of Sulfur from exhaust gas to obey Regulation 14 of the Annex VI of MARPOL as well as the
installation of selective catalytic reduction SCR to reduce the NOx emissions from ships aiming to comply with Tier III regulation of the international Maritime Organization IMO.

While main engines are switched off once at berth, ships still emit high amounts of air pollutants by keeping Auxiliary engines running to provide electricity needed to ensure vessel activities at ports such as heating, lightning, air conditioning, cooling, running of the galley as well as cargo loading and unloading procedure. Therefore, in order to limit the negative externalities from ships at berth such as noise, vibration, air pollution and in order to provide ships with electricity while Auxiliary engines are turned-off, one emerging technology could be the installation of shore-side electricity supply arrangement at berth, also known as ‘Cold-ironing’. This expression is a shipping industry term that started to be used when ships were equipped with coal fired engines in the past. Once the ship was tied up at port, there was no need to carry on feeding the fire, hence, the iron engines would eventually cool down. By consequence, the term "cold ironing" derives from this old engine phenomenon and continued to be used until those days (Arduino et al., 2011). Additionally, “Cold Ironing” technology is widely known by a variety of terms: “On-shore Power Supply technology”, "Alternative Maritime Power (AMP)", and "Shore side Electricity" according to (General et al., 2012). Cold Ironing is considered as an abatement technology used instead of diesel auxiliary engines and by supplying the electricity from national grid which is mostly characterized by lower emissions per MWh due to the source of energy used and the stringent regulations imposed on land power plants, this innovative solution lead to decrease air pollutants, noise and to some extent reduce GHG emissions from ships while at berth ensuring hence better air quality in ports and port cities (Report, 2005).

1.2. Aim of the Research

The international Maritime Organization IMO and E.U encourage ports development and incentives to facilitate the abatement of GHG emissions and air pollution including the implementation of new infrastructure supporting the transition to eco-friendly technologies at ports (International Maritime Organization, 2018). Besides, significant additional steps are definitely needed to force the pace of decarbonization and accelerate the energy transition to achieve the Paris climate targets and achieve the U.N sustainable development goals by 2030. In addition, the introduction of the NECA in the Baltic and North Sea in 2021 will certainly encourage the shipping stockholders to accelerate the investment in NOx abatement technologies and boost compliance with new IMO regulations.
In this whole context, this research is aiming to investigate and analyze the technical and economic feasibility of introducing onshore power supply in the Nordic Countries Ports aiming to boost the uptake of this technology to enhance port sustainability, reduce ship-port contribution in air pollution and decrease hence the negative externalities affecting human health and well-being. In addition, a review of the legal framework may help to emphasize the importance of this research in the international and national perspectives as well as the different policies developed by Nordic Ports.

Furthermore, this study aims to provide a business case model of onshore power supply installation in one of the Nordic Ports as well as the investigation into numerous possibilities of deployment of electricity from renewable sources and this system can be generalized afterwards to be widely utilized in other Ports.

Last and not least, a thorough investigation and analysis of the Technical, environmental and social aspects when implementing this abatement technology in one of the Swedish ports with the aim to provide a standard model of Onshore Power Supply installation to be used by the targeted stakeholders afterward in different Nordic and European Ports.

### 1.3. Problem statement

Cities close to ports suffer from a growing pollution from onboard power generation while ships are at berth. Although Cold Ironing represents an efficient way of decarbonization to make ports more environmentally friendly, this technology is facing a slow pace of implementation in the Nordic ports due to the uncertainty of investment and the lack of standard for installation. Therefore, a study of financial, technical and environmental aspects influencing OPS uptake in the Nordic ports is needed in order to break down the barriers and incentives of this technology.

Even though the Onshore Power Supply plays an important role to lower ship-port interface emissions, the fact that it is connected with the conventional grid is a downside for its holistic approach to tackle global warming and climate change. Since each port's power grid is mostly generated from non-renewable sources, the net contribution to save emission is somehow limited. Thus, one of the biggest challenges of installing Cold Ironing is the air pollution generated from the National grid. Although some studies have investigated the introduction of renewable sources of energy to supply ships through shore electricity such as (Kotrikla et al., 2017) and (F. Ballini & Bozzo, 2015), but it is worth mentioning that only few have considered case studies in order to give an insight of the practical challenges when designing
the systems (Innes & Monios, 2018). Therefore, this research aims to fill this literature gap and try to further investigate and analyze the possibility of supplying ships with electricity generated from renewable sources rather than the traditional power from the National grid. Moreover, the purpose of this paper is not limited to determine the emissions saving and the environmental benefits of establishing onshore power supply, but extend to touch upon the cost-effectiveness of the system in the context of Stockholm port.

1.4. Research outline
After presenting the international, national and local legislation concerning the air pollution and GHG emissions reduction within the ship-port interface, this study will emphasize one of the measures used so far consisting of the emerging concept of cold ironing which is discussed with its drivers and challenges. Next, a narrower approach will be conducted breaking down the concept of shore electricity fully powered by renewable energies sources within Ports using Wind Turbines and storage batteries. In order to explain the concept in a realistic situation, a simulation model of Stockholm Port in Sweden is presented including several scenarios and calculations. Last and not least, after interpreting the data collected and inputted in the model, the conclusions and recommendations are eventually outlined.

1.5. Research Questions
✓ How the International, National and Local regulations aim to mitigate the Ship-port interface emissions? (Literature Review)
✓ What are the main opportunities and challenges to ensure a rapid and effective uptake of this technology at Swedish ports? (SWOT Analysis)
✓ To what extent Cold ironing can be combined with Renewable sources and Energy storage? (HOMER Analysis)
✓ To what extent can Cold ironing reduce the air pollution and GHG emissions from Ports in Nordic countries? (Monte Carlo Simulation)
✓ What is the Cost-effectiveness of Onshore Power Supply in Stockholm Port taking the Emissions saving into consideration? (Crystal ball Analysis)

1.6. Scope and limitations
The main purpose of this study consists of providing a comprehensive vision of the state of the art of “Cold Ironing” and using electricity from renewable sources as well as the international and national regulations and incentives supporting its implementation on a broad front with particular attention to the on-going installations and projects in the Nordic
countries. However, the research is limited by the scarcity of data related to the economic aspects of the OPS investment although some Port reports and secondary sources are available. Thus, online interviews have been carried out in order to offset this literature gap. However, it is worth mentioning that due to the COVID-19 pandemic situation during the period of this research, the condition of getting required quantitative data from the port of Stockholm was not an easy task, hence, it was a limiting factor in the accuracy and efficacy of the study.

Besides, with regards to the geographical scope, a holistic overview of the Nordic Ports area will be carried out in order to investigate the role of different stakeholders involved in the development and implementation of the “Cold Ironing” system as well as a specific attention to the Swedish ports context.

1.7. **Dissertation Outline**

![Flow chart showing Overview of the Dissertation outline](Author)
Chapter II: Literature Review

2.1. Introduction
Global warming and climate change are two of the most pressing issues confronting humanity, and individuals from all walks of life must strive to save energy and decrease emissions. In recent decades, there has been a growing concern about the environmental impact of port activities and growth. Ports, as vital nodes in the worldwide shipping sector, play a key role in a country's economic, social, and environmental growth at the national, regional, and local levels. When compared to other sectors, however, port activities have a significant damaging impact on the environment, ranging from GHG emissions that cause climate change to water pollution from ballast water, fuel, and cargo residues that harm marine ecosystems around the ports. Respiratory illnesses, cardiovascular disease, lung cancer, and early death are among the health impacts of air pollution on the inhabitants of the local community surrounding ports (Chen, Huang, et al., 2019).

As a result, public, media, governmental, and non-governmental organizations are putting more pressure on ports, which are at the core of this debate on sustainable development. In this setting, environmental concerns are becoming an increasingly important part of the maritime sector.

2.2. International regulations
In the age of global warming and sustainable development, the contribution of ship-port interfaces to air quality degradation and greenhouse gas emissions has become a big issue to overcome. Ports and shipping activities are responsible for 3% of global GHG emissions, 6% of SOx emissions worldwide and 10 to 15% of global NOx emitted (Chen, Zheng, et al., 2019). Regulations and incentives were therefore the most effective drivers creating a “level playing field” to reduce air pollution, GHG emissions and improve energy efficiency in the maritime sector (International maritime organization, 2015). The International Maritime Organization IMO which is the United Nations specialized agency responsible for the
prevention of marine pollution by ships has adopted in this context several environmental regulations in order to control the greenhouse gas emissions as well as air pollutants from ships in coastal areas in order to force an environmentally friendly sector ensuring hence a sustainable shipping development.

In May 2005, Annex VI of the International Convention for the Prevention of Pollution from Ships MARPOL adopted by IMO came into force. In order to tackle the GHG emissions from ships, mandatory technical and operational energy efficiency measures (Table 1) had been introduced after a long debate and work in the Annex VI of MARPOL consisting essentially of an Energy Efficiency Design Index EEDI applicable to all new constructed ships after January 2013 with gross tonnage superior to 400 GT as well as the obligation of developing a Ship Energy Efficiency Management Plan SEEMP for the existing ships.

The EEDI is defined by IMO as an index that indicates the energy efficiency of a ship in terms of g CO2/ton-mile. This Latter is calculated for a specific reference ship and operational conditions. The IMO, by imposing limits on this Energy Efficiency index, aims to be able to drive ship technologies to more energy efficient ones in the next few years. Over time, efforts are made to tighten up gradually this technical index aiming hence to more energy efficient ships (Bazari, 2016).

On the other hand, in order to improve the energy efficiency of a ship during its operational life cycle, the IMO adopted the SEEMP as a management tool consisting of the planning, implementation, monitoring and reviewing of numerous energy efficiency measures to ensure a continuous improvement/management cycle (Bazari, 2016).
The International Maritime Organization (IMO) announced a strategy in 2018 aimed at decreasing greenhouse gas emissions from international shipping, with the goal of reducing emissions by at least 50% by 2050 compared to 2008 levels. The ultimate goal is to eliminate greenhouse gas emissions from the industry by the end of the century (IMO, 2018). Furthermore, the IMO strategy released in 2018 includes goals to enhance ship energy efficiency and reduce the shipping sector's carbon intensity by lowering CO2 emissions per unit of transport work done by at least 40% by 2030, and even more by 70% by 2050 (Fig 2).

<table>
<thead>
<tr>
<th>Type</th>
<th>Years</th>
<th>Measure</th>
<th>Target</th>
<th>Current status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-term</td>
<td>2018-2023</td>
<td>New Energy Efficiency Design Index (EEDI) phases</td>
<td>New vessels</td>
<td>-10% in 2015 -20% in 2020 -30% in 2025</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Operational efficiency measures (e.g. SEEMP, operational efficiency standard)</td>
<td>In-service vessels</td>
<td>SEEMP planning required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Existing fleet improvement program</td>
<td>In-service vessels</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Speed reduction</td>
<td>In-service vessels</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Measures to address methane and VOC emissions</td>
<td>Engines and fugitive emissions</td>
<td>—</td>
</tr>
<tr>
<td>Mid-term</td>
<td>2023-2030</td>
<td>Alternative low-carbon and zero-carbon fuels implementation program</td>
<td>Fuels/new and in-service vessels</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Further operational efficiency measures (e.g. SEEMP, operational efficiency standard)</td>
<td>In-service vessels</td>
<td>SEEMP planning required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Market-based Measures (MBMs)</td>
<td>In-service vessels/fuels</td>
<td>—</td>
</tr>
<tr>
<td>Long-term</td>
<td>2030+</td>
<td>Development and provision of zero-carbon or fossil-free fuels</td>
<td>Fuels/new and in-service vessels</td>
<td>—</td>
</tr>
</tbody>
</table>

*Table 1: Candidate measures adopted by IMO (IMO, 2018)*
Referring to the low quality of fossil fuel bunkered in ships, there is a range of air pollutants which are of more concern in relation to the shipping industry and of greater immediate concern than GHG emissions generated by the shipping industry. (Gilbert & Bows, 2012) emphasises that international efforts to reduce the environmental impact from shipping industry did not focus traditionally on GHG emissions and climate change, but on local air pollutants such as nitrogen oxides NOx, Sulphur oxides SOx and Particulate matters PM which obviously dominate the environmental and social risks when emitted in the atmosphere.

Therefore, IMO adopted stricter measures and regulations to establish the limits of SOx, NOx and PM emissions from ships (Serra & Fancello, 2020). Pollutants from Shipping industry have a huge impact not only on the economic and environmental side, but negative externalities have been proven to affect human health at the same time. Around 5% of lung and trachea cancers are attributable to particulate matters pollution (F. Ballini & Bozzo, 2015) and approximately 60,000 of cardiopulmonary deaths in the world each year are caused by the particle emissions from ships (Chen, Zheng, et al., 2019). Based on this fact, the international communities represented by the International Maritime Organization IMO had urgently adopted new regulations concerning the limits of air pollutants by ships.
When bunker fuel is burned in the engine, the remaining sulfur is converted into sulfur dioxide SOx, which is literally an acidic gas that is emitted into the air. This gas may cause irritation to the eyes, nose, and throat and, in some cases, can contribute to asthma and other breathing diseases. Another concern is that SOx can also react with other compounds in the atmosphere, forming volatile organic compounds (VOCs) which negatively affect human health. In terms of environmental externalities, SOx contributes fundamentally to acid rain which interferes with the growth of flora and fauna and with water life (Cullinane & Cullinane, 2018).

In this context, the limit of Sulphur emissions was fixed by the international maritime organization to 0.5% m/m from ships by 1 January 2020 rather than 3.5% m/m from 1 January 2012. (Corbett et al., 2007) claims that emissions from shipping traffic are contributing for a massive number of premature deaths globally essentially by emitting huge amount to the ambient levels of fine particulate matters PM$_{2.5}$ (particles with a diameter of less than 2.5 μm). According to (Karl et al., 2019), the worldwide use of cleaner marine fuel with 0.5% of Sulphur rate, will definitely decrease the ship-related premature mortality by 34% as well as morbidity by 54%.

To form acid rain, SOx may react also with other air pollutants such as the oxides of Nitrogen NOx that result from the combustion at high temperature of fossil fuel inside the engine. (Anenberg et al., 2017) point out that NOx is responsible for around 70,000 deaths per annum and this number may reach 174,000 in 2040 if no urgent actions are taken. In addition, (EEA, 2017) has estimated that within European countries, 78,000 premature deaths were directly linked to long-term exposure to NOx in 2014.

Therefore, and based on the fact that 15% of global NOx are emitted from shipping activities (Chen, Zheng, et al., 2019), and to further strengthen the control over air pollutants, the IMO has defined in Annex VI of MARPOL the limit of nitrogen oxides NOx emissions from ships and the amendment of 2008 has specified Tier I, Tier II and Tier III for ships to comply with, depending on the geographical areas where the ships are sailing as well as the characteristics of diesel engine fitted onboard with output power superior or equal to 130 Kw (Table 2).
Table 2: MARPOL Annex VI NOx emissions limits (Holmgren, 2020)

<table>
<thead>
<tr>
<th>Tier level, date and comprehensiveness</th>
<th>Effective from</th>
<th>Rpm&lt;130</th>
<th>Rpm 130-&lt;2000&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Rpm&gt;2000&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>I – includes vessels built between 2001 – 2010 and applies globally&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2005</td>
<td>17.0 g NO&lt;sub&gt;x&lt;/sub&gt;/kWh</td>
<td>45°&lt;sup&gt;n&lt;sub&gt;0.2&lt;/sub&gt;&lt;/sup&gt;</td>
<td>9.8 g NO&lt;sub&gt;x&lt;/sub&gt;/kWh</td>
</tr>
<tr>
<td>II – includes vessels built from 2011 and onwards and applies globally</td>
<td>2010</td>
<td>14.4 g NO&lt;sub&gt;x&lt;/sub&gt;/kWh</td>
<td>44°&lt;sup&gt;n&lt;sub&gt;0.23&lt;/sub&gt;&lt;/sup&gt;</td>
<td>7.7 g NO&lt;sub&gt;x&lt;/sub&gt;/kWh</td>
</tr>
<tr>
<td>III – includes vessels built from 2016 and onwards, in the North American and US Caribbean NECA – while it applies for vessels built from 2021 in the North Sea and Baltic Sea NECA areas</td>
<td>2016/2021&lt;sup&gt;c&lt;/sup&gt;</td>
<td>3.4 g NO&lt;sub&gt;x&lt;/sub&gt;/kWh</td>
<td>9°&lt;sup&gt;n&lt;sub&gt;0.2&lt;/sub&gt;&lt;/sup&gt;</td>
<td>1.96 g NO&lt;sub&gt;x&lt;/sub&gt;/kWh</td>
</tr>
</tbody>
</table>

2.3. Emission Control Areas

The revised annex VI consists of articles not only on technological regulation but also on spatial regulation called an Emission Control Area (ECA). The IMO in 2008 defines the Emission Control Area ECA as “an area where the adoption of special mandatory measures for emissions from ships is required to prevent, reduce and control air pollution from NOx or SOx and particulate matter or all three types of emissions and their attendant adverse impacts on human health and the environment”. A country or countries aiming to establish an ECA area in a nearby ocean intended to reduce shipping-related air pollution in coastal sea areas, can submit proposal documents to the MEPC which will study the proposal and deliberate afterward the merits of establishing an ECA in this proposed region. If the MEPC accepts the proposal, then the country or countries can establish an ECA in their ocean.

The ECA, according to Regulation 2 of MARPOL Annex VI, is an area where special mandatory measures for ship emissions are required to prevent, reduce, and control air pollution from NOx, SOx, particulate matter PM, or all three types of emissions, as well as their negative effects on public health and the environment. Emission Control Areas shall include those listed in, or designated under, regulations 13 and 14 of Annex VI (Pyć, 2018). For the Sulphur emission control areas (SECAs), a stricter SOx limit was adopted where the maximum Sulphur content allowed in marine fuel is reduced significantly from 1.0% m/m to 0.1% m/m (Table 3) since 1 January 2015 (Fan & Gu, 2020).
On the other hand, fuels with higher sulfur content may be used while must be combined with emission reduction technologies such as exhaust gas cleaning systems or scrubbers reducing sulfur emission to levels equivalent to the use of compliant low-sulfur fuels.

The health-related externalities from the shipping industry in the Baltic Sea and North Sea dropped significantly by 36% in 2020 compared to 2000 value according to (Brandt et al., 2013). This was mainly a consequence of the international efforts leading to the introduction of the Sulphur emission control area SECA for the Baltic Sea and North Sea enforced respectively in 2005 and 2006, which stepwise reduced sulfur content in ship fuels.

Particulate Matter PM emitted in the atmosphere resulting from incomplete combustion of fuel oil with Sulphur content, are composed mainly from a mixture of chemical species of both natural and anthropogenic origins. Studies has shown that the contribution of shipping traffic in the Baltic and North sea at 2014 has been remarkable in the coastal zones especially in Denmark, Sweden and Finland and other surrounding countries which has encouraged those countries to establish in compliance with the IMO new Sulphur limit by January 2015 (Eiof Jonson et al., 2019).

Ships' NOx emissions, on the other hand, contribute to oxidized nitrogen depositions, creating significant loads for critical phenomena such as marine acidification and eutrophication, as well as affecting particle formation and ozone levels. Because the lifespan of nitrogen dioxide NOx is so brief, the concentrations generally follow the locations of the major sources. NO2

Table 3: MARPOL Annex VI SOx emissions limits (Holmgren, 2020)
concentrations are high in central Europe and the English Channel, but significantly lower north and east of the Baltic Sea area. Ship emissions in term of Nitrogen Oxides NOx account for more than 50% in central parts of the Baltic sea and for a significant percentage reaching almost 15% of the total Nitrogen depositions in coastal zones in Denmark, Sweden, Finland and the other Baltic states namely Estonia, Latvia and Lithuania (Eiof Jonson et al., 2019).

Consequently, the North Sea and Baltic sea are not designated only as SECAs by the IMO. However, these two sea areas are also accepted as NECAs (NOx Emission Control Areas) from January 2021 (中島 et al., 2017). Although new ships operating in the Baltic and North Sea must comply with IMO Tier III standards beginning in 2021, NOx emissions in the NECAs are projected to decline gradually as these regulations only apply to new ships or when substantial adjustments were made to existing ships.

2.4. E.U Regulations

In addition to the international regulations adopted by IMO, the European committee has strengthened his effort to create a toxic-free environment through more directives and regulations aiming to prevent harmful air pollutants to be generated and emitted as well as encouraging and promoting solutions through new alternatives and technologies to address this issue within the European countries.

The EU’s purpose through those initiatives is to prevent, monitor, report, and tackle pollution in order to not only contribute to achieving the U.N Sustainable Development Goals in 2030 but mainly to improve Europe’s citizens’ lives and the sustainability of the natural ecosystems. During the last decades, the EU committee has been working highly to tackle climate change and global warming by controlling not only emissions of harmful substances into the atmosphere, but also mitigating noise problems and promoting energy efficiency emphasizing hence the importance of energy conservation by integrating more environmental protection requirements (Alhogbi, 2017).

2.4.1. Air Quality Issue

According to the (European Environment Agency (EEA), 2020) report published in November 2020, notwithstanding the drop in most air pollutants emissions within the EU areas in recent years (Fig 3), air pollution continues to be a remarkable issue to overcome in order to minimize harmful effects on human health and the environment. Air pollution is contributing to more than 400 000 premature deaths every year in E.U and almost two-thirds of ecosystem areas are exposed to eutrophication.
Air quality has gained more attention as one of the highest priority on the environmental and political agenda of the European Union therefore, air pollution was often considered a principal target of the regulatory control. It goes without saying that transport is one of the main contributors to air pollution and within which the air emissions from the shipping industry represent an important amount in the EU. In addition, most air pollution from ships takes place at sea, emissions that take place in port areas and port-cities are the most noticeable part with almost 70% of the ship exhaust gas directly affecting the neighboring port’s area (F. Ballini & Bozzo, 2015). Therefore, a strategy to reduce air pollution generated by ship traffic was drafted and published by the EU Commission in 2002, along with a proposal of limiting the Sulphur content for the marine fuel oil burned in engines within ships at berth. The proposal (COM/2002/0595 final) has been adopted and published afterward as directive (2005/33/EC) with main purpose to promote the abatement of SOx emissions through the limitation of Sulphur content levels under 0,1% for ships berthing within EU ports.

The European Commission has made it obvious that adopting and enforcing air-related regulations such as the 2008/50/EC Directive on ambient air quality and cleaner air for Europe is considered as a top priority in their political agenda. Furthermore, the EU has
conducted a systematic evaluation of its air policies in order to reach improvement on air quality conditions and avoid undesirable health and negative environmental consequences through the adoption of urgent actions required to further tackle air emissions linked to the most problematic air pollutants such as Sulphur oxide, Nitrogen dioxide and particulate matters. Those strengthened actions came as a normal response to mitigate the effects of the rapid increase in shipping traffic and to boost the efforts for decarbonization in the maritime industry (Allen et al., 2012).

The effects of air emissions not only affect the environment and human health, but might harm the reputation of ports in relation to their nearby suburban areas and place a huge pressure on port development and sustainability plans. In reality, when it comes to economic growth strategies and port development programs, air quality is often at the center of political and societal discussion of the EU. As a result, European governments place a high emphasis on reducing air pollution emissions from port operations. However, the main challenge remaining to Port authorities is how to apply appropriate control mechanisms in order to manage and reduce port related air pollution.

2.4.2. Energy conservation issue

Another concern has been and still in the center of interest of the European Union is greenhouse gas emissions. The demand for energy in Europe is massive and is expected to increase over the years which lead to more and more GHG emissions that result in tremendous effects on our climate. Therefore, EU has adopted the EU’s Energy policy in 2010 that consists of a roadmap aiming for a large decarbonized society in the EU by 2050 leading to high energy security, lower energy prices and GHG emissions reduction which would consequently provide better air quality as well as favorable health conditions (Langsdorf, 2011). This policy and other related directives established by the European council such as the EU Renewable Energy Directive (2009/28/EC), containing a binding objective to ensure a reduction in EU greenhouse gas emissions of at least 20% below 1990 levels in 2020 as well as increasing by 20% the energy used in the European Union and generated from renewable sources such as wind energy, solar energy or solid biomass (Schöpe, 2008).

2.4.3. Noise issue

In addition to air pollution and GHG emissions, one of the most common criticisms in connection with shipping transportation is noise pollution, which is described as an unusual or irritating level of excessive sound in a specific location. Noise is not only disturbing, but it
also leads to health issues like stress, cardiovascular disease, and hearing loss. It may also cause problems with sleep and normal function.

Noise pollution is a big societal issue with significant implications for port activities. As far as noise comes from a variety of sources in ports, including direct port operations as well as ships traffic and auxiliary engines running at berth to supply power to ensure ship activities once moored, this issue has to contribute to a higher direct impact on people in surrounded areas more than any other kind of pollution.

Recent studies have been conducted and more information has been provided to underscore the health impacts of noise, such as a World Health Organization publication estimating that transport-related noise accounts for over 1 million healthy years of life lost each and every year in EU and other Western European countries (WHO, 2011).

By consequence, the EU committee has adopted and published the Environmental Noise Directive (2002/49/EC) as an important regional legislative requirement (Parliament et al., 2001) as well as the European guideline highlighting how dangerous the environmental noise represent (European Commission, 2016) in order to support the effort of Ports to avoid, prevent or reduce on a prioritized basis the negative effects due to the exposure to environmental noise from Shipping traffic and Port activities.

### 2.5. National Regulations in Sweden

The raising concern of the general society and the maritime community in particular about limiting shipping pollution to the atmosphere has resulted in the establishment and adoption of a number of actions, strategies, and incentives by a variety of players, ranging from intergovernmental organizations to regional and national public agencies and private associations, all aimed at achieving this objective (Christodoulou et al., 2019).

#### 2.5.1. The Swedish Climate Policy Framework

In order to contribute to the Paris Agreement requirement aiming to keep global average temperature increases well below 2 degrees Celsius and to pursue attempts to restrict temperature increases to 1.5 degrees Celsius, the Swedish parliament (Riksdag) voted in June 2017 with a broad parliamentary majority to adopt a climate policy framework with a climate plan for Sweden. This system represented since then the most significant climate reform in Swedish history pointing out clearly how the Paris Agreement can be implemented in Sweden. (Ministry of the Environment and Energy, 2018).
The Swedish long-term climate goal is to achieve net-zero greenhouse gas emissions by 2045, supplemented by negative emissions. This long-term strategy is supplemented by a number of short-term objectives. In this context, the Swedish Parliament adopted on 1 January 2018 the Swedish Climate Policy Council which has given the responsibility to ensure that the Government’s overall development of policies is in line with the climate targets adopted by the Parliament and the Government (Ministry of the environment & Government offices of Sweden, 2020).

In comparison to what would have been done without the action plan, the Climate Policy Council estimates that the action plan would decrease pollution by 1–1.5 million tons by 2023 which is approximately equivalent to 2–3% of Sweden's overall greenhouse gas emissions and may have a more significant long-term impact if the ambitions of the plan were to be fully realized in an effective manner (Bonde I, Kuylenstierna J, Bäckstrand K, Eckerberg K, Kåberger T, Löfgren Å, Rummukainen M, 2020).

The criteria for making the climate transition vary by industry, placing various demands on policies and instruments. In order to meet the EU's latest 2050 climate neutrality goal, the Climate Policy Council welcomes the government's emphasis on the emissions trading system as the key tool for reducing industrial emissions with more emphasis to reduce the overall number of carbon allowances. Furthermore, additional instruments will be needed to accelerate environmental development and establish the long-term measures to ensure that Sweden meets its 2045 national emissions goal. The roadmaps established under the Fossil Free Sweden initiative will play an important role in this regard, however, it must be more precisely connected to the government's other industrial-related initiatives and instruments (Bonde I, Kuylenstierna J, Bäckstrand K, Eckerberg K, Kåberger T, Löfgren Å, Rummukainen M, 2020).

2.5.2. The national air quality and pollution policy framework

The overarching national goal of environmental policy is to hand on a society to the next generation in which significant environmental issues have been addressed without causing further environmental and health problems outside of Sweden's borders (National Air Pollution Control Programme, 2019). This national policy aim is to allow Sweden to meet its commitments to reduce emissions of certain atmospheric pollutants to achieve its commitments under the Emissions Reduction Directive (Directive (EU) 2016/2284). Thus, Sweden's environmental quality regulations are designed to safeguard human health and protect the environment, as well as to comply with EU directives on air quality target and
limit values. As shown in the (Table 4) below, within this air quality policy, Sweden is aiming to reduce NOx emissions 66% by 2030 compared to 2005 and SOx, PM by 22% and 19% respectively by 2030 as well (National Air Pollution Control Programme, 2019).

<table>
<thead>
<tr>
<th>The national emission reduction commitments compared with 2005 base year (in %)</th>
<th>SO₂</th>
<th>NOₓ</th>
<th>NMVOCs</th>
<th>NH₃</th>
<th>PM2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020 to 2029</td>
<td>22</td>
<td>36</td>
<td>25</td>
<td>15</td>
<td>19</td>
</tr>
<tr>
<td>From 2030</td>
<td>22</td>
<td>66</td>
<td>36</td>
<td>17</td>
<td>19</td>
</tr>
</tbody>
</table>

*Table 4: Swedish air quality forecast by 2030 compared to 2005 (National Air Pollution Control Programme, 2019)*

### 2.5.3. Environmentally differentiated port dues

By incorporating environmentally differentiated port dues to facilitate a transition to a more environmentally efficient shipping industry through new technology and renewable fuels, ports, as essential parts of international transport chains, will profoundly contribute to environmental and climate objectives (Styhre et al., 2019).

However, the regulatory context of this measure is heavily influenced by the geographical spectrum. The advantage of coordinating environmental differentiation of port dues among Swedish ports, with other EU countries, or even in a larger global context, is that shipping companies are better rewarded for environmental improvements measures. On the other hand, environmentally differentiated port dues may be a good way for individual ports to pursue their environmental commitments, take social accountability, and improve their environmental reputation. In this context, Shipping’s environmental efficiency can be assessed in a variety of ways and a variety of indexes and reward programs are currently in place that give reduced port dues, but the criteria that are prioritized and priced differ (Styhre et al., 2019).

### 2.5.4. Clean Shipping Index

In 2007, Sweden launched the Clean Shipping Project to focus more attention on shipping’s environmental issues (Wuisan et al., 2012).

Clean Shipping Index represent an independent and labelling system for ships’ environmental efficiency, as well as a useful tool for differentiating port fairway fees. The CSI consists of a
method to identify environmentally friendly ships. In this context, Ship-owners have to present their fleet's environmental profile to a group of stakeholders including cargo owners, ports, forwarders, and maritime technology providers (Styhre et al., 2019) than if cargo owners choose high-ranking shipping companies based on the Clean Shipping Index on a regular basis, these shipping companies would gain a competitive advantage. This concept provides an opportunity for other shipping firms to invest in emissions reduction initiatives in order to increase their rating. Therefore, by establishing requirements that go beyond IMO rules, the CSI aims to raise the bar for policymakers and accelerate new regulatory processes (Wuisan et al., 2012).

The Clean Shipping Index tool is a questionnaire with 25 simple questions about ship environmental efficiency that all go beyond current rules and regulations and include existing ships of various types. For each vessel, shipping companies must complete a questionnaire (Clean Shipping Index, 2020). Points can be obtained in five different areas: (1) SOx and PM emissions, (2) NOx emissions, (3) CO2 emissions, (4) use of chemicals, (5) water and waste management (Fig 4).
As shown in Figure 5, each parameter is given a maximum of 30 points, and the final index score is calculated by multiplying the total average score by the percentage of registered ships in the total owned or operated fleet (Clean Shipping Index, 2020).
A clean vessel, according to the CSI, is described hence by the following environmental measures: Low-sulfur fuels, energy efficiency or CO2 mitigation measures, active bilge water cleaning equipment, the use of Onshore Power Supply while at berth, ballast water treatment, sewage treatment, and cooling water treatment installed onboard the ship. As a consequence, the Cleaning Shipping Index is a welcome move, as it establishes higher expectations in a shorter time span, gradually increases transparency, and creates more balanced burden-sharing in the sector. This not only makes it easier to comply, but it also calls for higher regulatory standards (Wuisan et al., 2012).

2.5.5. The Environmental Ship Index

The Environmental Ship Index (ESI), which was created in 2011 and first introduced by the International Association of Ports and Harbors (IAPH) in 2013, is a voluntary instrument that mainly provides a formula-based assessment of vessels' nitrogen oxide (NOx) and sulfur oxide (SOx) emissions. The measure also recognizes vessels that are fitted to use onshore power and that have improved their fuel consumption over time, lowering NOx, SOx and particulate matter (PM) emissions. Besides, the Environmental Ship Index (ESI) has also started evaluating performance in the field of CO2 emissions as of 1 July 2017 (Andersson et al., 2017). The ESI scheme assigns points based on NOx, SOx, PM, CO2 emissions, and whether or not the vessel will use Onshore Power Supply with a maximum ESI score of 100. Therefore, a ship that receives a high score in the ESI system must emit less NOx and SOx than is required by law. (Styhre et al., 2019).

Since the ESI depends on self-declaration and may not need any data to be validated or approved by external auditors, ship owners have to pay no fees for participation as well as no fees are owed for audits and inspections. Instead, the data is randomly reviewed for discrepancies and apparent errors. As a result, the Environmental Ship Index is by far the most widely used environmental charging program in the EU, with a rising number of ports and ship owners signing up. Since both ports and ship owners are more likely to select an index if it is recognized internationally, this is a strategic advantage that means adoption will continue to rise in the future (Cogea, 2017).

2.5.6. Onshore Power Supply Regulations

In addition to the above mentioned initiatives and measures, Swedish Ports has adopted a port rebate linked to Onshore Power Supply (OPS) as an action mechanism to have the most positive effect on port sustainability. This measure was considered as one of the greatest potential to minimize not just air pollutants like NOx, SOx, and PM, but also vibration and
noise pollution from ships at berth. Consequently, Swedish ports had to introduce rebates oriented to ships using onshore power supply while at berth ranging from 1 million SEK such as in the port of Stockholm to 40% of the port dues based on Gross Tonnage in other Swedish Ports (Styhre et al., 2019).

There is currently no International legislation on OPS adopted from IMO. In reality, aside from those that are strictly needed for ship design, operation and energy efficiency, the IMO has established limited regulations on port development and operation. As a consequence, there have been plans to amend MARPOL Annex VI to include certain additional technical criteria for ships in order to expand the use of OPS in the future. It is recommended according to (Efficient & Operation, 2016), for instance, that ships assess the environmental benefits as well as the cost-benefit of tackling pollution from ships at berth. It should be considered how the supplied electrical power is provided, as well as whether comparable environmental benefits may be accomplished by other, more cost-effective ways.

(MARIEMS Merenkulun Koulu tusohjelma, 2018) point out that Sweden has submitted to MEPC 55 in 2006 a proposed draft regulation where some recommendations had been suggested in order to scale up the use of OPS by ships at international level including:

- If no other local conditions require differently, ships that can report that their on-board power output emits less cumulative pollutants than the supplied shore-side electricity, should be exempted from the need to connect to shore-side electrical power.

- When the expected port stay at the actual berth is less than a couple of hours, no ship should be required to connect to OPS.

- During the port call, the port or terminal must have adequate electrical power to support all regular operations, including measured peak periods.

- The cost of connecting the ship to shore power at berth does not surpass the average comparable costs of port services in general.

The above suggestions appear to be aimed at protecting ship owners from excessive pressure from ports to use OPS without good and rational economic or environmental justifications.

Consequently, (Table 5) present a short summary of the different incentives adopted by the Swedish Ports until 2017 (Styhre et al., 2019).
<table>
<thead>
<tr>
<th>Port</th>
<th>Environmental Ship Index/Clean Shipping Index combination</th>
<th>Environmental Ship Index</th>
<th>NOx emission</th>
<th>LNG usage</th>
<th>Onshore Power Supply usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Falkenberg</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
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<tr>
<td>Gävle</td>
<td>X</td>
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<tr>
<td>Göteborg</td>
<td>X</td>
<td></td>
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<td>X</td>
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<tr>
<td>Hargshamn</td>
<td>X</td>
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<td>Helsingborg</td>
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<tr>
<td>Luleå</td>
<td>X</td>
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<tr>
<td>Målarhamnar</td>
<td>X</td>
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<tr>
<td>Norrköping</td>
<td>X</td>
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<tr>
<td>Piteå</td>
<td>X</td>
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<tr>
<td>Skellefteå</td>
<td>X</td>
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<tr>
<td>Stockholm5</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Sundsvall</td>
<td>X</td>
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<td>X</td>
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<tr>
<td>Södertälje</td>
<td>X</td>
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<tr>
<td>Sölvesborg</td>
<td>X</td>
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<tr>
<td>Uddevalla</td>
<td>X</td>
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<tr>
<td>Vänerhamn</td>
<td>X</td>
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<tr>
<td>Wallhamn</td>
<td>X</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Ystad</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Åhus</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 5: Incentives embraced by Swedish Ports (Styhre et al., 2019)*
Chapter III: Research Methodology

3.1. Background
The purpose of this chapter is to introduce the strategy used in terms of the research design, how the data is collected during the research and the approaches utilized afterward to analyze the data obtained. The design of the research represents a set of steps that aim to move from ‘here’ to ‘there’, where ‘here’ defines the research questions to answer and ‘there’ refers to the findings and conclusion after ensuring the collection and analysis of the Data required (Yin, 1994).

3.2. Research Strategy
The ‘quantitative research’ and ‘qualitative research’ are the two types of research strategy that had been applied based on the purpose of this study as well as the type and availability of the data required. In order to achieve the projected objectives and the aim of this research, the current study used the Triangulation method which is according to (Deacon et al., 1998) a multi-method research consisting of the combination of ‘qualitative research’ and ‘quantitative research’. The ‘qualitative research’ serves to provide a subjective assessment of the problem statement through different opinions and perceptions. However, the ‘quantitative research’ on the other hand is an objective measurement used usually to investigate and to establish relationships between facts and to draft conclusions and findings based on that evidence (Naoum, S. G., 2012). Therefore, this mixed-method is applied in order to provide a holistic approach through a quality comprehension and a thorough investigation and discussion of the feasibility to supply ships with onshore power from renewable sources while at berth (Table 5).
### Table 6: Qualitative and Quantitative method characteristics (Deacon et al., 1998)

<table>
<thead>
<tr>
<th></th>
<th>Qualitative</th>
<th>Quantitative</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Role</strong></td>
<td>Views and perceptions measurement based on opinions</td>
<td>Fact-finding based on evidence</td>
</tr>
<tr>
<td><strong>Relationship between theory and research</strong></td>
<td>Emergent/Development</td>
<td>Testing and confirmation</td>
</tr>
<tr>
<td><strong>Nature of Data</strong></td>
<td>Deep and Rich</td>
<td>Reliable data</td>
</tr>
</tbody>
</table>

#### 3.3. Research Design

In this section, the overall design of the research is breaking down from the choice of the research method applied and the selection of the data required for these methods, to the collection methods and the analysis techniques utilized to extract facts (Fig 6).

Primary and secondary data had been collected for the aim to conduct an exploratory approach and get an overview of ideas, opinions and experiences of experts in terms of the recognized problem statement of this research. The raw data provided will be classified afterward into the SWOT Analysis framework.

In addition, in order to find facts about the feasibility of Onshore power from renewable sources in the Nordic Ports, quantitative research is carried out through a case study approach where this hypothesis is grounded in a theoretical framework, measured with numbers and analyzed eventually with statistical models (Naoum, S. G., 2012).
Figure 6: Methodology Design applied in this research (Author)
3.4. Data Collection Methods

The acquisition of data depends essentially on the nature of investigation conducted as well as the availability of such required data. In this context, two different approaches of data collection had been adopted in this research, the fieldwork or primary data namely semi-structured interview and case study in addition to desk study or secondary data such as literature review of books, journal articles and reports from the other hand used eventually to conduct the qualitative and quantitative researches (Naoum, S. G., 2012).

3.4.1. Semi-structured Interview

The choice of interview method is based on the suitability of this latter approach to provide deep and detailed information of the topic through the interaction between the interviewer and the respondent (Oko, 1992) in addition to the possibility to benefit from unexpected revealed details that the interviewer might take advantage (Mann, 2016). This technique is used to collect information and opinions through a set of predetermined questions using an ‘open-ended’ questioning approach taking place with participants known to be involved with their experiences in this specific topic of the research around which the interview is built. In order to set up a good connection with the interviewee, indirect questions are asked in the beginning of the interview followed by the ones in relation with the specific issues of the subject investigated (Naoum, S. G., 2012).

In the current study, the interview with two experts from the port authority of Stockholm Port has been conducted online through a zoom application. Forty questions were planned taking in consideration the objectives and research questions of this research while trying to draft open questions to let the respondents elaborate their answer. The interview questions were categorized into four main categories: general, technical, environmental and economic questions. Moreover, the interview was divided in two main parts, the first aim to get a deep insight of the onshore power supply technology in the port of Stockholm, the barriers and incentives to scale up such technology as well as the opinion of the interviewee concerning the already installed facilities. The second part was essentially targeting the opinion of the experts concerning the introduction of renewable energy as a zero-emission and economic solution to supply electricity to ships while at berth. The obtained responses are afterward analyzed, compared and correlated with the information and data extracted from the literature review in order to build up a SWOT analysis of the application of Cold Ironing in Stockholm Port.
3.4.2. Secondary Data

Previous research had resulted in a large amount of data which had been collected, analyzed and archived, thus it is made easily accessible for further analysis and interpretation from different other perspectives. Therefore, for many researchers, the utilization of this existing data during a process of inquiry represents a viable method to overcome limited time and sources as well (M. P. Johnston, 2014). Generally, when it is somehow costly to collect primary data and a stringent budget is imposed, researchers resort to a desk study approach avoiding the constraint of time when collecting required data for new research topics (Naoum, S. G., 2012).

According to (Daas, 2012), information and data that are not based on personal first-hand experience or resulted from event participation are considered as secondary data and can be utilized for a purpose different from the one they were originally collected.

In this context, a desk study approach has been conducted in order to collect secondary data for the aim to achieve the objectives of this research. Both numerical and descriptive data from numerous sources namely books, journal articles and official reports were targeted to extract required data for the qualitative and quantitative research as well. Descriptive data has been applied as a comparative tool to assess and evaluate the primary data extracted from the interview to draft the SWOT analysis. On the other hand, the numerical data was a useful source to build assumptions while investigating the Cold Ironing technology in the context of Stockholm port as a case study.

3.4.3. Case Study investigation

According to (Khosravi et al., 2014), a useful definition provided by Yin in 2014 states that: “A case study is an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident”. Therefore, the Case study approach is utilized in this research in order to provide an in-depth analysis concerning the feasibility of supplying ships with Onshore electricity from renewable sources with a particular focus on the context of Stockholm Port.

3.4.4. Ethical considerations

General ethical codes are acknowledged by researchers once quantitative or qualitative approaches are applied. Referring to (E. Bell & Bryman, 2007), several ethical principles had to be taking in consideration by researchers such as:
• The need to ensure the full consent of the participants.
• The protection of the privacy and confidentiality of the research data.
• The protection of anonymity of the individuals participating in the research.
• The need to avoid misunderstanding or false reporting of the data and the findings.

In this context, this research which is conducted for academic purposes has always kept those ethical codes under consideration during the whole process of the study. The data collected, the audio-recording and transcripts are kept stored and protected in the laptop and hard disc with strong password and will be deleted from the laptop upon completion of the study.
Chapter IV: Feasibility study of cold ironing at Port of Kapellskär in Stockholm

4.1. Overview of the Port

Divided between Stockholm, Kapellskär and Nynäshamn, the Port of Stockholm is obviously one of the main ports in the Baltic Sea with a traffic volume hitting the records of 9.7 million tons of freight and 12 million passengers recorded in 2017 (Ports of Stockholm, 2017). But there are dark clouds too, the fact that the port is strategically located in the largest growing population areas in Sweden (Fig 7) represent a big concern for the port and the city as well due to this heavy shipping traffic undoubtedly linked to negative externality affecting the port’s surroundings. The port is owned by the municipality of Stockholm, hence, the port Authority and the city council have developed a common strategy to challenge the environmental effects of shipping industry within the port areas to ensure sustainable and efficient port-related activities within the sustainable 2030 agenda of Stockholm city (The City of Stockholm, 2016).
4.2. Onshore Power Supply in Stockholm Port

In addition to the environmental rebates to encourage customers to shift towards eco-friendly measures, the Port of Stockholm has highly prioritized supplying ships with shore electricity once at berth in order to mitigate not only the port environmental footprint, but also the vibration and noise pollution. It was back in 1980 when two of the Viking line ships Gabriella and Mariella were able to connect to the shore power facility (Ports of Stockholm, 2017). The vessels are connected with a Low-voltage system of 400V and 50Hz frequency through 9 cables capable of supplying 2.5 MW of power (Ericsson, 2008). Since 2019, four Tallink silja ships Silja Symphony, Silja Serenade, Baltic Queen and Victoria connecting Helsinki and Tallinn to Stockholm in regular traffic, were successfully able to shut-down their auxiliary engines and connect to shore electricity once they berth. Besides, two High-voltage OPS projects are underway in Port of Kapellskär and the central quay of the Port of Stockholm to allow ferries and cruise ships to connect to the shore electricity by 2024 (Ports of Stockholm, 2017).

The Port of Stockholm is working hand in hand with energy providers, ship owners and other neighbor ports for further expansion of the OPS facilities. From the financial aspect, the
collaboration with Stockholm Municipality had resulted more investments to build new OPS facilities. However, this was not enough to speed up the uptake of this technology. Therefore, the Port Authority has joined the EU coordinated supply of Onshore power in Baltic seaports projects and has successfully received an EU funding of 2.3 million € (Ports of Stockholm, 2017), in addition to a significant local financial support from the Swedish Environmental Protection Agency estimated to 2.7 million € to equip two central quays for cruise ships in Stockholm port with OPS installation which according to the expert of Stockholm Port in our interview is planned to be ready by 2024. On the other hand, in order to offer more vessels onshore power connection at the quayside, the Port of Stockholm is working from a plan of action including a grant of SEK 1 million offered to every ship that carries out retrofitting operations to be enabled to connect to onshore power supply. This applies for the quays where Ports of Stockholm offers onshore power supply (Ports of Stockholm, 2017).

**4.3. Strengths, Weaknesses, Opportunities and Threats analysis**

A SWOT (strengths, weaknesses, opportunities, and threats) analysis is a strategic management tool that establishes a connection between the internal and external aspects of a concept or product. The emphasis of a SWOT analysis is on both positive and negative sides (G. G. Bell & Rochford, 2016).

Business analysts frequently use this method at the start of a decision-making phase. The benefits of using a SWOT analysis are that it is simple, takes little time, and allows for the incorporation of several points of view. Besides, another reason is that the analysis considers both internal and external factors, establishing either a relation or gap between the product or the process and its environment (Helms & Nixon, 2010).

The method divides the variables into two categories: internal and external influences, as well as stimulating and hindering factors as shown in (Table 6).
While the advantages and downsides of Cold Ironing installation on Stockholm Port may be confusing to many stakeholders, the SWOT analysis was utilized in this study because it links internal and external elements and analyzes benefits and drawbacks. In this research, the SWOT analysis, which is a technique helping in developing a technology rather than executing it, is used to assess virtuous and vicious elements in addition to technical factors.

The goal of this section is to identify the favorable and negative internal elements of shore-side electrical technology, as well as external variables. This is done to see what kind of influence this technology may have. Internal variables include the OPS's strengths and limitations, such as technological components and pollution reduction. External factors are aspects of the OPS system that are influenced by it, such as port personnel safety and future job opportunities (Program & Energy, 2019).

To gain deep insight in the OPS technology using the SWOT analysis, a desk research of scientific articles, journals and reports was performed to prepare the ground for a semi-structured interview with experts which can provide help to overcome uncertain situations thanks to their extensive knowledge. Finally, a questionnaire is conducted with Stockholm Port Stakeholders to define the broader impacts of the technology.

<table>
<thead>
<tr>
<th>Virtues</th>
<th>Inhibitors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal</strong></td>
<td><strong>Strengths</strong></td>
</tr>
<tr>
<td><strong>External</strong></td>
<td><strong>Opportunities</strong></td>
</tr>
</tbody>
</table>

Table 7: SWOT Analysis Matrix (Program & Energy, 2019)
<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>➢ Reduction of local air pollutants from ships (NOx, SOx and PM).</td>
<td>➢ High investment cost for both Port Authority and Ship-Owners.</td>
</tr>
<tr>
<td>➢ Lower GHG emissions from Ships at Port.</td>
<td>➢ Long pay-back period.</td>
</tr>
<tr>
<td>➢ Reduction of Vibration and Noise pollution.</td>
<td>➢ Different frequencies (50/60Hz) for ships calling the Port (need for Frequency converters which are costly).</td>
</tr>
<tr>
<td>➢ Compliance with existing and future regulations.</td>
<td>➢ Technology available only on a few Ports.</td>
</tr>
<tr>
<td>➢ Maturity of the OPS technology.</td>
<td></td>
</tr>
<tr>
<td>➢ International Standards for OPS installation are available (ISO80005-1:2019 HVSC and ISO 80005-3 LVSC).</td>
<td></td>
</tr>
<tr>
<td>➢ Larger Auxiliary engines maintenance frequency.</td>
<td></td>
</tr>
<tr>
<td>➢ Lower infrastructure cost compared with other solutions (e.g. LNG).</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>➢ EU and government subsidies and incentives to Port.</td>
<td>➢ Local Power Supply and Extra Loads</td>
</tr>
<tr>
<td>➢ Incentives to Ships complying with OPS technology.</td>
<td>➢ No International regulations adopted for OPS installation.</td>
</tr>
<tr>
<td>➢ Collaborations with Ship-Owners &amp; Other Ports</td>
<td>➢ Competence with other alternatives (LNG, Low-Sulphur Fuel…).</td>
</tr>
<tr>
<td>➢ Increasing Customers Demand to OPS facilities</td>
<td>➢ Lack of available space at Port.</td>
</tr>
<tr>
<td>➢ Tax reduction for electricity price</td>
<td>➢ Safety issues due to High voltage handling.</td>
</tr>
<tr>
<td>➢ New Job opportunities</td>
<td>➢ Specific training requirements for Ships crew and port employees.</td>
</tr>
</tbody>
</table>
4.3.1. **Strengths**

4.3.1.1. **Reduction of local air pollution from ships**

All pollution and noise from berthed ships in the port may be minimized by using a shore connection instead of auxiliary engines. Of course, to measure total emissions reductions, the entire electricity production supply chain must be taken in consideration, including grid emissions factors. According to an Entec report in 2005, power plants have a far higher performance than ship power Auxiliary Engines in terms of pollution. As OPS is used instead of bunker fuel, NOx, SOx, and PM are reduced by around 90% on average even if a fossil fuel power plant provided the shore connection to vessels (Entec, 2005).

Indeed, according to (Arduinno et al., 2011), the OPS system allows for the reduction of more than 30% of CO₂ emissions and more than 95% of NOx and particulate matter emissions thanks to its higher performance and pollution limiting capabilities. It has been shown that a cruise ship’s emissions fell from 72.2 to 50.1 tons of CO₂, from 1.47 to 0.04 tons of nitrogen oxide, and from 1.23 to 0.04 tons of Sulphur oxide during 10 hours at berth.

Additionally, power plant emissions such as air pollution, noise, and vibrations are more likely to be released in less densely inhabited regions rather at ports, resulting in reduced external costs. Low-sulfur gasoline, on the other hand, reduces SOx emissions from ships while having no effect on NOx or CO2.

4.3.1.2. **Lower GHG Emissions from Ships at Port**

In order to achieve the maximum reduction of emissions from ships while at berth, the Port of Stockholm, one of the forefront implementing clean technologies to meet the expectations of the city of Stockholm to become fossil fuel free city by 2040. In this context, and in order to contribute to this target as a public port owned by the city, and knowing that the use of OPS rather than Auxiliary engine reduce CO₂ emission by 50% in average (Entec, 2005), the Authority of Stockholm Port get the support from the city to widen the use of OPS facilities aiming to reach the first milestone aiming to decrease by 25% the GHG emissions compared to 2019 which is approximately 8,000 ton of CO₂ reduction in 4 years declared the environmental expert of Stockholm Port: “We need to decrease the CO₂ emissions from shipping activities by 8000 tons during this 4 years’ period”. Once this mission is accomplished, 50% less CO₂ emissions is the next goal to reach by 2030 than aiming to be zero carbon emissions Port by 2040 as the port expert explained in the interview: “We have a target of 25% decrease in CO₂ emissions by 2025 then we plan for 50% decrease by 2030 and
aim for zero emission by 2040” (Charlotta Solerud: Stockholm Port Environmental Strategist, interview 2021-07-01).

### 4.3.1.3. Reduction of Noise and Vibration from Ships at Port

An additional benefit of supplying vessels with shore electricity at berth and switching off the Auxiliary engines, is obviously the elimination of mechanical and exhaust Noise generated together with mechanical vibration resulting from diesel combustion cycle (Entec, 2005). Therefore, for the personnel working in close proximity to the Auxiliary engines or involved in loading/unloading operations, eliminating noise level ranging from 90 to 120 dB is one of the strength of using OPS at ports (Program & Energy, 2019). Although the Port and the city of Stockholm are getting closer and many building are in proximity to the Port areas referring to the expert of Stockholm port, the study conducted shows almost no difference in term of noise level when the ship is connected to OPS or not: “This noise study shows almost no difference in the noise levels when ship is connected and when it is not” (Svante Åberg Gassbo: Electrical Manager Stockholm Port, Interview 2021-07-01). However, the port Authority plan the effect when it comes to cruise ships connected to shore power once the installations are ready in place and compare the results.

### 4.3.1.4. International Standards for installation:

A big issue of scaling up Cold Ironing was the lack of international standards for the equipment, which consequently resulted in a jungle of different kinds of frequency, transformers, plugs and safety regulations.

IEC, ISO, and IEEE, three international standardization organizations, have collaborated to ensure that ships can connect to shore power in a consistent, quality-assured, secure, and efficient manner. As a result, shore grids specifications have been established that cover both high voltage standards (IEC/ IEEE DIS 80005-1) and low voltage shore connection schemes (IEC/ PAS 80005-3). Besides, (ISO_354, 2003) indicates that a protocol for data transmission for monitoring and control of high and low voltage shore connections has already been released by the standardization organizations under the standard (IEC/ IEEE DIS 80005-2). The High Voltage standard applies to applications requiring more than 1000KVA of power, while the Low Voltage standard applies to applications requiring less than or equal to 1000KVA of power (Bergen og Omland Havnevesen, 2018).

Therefore, Ships can now call at various ports without having to make changes to their installed systems thanks to the standardization of shore connection facilities. A standardized
system of connecting, in addition to the previously stated advantages of performance and safety, allows for greater use of the existing shore connection systems onboard ship and in port, potentially enhancing the overall economic case and return on investment.

The specifications provided by the international guidelines for the following High Voltage (INTERNATIONAL, 2019) and Low Voltage (Pas, 2008) shore connection installations in terms of design, operation, testing and equipment such as:

• Shore distribution systems
• Shore-to-ship connection and interface equipment
• Transformers
• Semi-conductor/rotating convertors
• Ship distribution systems
• Control, monitoring, interlocking and power management systems.

However, functional elements such as the location of the plug connection on the vessel side are not covered by the standard. Since ships do not have a regular communication point, mobile facilities in ports are needed. The cost of establishing and operating a mobile facility is higher than that of a fixed facility, raising the OPS investment costs (Bergen og Omland Havnevesen, 2018).

4.3.1.5. Larger Auxiliary engines maintenance frequency

The ship operator's public image is from big importance nowadays not only within the shipping industry but for the customers as well that become as much as a fundamental criterion for the selection of the ship for the charterer for instance to benefit from lower fees and environmental incentives and for the cruise ships as well as the competence is within its high level and influenced by details related to the wellbeing of the people and environment surrounding the Port areas. Thus, by retrofitting their fleet with installation to connect to OPS, ship-owners not only seek public satisfaction as the expert of Stockholm port mention about cruise ship-owners: “The awareness among the cruise shipping companies is quite high now” (Charlotta Solerud: Stockholm Port Environmental Strategist, interview 2021-07-01), but one of the biggest driver will be the lower maintenance costs resulting from the use of electrical power rather than high-priced Low-Sulphur diesel. In this context, ship-owners will kill two birds with one stone so to speak, no diesel consumption while the vessel is laying at berth in
addition to the maintenance cost saving from less auxiliary engines function hours. As a result, ship owners will be motivated to use OPS services as much as possible in order to support their investments (Zis, 2019).

4.3.2. Weaknesses

4.3.2.1. High investment cost

It is obvious that infrastructure is a fundamental part in the expansion of any emerging technologies. Thus, Ports have been the subject of incentives and regulations to implement OPS on a European basis. However, those legislations primarily result in strong investment expenditure at the port level, with very little expectation of future profits and the expert of Stockholm port emphasis this point in the interview by claiming that: “I would say that the major barrier to overcome in OPS solution is that it’s very hard to get the investment profitable (Svante Åberg Gassbo: Electrical Manager Stockholm Port, Interview 2021-07-01).

As a result, this unprecedented situation in which new OPS infrastructures are needed for ships to reduce in-port pollution poses a burning question: who should be in charge for it? Since there are so many players concerned in various business scenarios in ports such as government, Port Authority, terminal Operators and ship owners, the answer isn't straightforward (Winkel et al., 2016).

Although from the port's view, the OPS investment could result in lower pollution, cleaner air, and a better public perception, however, if the number of ships calling the Port and able to receive shore power is not enough, the advantages of installing OPS at berths would be minimal, and other green investments, such as renewable fuel or speed reduction, could be preferable (Zis, 2019). The preceding analysis reveals that ports share the majority of the financial pressure, which is handled explicitly by regulations to provide facilities for OPS but does not benefit from offset initiatives. On the contrary, it seems that energy producers and suppliers benefit from these laws without having to make any contributions.

4.3.2.2. Technology available only on few Ports

If just a few ports are able to supply shore power technology, the ship operator may select other options. As a result, depending on the vessel and terminal type, this matching may be easy for Ro-Ro ships that just sail between two or a few more terminals, or highly complex for large containerships that travel to dozens of ports. Besides, the port of Stockholm for instance gives 1 million SEK as incentive to retrofit ships to connect with OPS. However, right now, these incentives are given merely to Ro-Ro ferry ships because those type of ships
usually sail between only two ports which make the installation more profitable for the ship (more lay time at berth) as the expert of Stockholm port clearly mention it: “that one million Swedish crowns, that's for the regular traffic. So that's for the Ro-Ro ferry traffic mainly” (Charlotta Solerud: Stockholm Port Environmental Strategist, interview 2021-07-01). This dilemma puts the Port Authorities in a difficult situation when it comes to scaling up OPS technology in all berths. Stockholm Port Authority for example is in continuous discussion not only with other neighbor Ports such as Helsinki and Copenhagen but also with Cruise ship owners which own cruise ships that sail mainly between those 3 ports, in order to find a compromise on how they can participate partially in the capital cost of the investment to reach a rational agreement to get the ball rolling as it is pointing out by our expert: “the cruise customers have to pay at least a part of the investment” (Charlotta Solerud: Stockholm Port Environmental Strategist, interview 2021-07-01). The previous situation can be viewed as a chicken-and-egg issue, in which ports will not invest until a sufficient number of ships are able to use OPS facilities, and shipping companies will not retrofit vessels until enough ports are able to provide shore electricity (Zis, 2019).

### 4.3.2.3. Different frequencies and voltages for ships calling the Port

The major challenge to broad ColdIroning adoption has been the shortage of compatibility between the ship and the Port grid, as there is no international standard for voltage and frequency. This lack of compatibility concerns electricity parameters due to the difference of standards in international yards, Ships have no uniform voltage and frequency requirement. Some vessels use 50 Hz frequency and some use 60 Hz. Furthermore, primary distribution voltage can vary from 440 volts to 11 kilovolts depending on the vessel type and equipment’s need. Load requirement varies from ship to ship and ranges from a few hundred kW in case of car carriers to a dozen or more MW in case of passenger or cruise ships (The et al., 2011).

The European Union grid, for example, use 50 Hz as frequency, while that of the US and Japan is 60Hz. Thus, the frequency used onboard vessels can be either 50 or 60 Hz. Some equipment onboard ships running on 60 Hz, such as lighting and heating, may be able to run on 50 Hz, but this is a minor portion of the ship's overall power demand. However, machinery such as pumps and cranes that are powered by single or three-phase motors that mainly rely on frequency level to determine their speed of operation, would be unable to operate at their design speed and might cause damage to the equipment in case of different frequency use. A ship using 60 Hz electricity will therefore require that the frequency in the European grid be converted from 50 to 60 Hz using frequency converter before connection to Onshore Power.
Supply (Ericsson, 2008). The majority of onshore power in Stockholm Port for instance is supplied to vessels with 50Hz frequency while referring to the expert of Stockholm Port, a frequency converter is using to supply 60Hz frequency to some ships and they are planning more frequency converter installations to be able to supply cruise ship in the coming OPS project as he declared in the interview: “We have 60 hertz and the rest of them are 50Hz. But now we're also building cruise ships, and they are 50/60 Hertz. But otherwise we are going 50Hz with the Ferry vessels” (Svante Åberg Gassbo: Electrical Manager Stockholm Port, Interview 2021-07-01).

4.3.2.4. Long Pay-Back Period
One of the criteria considered when evaluating the effectiveness of an investment is the Pay-Back Period. In our case, investing in Onshore Power facilities represents a big challenge for Port Authorities when it comes to the financial aspect. It is extremely difficult for some Ports to engage in implementing this technology without any subsidies or incentives from the government or other non-governmental entities. To explain more this issue, the Port Authorities in Sweden for example are not allowed to sell electricity supplied at berth, therefore, the benefit from installing OPS is limited to the additional Port’s fee required from the ship-owners and the expert of Stockholm Port emphasis this issue by claiming that: “As a public port, we are not allowed to sell the electricity, so we only transfer the same cost, because we have the agreement with the electricity supplier, and then we just transfer the electricity, and the same price that we pay, to the vessel, to the ship company. So we do not get any profit on the electricity, we have just what we call a service fee, an annual service fee that the shipping company is paying every year for the installation” (Charlotta Solerud: Stockholm Port Environmental Strategist, interview 2020-10-26). As a result, the Pay-Back Period of the Cold Ironing investment is very long compared to other alternatives such as the use of LNG.

4.3.3. Opportunities

4.3.3.1. EU and government subsidies and incentives to Port
Notwithstanding the fact that Onshore Power Supply is one of the best alternatives to tackle air pollution, GHG emissions, Noise and vibration at Ports, financing this technology is still a big challenge for Port Authorities. In this context, the Port of Stockholm for instance has joined the EU coordinated supply of Onshore power in Baltic seaports projects and has received an EU funding of 2.3 million € (Ports of Stockholm, 2017), in addition to a significant local financial support from the Swedish Environmental Protection Agency
estimated to 2.7 million € to equip two central quays for cruise ships in Stockholm port with OPS installation which according to the expert of Stockholm Port in our interview is planned to be ready by 2024 as he highlighted: “It's actually larger than the EU funding. When it comes to the Cruise ship OPS investment, the funding from the Swedish national funding is very important and bigger than the EU funding, actually I think it's 2.7 perhaps million Euro” (Svante Åberg Gassbo: Electrical Manager Stockholm Port, Interview 2021-07-01).

4.3.3.2. Port incentives to ships complying with OPS connection
A grant of SEK 1 million is offered from the Port of Stockholm to every ship that carries out retrofitting operations to be enabled to connect to onshore power supply. This applies for the quays where Ports of Stockholm offers onshore power supply (Ports of Stockholm, 2017). Furthermore, from the interview conducted with an expert from Stockholm Port, she claimed that the ship seeking for this incentive should be in regular traffic for at least 3 years to Stockholm Port as she said: “the ship has to be at least three years in traffic at this quay in Stockholm, in regular traffic, to be able to get this one million” (Charlotta Solerud: Stockholm Port Environmental Strategist, interview 2020-10-26).

4.3.3.3. Collaboration with other Ports
To raise the investment profitability of Cold Ironing, the investment expenses must be decreased or the operating time during which Ships are connected to shore electricity, must be increased. In this Context, collaborating with other ports may be beneficial not only for Port Authorities but for Ship-owners too. Therefore, the Stockholm Port has intensified the collaboration with other ports in the Baltic sea such as the Port of Helsinki and Tallinn in order to unify and to ensure the compatibility of the equipment installed in those Ports and onboard ships berthing within those regions as claimed our expert from Stockholm Port: “It’s very important, to have a dialogue with other ports on the other side of the Baltic Sea, such as the Port of Helsinki and the Port of Tallinn. It’s very important that the technique that they are using in that port, is also compatible with our port and with the technique onboard” (Charlotta Solerud: Stockholm Port Environmental Strategist, interview 2021-07-01).

4.3.3.4. Increasing Customers Demand to OPS facilities
The high price of Marine Diesel Oil MDO, the long stay at berth in addition to the high fuel consumption while at port, result in the emerging demand from many shipping companies to have OPS facilities in place to enable ships to lower fuel consumption and emission as well as benefiting from the Port incentives.
In this context, the manager of the Port of Stockholm has received after a successful dialogue, a confirmation from six cruise shipping companies that they will retrofit their ships to be able to connect to the shore electricity once it is available in 2023 as the expert said in the interview: “We have that dialogue as well with the customers, so we know that they are prepared and they are willing to use the investment”, “we have letter of support from six cruise shipping companies, that say that, if you in Stockholm, you have this OPS installation in 2023, we will use it when we come with our ships” and “Historically, it has been quite low, the customer demand, but now we can see that it’s increasing. But the low customer demand has been a challenge before” (Charlotta Solerud: Stockholm Port Environmental Strategist, interview 2020-10-26).

**4.3.3.5. Tax reduction for electricity price**

To be more competent compared to the use of fossil fuels by ships at berth, incentives such as tax exemption for electricity supplying power to ships must be preserved by the Swedish government. This exemption is critical in providing a financial incentive to utilize shore-side power. The use of a lower-tax rate would improve the competitiveness of shore-side power in comparison to the tax-free burning of bunker fuels onboard ships at berth. Otherwise, the cost to produce onshore electricity is 2 to 4 times higher than when the ship is using an auxiliary engine on HFO or MDO without electricity tax exemption (Program & Energy, 2019). The expert of Stockholm Port confirms this statement in the interview by saying that: “We have an exemption now, in Sweden, to have that reduction. And I think that they are planning to implement this electricity tax exemption in the whole of the EU, perhaps in one or two years” (Charlotta Solerud: Stockholm Port Environmental Strategist, interview 2020-10-26).

**4.3.4. Threats**

**4.3.4.1. Local Power Supply and Extra Loads**

Installing Onshore Power Supply is highly dependent on the abundance of the power supplied to Ports, due to the extra loads needed from the national grid to ensure generating electricity to many Ships berthing simultaneously. Therefore, the Port Authority, when considering to implement and to scale up OPS technology, should discuss and get consultation from the Local Supplier Company to investigate the impacts of extra electric loads on the Port Local grid possibility to keep providing decent power. The expert from the Port of Stockholm confirm those steps in the interview by pointing out that in Stadsgården Port for example, they have planned to install OPS facilities with 8 and 16 Megawatts which represent a big power demand and they have to discuss all the details with the grid owner before carrying out
any retrofitting operations: “You have to have this very active dialogue with the grid owner so you know that it’s possible to get the power that you need in the port” and “So the grid owner is very important, because if they say it’s not possible, then it will be very difficult” (Charlotta Solerud: Stockholm Port Environmental Strategist, interview 2020-10-26). It is recommended in some cases to upgrade related equipment such as transformers or cables and to add developed generation units to the local grid, namely additional power sub-stations (Tech, 2007).

4.3.4.2. Safety issues
The port operators must ensure that the docked ships have safe and dependable electrical connections. The IEC/ISO/IEEE 80005-1 standard establishes universal standards for connecting vessels from all over the globe to complying ports. The electrical wiring between the shore and the ship, as stated in the standard, may pose a risk, especially as the interface region between the shore and the ship is a high-risk area for electric shocks. These issues include not just the operators' safety from ground fault interferences resulting in transmitted touch potentials, but also the ship's integrity from galvanic corrosion (Ieee & Ieee, 2016).

4.3.4.3. Lack of available space at Port
Among the problems to overcome to make OPS technology more promoting, is the lack of space to retrofit the existing quays with Cold Ironing installations due to the huge equipment needed such as transformers, frequency converters, and cables which consists not only a space problem but also it might affect the aesthetic view of the Port. In addition, it is worthy to be mentioned that the size of those equipment is highly dependent on the power supplied and the type of ships. For instance, this Problem is highlighted by the expert of Stockholm Port when she said that: “the problem is how to make room for this installation in the Port of Stadsgården. Because it’s quite big, it requires quite a lot of space. And then we also look at the aesthetic point of view, because it’s a very public area, and I think it will be a problem to have containers standing in the port. It will not look that great” (Charlotta Solerud: Stockholm Port Environmental Strategist, interview 2020-10-26).

4.3.4.4. Competence with other alternatives
Many ship-owners are still reluctant to invest in retrofitting their fleets to connect to shore power especially when there is no binding regulation so far to comply with. Thus, they stuck with the use of auxiliary engines to generate electricity while at berth in a simple and low-cost way. Moreover, emerging solutions have gained interest beside OPS, such as the use of Liquefied Natural Gas LNG which can generate power directly when used as fuel or provide
electricity that will afterward supply vessels while laying at berths. LNG can be supplied to ships by several ways namely by pipeline to ship, truck to ship or ship to ship. For that reason, LNG Barge technology might present for instance a strong business case compared to OPS technology due to the massive gap when it comes to the cost of infrastructure. Thus, in addition to the significant NOx, SOx and PM emissions reduction due to the deployment of LNG, this latter can generate power either at 50Hz or 60Hz without the need to extend the grid connection, to install additional transformers, or to use frequency converter to get the right frequency. Hence, LNG technology might be relevant when the space at berth are quite limited to install OPS facilities or when there is an issue emerging while investigating the extension of the national grid for power supply.
Chapter V: Optimization of Renewable Energy System using HOMER

In order to investigate the techno-economic feasibility of a Renewable energy grid option in the port of Kapellskär, we decided to utilize HOMER (Hybrid Optimization Model for Electric Renewables) which is a software developed by National Renewable Energy Laboratory (NREL) of the US department of Energy (DOE) widely used to evaluate designs both on and off-grid for different applications (Homer Energy, 2019).

Simulation, optimization and sensitivity analysis are conducted through HOMER to compare the results of a variety of energy models and to determine the optimum configuration system based on technical and economic factors (Healthcare & Using, 2017). Therefore, this simulation requires a number of data inputs such as the area of research, Load data, wind resources as well as capital and operational costs of the equipment considered within the energy system.

5.1. Geographic Area of research

The port of Kapellskär has been chosen to conduct this investigation (Fig 8). The port consisting of 5 berths for Ro-Ro passengers and Ferries ranging from 130m to 245m of length, is located 90 km north of Stockholm which make it in strategic position enabling rapid and smooth passenger and goods transport from Sweden towards Finland, Norway, Russia and other European countries (Ports of Stockholm, 2017).
5.2. The model inputs and assumptions

For this part of the research, the inputs are divided into constant and variable ones. In addition, to overcome the lack of some data, assumptions are considered in a way to ensure a realistic simulation results.

- **Constant Input Data:**
  - Project lifetime
  - Capital cost of wind turbine, battery and converter.
  - Operational cost of wind turbine and battery
  - Replacement cost of wind turbine and battery.
  - Emission factors of the National Grid.

- **Variable Input Data:**
  - Grid power price
  - Nominal Discount Rate
  - Average Wind Speed

- **Assumption Data:**
  - Annual average power consumption of the Port is assumed at 38,000 kWh/day.
  - Electric Load Profile of the Onshore Power Supply.
  - Grid sellback price is assumed at 0.050 €/kWh.
5.3. The Port Load Data

The yearly Load profile of the port is created based on general assumptions of an industrial profile with July considered as peak month in terms of the Port energy consumption (Fig 9).

![Seasonal Profile of Kapellskär Port (HOMER)](image)

*Figure 9: Seasonal Profile of Kapellskär Port (HOMER)*

After reviewing the history of vessel calls from the port website, we noticed that the peak of power consumption ranges from 7am to 14pm which consequently provide us the following daily load pattern (Fig 10):

![Daily Load profile of Kapellskär Port (HOMER)](image)

*Figure 10: Daily Load profile of Kapellskär Port (HOMER)*

Lately, the annual electric Load of the Port is illustrated by the software in a graph pointing out the density of the power consumption throughout the whole year as shown in (Fig 11).
5.4. Components of the Hybrid model

5.4.1. National Grid connection

The model is connected essentially to the National grid from which the Nordic energy mix is supplied. This latter consists of electricity generated in major part from renewable resources such as Nuclear power and Hydropower as well as power produced from biomass. However still a percentage of this electricity is provided from non-renewable sources which explain the emissions resulting from the use of it (Table 7).

![Table 8: Emissions factors of Nordic Energy mix (Development, 2015) & (Fischer et al., 2020)](image)

According to (Republic & Kingdom, 2014), the price of industrial electricity purchased in Sweden in the second half of 2020 is 0.0583 €/kWh (Fig 12). However, for Sensitivity analysis, 0.05 €/kWh and 0.065 €/kWh electricity costs are introduced in the model to overcome the uncertainty of the power purchase values.
5.4.2. Wind Resources Data

The appropriate onshore wind turbine model for this study Vestas V47/660 kW (Table 8) has been chosen based on several criteria such as the power output, the power curve (Fig 13) and wind speed Data in the Port area (Fig 14). This latter is sourced from NASA wind database prediction of worldwide energy resources available for the geographic region selected (Homer Energy, 2019).
According to the HOMER database, the annual average wind speed in Kapellskär Port is estimated at 6.80 m/s. Thus, we introduced the values 5.5, 6, 6.5 and 7 m/s to perform the sensitivity analysis of this hybrid model.

![Figure 14: Monthly Average wind speed data of Kapellskär Port (HOMER)](image)

In addition, HOMER software requires input the capital cost, the replacement cost if the project lifetime exceeds the wind turbine lifetime and finally the operation and maintenance cost in order to ensure the optimization and determination of the number of wind turbines needed for an optimum hybrid system. In our case, the cost of onshore wind turbine is extracted from (Gupta et al., 2020) where it is estimated that the capital cost is 2009 €/kWh, the turbine replacement cost is 1738 €/kW and O&M cost is assumed as 74 €/kWh/year.

5.4.3. Li-ion Storage Battery

The integration of energy storage systems has become a crucial step to overcome the surplus of wind energy at off-peak time. Therefore, to investigate the techno-economic feasibility of storing and reusing the excess of renewable energy, we have chosen Generic Li-ion battery 4hr/1MW from the database of HOMER software (Table 8) due to the increase deployment of this type of batteries across large-scale industries due to their energy, power and high performance (K Mongird et al., 2019). Additionally, we had input the values of Capital Cost (Fig 15) referring to (Kendall Mongird et al., 2020), as well as the Replacement and O&M Costs to our system model according to (Gupta et al., 2020).
5.4.4. Converter

The introduction of a converter in the system is fundamental due to the existence of both AC and DC elements. Thus, the Eaton Power Xpert 2250kW converter has been chosen to fit within this model and convert the DC energy generated by the storage batteries to AC energy and supplied to the Port grid connection. Capital and operational Costs has been extracted from the Manual of the manufacturer (Solutions, n.d.).

5.5. Schematic configuration of the hybrid model

After specifying the geographic area, defining the annual electric load and determining the component characteristics of the model (Table 8), the discount rate was also included with 5, 6 and 7% as values to perform a sensitivity analysis as well as a fixed 2% expected inflation rate. Hence, the project which the lifetime is assumed to be 20 years consists of the National grid connection, the wind turbines connected to the AC bus supplying power to the load and when there is a surplus, the storage batteries are charged. Once the demand exceeds the electricity production, the batteries will then supply the power. However, in case of
batteries completely charged and the generation of power still beyond the load, the surplus of power produced will be sold back to the National Grid (Fig 16).

Figure 16: Schematic hybrid model design using HOMER
<table>
<thead>
<tr>
<th>Components</th>
<th>Wind Turbine</th>
<th>Storage Battery</th>
<th>Converter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type/Size</strong></td>
<td>Vestas V47/ 660 kW</td>
<td>Generic Li-Ion 4hr 1MW</td>
<td>Eaton Power Xpert 2250kW</td>
</tr>
<tr>
<td></td>
<td>(Vestas Wind Systems, 2011)</td>
<td>(HOMER)</td>
<td>(HOMER)</td>
</tr>
<tr>
<td><strong>Capital Cost</strong></td>
<td>2009 €/kWh</td>
<td>381 €/kWh</td>
<td>330 €/kW</td>
</tr>
<tr>
<td></td>
<td>(Gupta et al., 2020)</td>
<td>(Kendall Mongird et al., 2020)</td>
<td>(Solutions, n.d.)</td>
</tr>
<tr>
<td><strong>Replacement Cost</strong></td>
<td>1738 €/kWh</td>
<td>270 €/kWh</td>
<td>178 €/kW</td>
</tr>
<tr>
<td></td>
<td>(Gupta et al., 2020)</td>
<td>(Kendall Mongird et al., 2020)</td>
<td>(Solutions, n.d.)</td>
</tr>
<tr>
<td><strong>O&amp;M Cost</strong></td>
<td>74 €/kWh/year</td>
<td>9 €/Kw/year</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>(Gupta et al., 2020)</td>
<td>(Gupta et al., 2020)</td>
<td></td>
</tr>
<tr>
<td><strong>Lifetime</strong></td>
<td>20 years</td>
<td>10 years</td>
<td>15 years</td>
</tr>
<tr>
<td></td>
<td>(Vestas Wind Systems, 2011)</td>
<td>(K Mongird et al., 2019)</td>
<td>(HOMER)</td>
</tr>
</tbody>
</table>

Table 9: Overview of Component properties and costs of the hybrid system

5.6. Results and Discussion
The large number of possible system configurations that might be considered in our project make the design decision confusing for the Port Authority. This is due essentially to the uncertainty in several variables such as Wind speed, the power price and the nominal discount rate. Therefore, HOMER optimization and sensitivity analysis allows us to determine the optimum scenario with high benefit and minimum Cost. In this context, and taking the components and the configuration explained above, we had been able to simulate
almost 10,030 feasible solutions from which 8,868 were omitted for some technical constraints and 1,162 will be considered for more investigation (Fig 17).

![Figure 17: Sensitivity and optimization process by HOMER software](image)

The results of the sensitivity analysis conducted using HOMER clearly illustrate that introducing renewable energy solutions in the Port Off-Grid highly depends on high prices of the electricity purchased from National Grid. Otherwise, using the power generated from the Nordic energy mix remains the Cost-effective option if the price of 1kWh of electricity does not exceed 0.05 € no matter the value of Wind speed and the Discount rate (Fig 18).

![Figure 18: Optimal system type for a power price of 0.05€/kWh (HOMER)](image)
However, fixing the Discount rate at 5%, the result of the simulation shows the penetration of renewable sources options in the optimal system which is explained by the cost-effectiveness of Wind power option compared to the purchase of high price electricity from the National grid in this case (Fig 19).

![Optimal System type with fixed Discount rate (5%)(HOMER)](image)

Figure 19: Optimal System type with fixed Discount rate (5%)(HOMER)

To be more realistic, fixed values had been chosen for the Optimization results which are 0.0583 €/kWh for the industrial power price in Sweden in 2020, 5% Discount rate and 6.80m/s average Wind speed from the NASA source used by the software for the Port of Kapellskär area. Consequently, 4 solutions were considered from the economic perspective (Table 9).

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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</tbody>
</table>

Table 10: Optimization results (Configuration systems and Costs) (HOMER)
According to the results showing above, installing 3 Onshore Wind turbines (V47/660Kw) with a Capital Cost of 3.98M€ blended with electricity purchased from National grid is the best option in term of Net Present Cost NPC (-11.8M€) and Levelized Cost of Energy LCOE (0.0522€) compared to the base Case consisting of power supply from National Grid connection (-12.1M€ NPC and 0.0583€/kWh LCOE) (Fig 20). However, the Discounted payback period for this option is estimated to 18.21 years with Internal Rate of Return IRR of 3.7% which can be ameliorated in case the cost of emissions savings by using wind power instead of Nordic Energy mix is taking into consideration in the feasibility study of this project.

![Graph: Proposed System Compared To Base System - Discounted](image)

*Figure 20: Optimum solution economically compared to the base case (HOMER)*

Furthermore, the breakdown of electricity production and annual power consumption indicates that 7,585 MWh comes from renewable energy production representing 50.1% of the total consumption. The annual wind power generation is unequally dispersed. It is notably low between May and August whereas it increases in the rest of the year according to (Fig 21).
As a result of the above Wind power configuration, a remarkable 1,256 MWh of surplus electricity has been produced by Wind turbines due to the high wind efficiency and low power consumption for this particular period clearly highlighted in (Fig 22) and (Fig 23).
As a consequence, this excess of wind power generated has been sold back to the National Grid at a sell price assumed to 0.050 €/kWh enhancing thus the overall project feasibility cost as shown in (Fig 24) and (Table 10).

<table>
<thead>
<tr>
<th>Month</th>
<th>Energy Purchased (kWh)</th>
<th>Energy Sold (kWh)</th>
<th>Net Energy Purchased (kWh)</th>
<th>Peak Load (kW)</th>
<th>Energy Charge €</th>
<th>Demand Charge €</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>179,234</td>
<td>315,400</td>
<td>-136,167</td>
<td>2,264</td>
<td>-€5,320.69</td>
<td>€0</td>
</tr>
<tr>
<td>February</td>
<td>188,715</td>
<td>245,464</td>
<td>-56,749</td>
<td>2,100</td>
<td>-€1,271.14</td>
<td>€0</td>
</tr>
<tr>
<td>March</td>
<td>258,987</td>
<td>236,334</td>
<td>22,654</td>
<td>2,286</td>
<td>€3,282.29</td>
<td>€0</td>
</tr>
<tr>
<td>April</td>
<td>273,393</td>
<td>166,678</td>
<td>106,715</td>
<td>2,005</td>
<td>€7,604.91</td>
<td>€0</td>
</tr>
<tr>
<td>May</td>
<td>509,211</td>
<td>81,751</td>
<td>427,460</td>
<td>3,050</td>
<td>€25,599.43</td>
<td>€0</td>
</tr>
<tr>
<td>June</td>
<td>1,044,446</td>
<td>11,261</td>
<td>1,033,186</td>
<td>3,614</td>
<td>€60,328.19</td>
<td>€0</td>
</tr>
<tr>
<td>July</td>
<td>984,956</td>
<td>11,854</td>
<td>968,052</td>
<td>3,898</td>
<td>€62,860.24</td>
<td>€0</td>
</tr>
<tr>
<td>August</td>
<td>1,059,984</td>
<td>9,342</td>
<td>1,046,642</td>
<td>3,883</td>
<td>€64,011.74</td>
<td>€0</td>
</tr>
<tr>
<td>September</td>
<td>895,737</td>
<td>14,223</td>
<td>881,514</td>
<td>3,750</td>
<td>€51,510.30</td>
<td>€0</td>
</tr>
<tr>
<td>October</td>
<td>798,720</td>
<td>3,674</td>
<td>795,046</td>
<td>3,442</td>
<td>€44,881.68</td>
<td>€0</td>
</tr>
<tr>
<td>November</td>
<td>632,167</td>
<td>51,088</td>
<td>581,080</td>
<td>2,911</td>
<td>€34,300.99</td>
<td>€0</td>
</tr>
<tr>
<td>December</td>
<td>569,827</td>
<td>79,703</td>
<td>490,124</td>
<td>3,150</td>
<td>€29,235.78</td>
<td>€0</td>
</tr>
<tr>
<td>Annual</td>
<td>7,541,376</td>
<td>1,256,770</td>
<td>6,284,606</td>
<td>3,898</td>
<td>€376,823.7</td>
<td>€0</td>
</tr>
</tbody>
</table>
On the other hand, the design model consisting of Wind turbine plus the storage batteries is ranked 3rd options in the optimization results with NPC equal to (-14.1M€) due to the high Capital cost of the components reaching almost (5.59M€) as well as a high LCOE equal to (0.0625€/kWh) which is far to be cost-effective compared to the two other options mentioned above (Fig 25). This can be explained by the additional cost of the Converter and the batteries for energy storage in addition to the extra replacement cost of the batteries due to their lifetime limited to 12 years unlike other components which clearly negatively affect the operational cost of the project later (Fig 26).

Figure 25: Cost Summary of the 3rd option (HOMER)

Figure 26: Discount cash flow of the project including Wind turbine & batteries
According to the annual power supply and demand graph and taking the state of charge of the batteries in consideration (Fig 27), we can clearly point out the effective role of the storage batteries in helping to benefit from the excess of wind power and supplied in the off-peak periods to the grid connection avoiding hence more electricity purchase from the National grid particularly at the period between October and May.

![Figure 27: Annual state of charge of the Storage Batteries (HOMER)](image)

However, is that sufficient to make a decision to deploy an energy storage system. The answer is no because when the energy demand of the Port is largely above the wind power generated, the batteries are not able to supply more electricity to the grid due essentially to the fact that the power demand between June and December highly exceeds the renewable energy produced (Fig 28). Moreover, even though the power purchased from the National grid is 6,961 MWh representing 47.9% of the total power less than the percentage mentioned for the first option but economically, the investment is not cost-effective due to the high capital cost.
The sensitivity and optimization analysis conducted using HOMER software give us a good understanding of the effectiveness of deploying renewable sources and energy storage systems to supply power that will be more cost-effective in the daily need of Ship’s electricity while at berth rather than keeping Auxiliary engines running or purchasing National grid power. However, the software is not able to include the cost of emissions saving from the shift to eco-friendlier sources of power compared to the National Grid. This downside drives us to resort to other methods that enable us to take this crucial environmental factor in consideration. Thus, we will try in the coming part to sort it out using Crystal ball software.
Chapter VI: Scenarios Modeling and Monte Carlo Simulation

6.1. Modeling, Data inputs and General Key Assumptions

Three scenarios have been created for the port of Kapellskär in Stockholm in order to investigate the cost-benefit of supplying power to vessels from renewable sources but in this case emphasizing the cost of emissions saving from this hybrid model.

The 1st scenario consists of the base case where Onshore Power Supply is installed and the electricity is supplied from the Nordic Energy Mix. Whereas in the 2nd scenario, Onshore Wind Turbines V47/660Kw are included and the emissions saving is calculated and converted to the amount of money saved. Last and not least, beside the Wind turbines, an energy storage system consisting mainly of Li-ion Batteries has been taking into consideration. The 3 scenarios have been investigated for the amount of 60% and 100% of ships berthing are able to connect to the OPS facilities. For this part of the study, a model has been developed using Excel sheets and the Crystal ball software has been utilized for the aim of ensuring the sensitivity analysis based on the uncertainty of some variables.

6.1.1. Constant Input Data

- The calculation period of the research will be set to 20 years starting from the year 2021 until 2041 which is perfectly in line with the lifetime of the main components of the model from the OPS to the Wind turbine to the Batteries.

- To be able to compare the emissions from ships at berth using Auxiliary engines running with MGO 0.1% Sulfur, emissions using OPS from National Grid and emissions using OPS from Renewable sources, (Table 11) highlight the emission factors used to calculate the amount of emissions saving for the 3 scenarios and the total money saved extracted from (Fischer et al., 2020) and (Development, 2015).
In addition to the emission factors, the estimated price of emissions in the Baltic Sea is utilized in this part of the research and pointed out in the (Table 12) where the values are given referring to (Fabio Ballini, 2013) & (Čokorilo et al., 2019).

The business case of Onshore Power Investment from Renewable sources depends on numerous elements. From those elements we can mention the future ship’s traffic, the future development and cost of the technologies and the future regulatory framework that might be a crucial factor for the decision makers. Therefore, the technology and the cost of the components provided in this study are based on the current known technology and cost.
6.1.2. Variable Input Data

- The calculation effectuated in this model has been made with an assumed Interest rate ranging from 3% to 8% to ensure a sensitivity analysis.
- Besides, a general increase of the general price level or the Inflation rate has been assumed to range between 1% and 3% throughout the total period of calculation.
- Although the price of Shore Power supply has been mentioned by (Port of Stockholm, 2015) that starts with 0.16 €/kWh, we decided to make this input variable due to the dependence on the National Grid price which is variable as well. Thus, in this calculation, the Shore Power Price is ranging from 0.12 €/kWh to 0.22 €/kWh for the sake of performing the sensitivity analysis.
- Usually, Port Authority receives incentives and subsidies to achieve Onshore Power Supply projects. Therefore, we assume for the sensitivity analysis that the incentives range from nothing to 3M€ in our calculation.

6.1.3. Ship Traffic and Port Calls

The port of Stockholm consists mainly of 3 major Ports. This study focuses on the Port of Kapellskär, one of those three ports where the majority of vessels calling are Ro-Ro and passenger vessels. This choice was made based on available data from the Port Authority in addition to the fact that the developed model and technology used do not exist yet in this part of Stockholm Port.

The type of ships, expected number of vessel calls as well as the average lay-time period of ships for this study have been provided from data from the Port Authority, the website of the Port and AIS data. The period investigated is from January 2019 to January 2020 and that’s due to the exceptional situation of the Shipping traffic after January 2020 which is largely affected by the COVID-19 pandemic after this period.

In order to off-set the uncertainty of the vessel traffic and the average lay-time at berth, some assumptions have been considered for the total period of calculations. In this context, the sensitivity analysis of this research has been ensured by assuming that the average power demand per vessel while at berth is ranging between 3 and 6 MW per hour. Besides, the total vessel calls were considered between 80 and 120 calls per year. Lastly, the average Lay-time per ship is assumed varying between 5 and 12.5 hours per call.

Finally, the base case considered for the research estimate around 60% of the ships calling the port will be able to connect to the OPS facilities. However, the prediction and ambitions of
the Port Authority lead us to take the effect of increase in the OPS use in the future into consideration by including an optimistic scenario including 100% of ships will use OPS facilities during their port’s stay, hence the effect of increase in OPS use in the sensitivity analysis.

6.2. Energy and Electricity Consumption using OPS

In this section, referring to the Port of Kapellskär Website and AIS data in 2019, the total number of vessel calls is assumed at 100 Calls/year (for the sensitivity analysis between 80 and 120 calls per year) and the average Lay-time for one ship is estimated at 10 hours/call (between 5 and 12.5 hours per call for the sensitivity analysis). Additionally, the average electricity consumption is estimated to range between 3 and 6 MW per ship. Thus, all data considered, the total electricity needed per year if 100% of ships are connected to OPS is 5 GWh/year and 3 GWh/year in case only 60% are able to connect. Those values are equivalent to respectively 1250 and 750 tons of MGO (0.1% S) consumption per year. Knowing that 0.25 Kg of MGO produces the equivalent of 1 kWh of electricity and the price of 1 ton of MGO is approximately 530 € referring to Rotterdam bunker prices 2021, (Table 13) clearly points out the difference of prices between vessels using MGO or OPS at berth.

<table>
<thead>
<tr>
<th>Average energy consumption per ship (MW)</th>
<th>Kapellskär Terminal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port Calls Per year</td>
<td>100 Call/year</td>
</tr>
<tr>
<td>Average Lay time /Ship</td>
<td>10 hours</td>
</tr>
<tr>
<td>Total hours of lay time</td>
<td>1000 hours/year</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Annual Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% MGO (Ton)</td>
</tr>
<tr>
<td>60% MGO (Ton)</td>
</tr>
<tr>
<td>100% Electricity use (MWh)</td>
</tr>
<tr>
<td>60% Electricity use (MWh)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Price of Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% MGO (Ton)</td>
</tr>
<tr>
<td>100% Electricity (MWh)</td>
</tr>
<tr>
<td>60% Electricity use (MWh)</td>
</tr>
</tbody>
</table>

Table 14: Summary of Energy Consumption per year for the port of Kapellskär (Author)
6.3. Externality Cost of Total Emissions Saving

According to the (Table 11) and (Table 12) presented above, the total emissions saving for all the scenarios developed using OPS from Nordic mix or Wind power and considering 60% or 100% of the total number of ships have been calculated and illustrated in the (Table 14) below.

<table>
<thead>
<tr>
<th>Total Emissions 100% MGO</th>
<th>Total Emissions 100% Elect Nordic mix</th>
<th>Total Emissions 100% Elect from Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGO</td>
<td>Electricity</td>
<td>Electricity</td>
</tr>
<tr>
<td>NOx</td>
<td>85 tons/year</td>
<td>NOx 1.75 tons/year</td>
</tr>
<tr>
<td>PM</td>
<td>2.625 tons/year</td>
<td>PM 0.15 tons/year</td>
</tr>
<tr>
<td>SOx</td>
<td>0.25 tons/year</td>
<td>SOx 0.35 tons/year</td>
</tr>
<tr>
<td>CO2</td>
<td>4000 tons/year</td>
<td>CO2 392.5 tons/year</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Emissions 60% MGO</th>
<th>Total Emissions 60% Elect Nordic mix</th>
<th>Total Emissions 60% Elect from Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGO</td>
<td>Electricity</td>
<td>Electricity</td>
</tr>
<tr>
<td>NOx</td>
<td>51 tons/year</td>
<td>NOx 1.05 tons/year</td>
</tr>
<tr>
<td>PM</td>
<td>1.75 tons/year</td>
<td>PM 0.09 tons/year</td>
</tr>
<tr>
<td>SOx</td>
<td>3.75 tons/year</td>
<td>SOx 0.21 tons/year</td>
</tr>
<tr>
<td>CO2</td>
<td>2400 tons/year</td>
<td>CO2 199.5 tons/year</td>
</tr>
</tbody>
</table>

*Table 15: Total Emissions Saving in tons per year (Author)*

It seems that shifting from MGO to Onshore power supplied from Nordic Mix or Wind energy is of extreme importance in terms of tackling CO₂ emissions and air pollutants and hence, fundamentally beneficial for the local environment of the port. According to (Table 15), more than 90% of CO₂ emissions and air pollutants had been removed using OPS from Nordic energy mix rather than MGO and almost 98% of CO₂ if we use electricity generated from wind turbines. Therefore, calculating the amount of equivalent money saved from avoiding those emissions is crucial in this study to highlight how vital it is to deploy OPS facilities from renewable sources instead of generating electricity from Ship’s Auxiliary engines while at berth. Although it seems that the amounts of money from emissions saving using whether Nordic Energy Mix or Wind Energy are not quite different, we will investigate
in the next part the cost-benefit of all the scenario developed to get the big picture and conclude which model is better to install in the port of Kapellskär.

### Table 16: Externality Costs of Total Emissions Saving per year (Author)

<table>
<thead>
<tr>
<th>Emission Saving 100% Elect Nordic mix</th>
<th>Price of Emissions</th>
<th>Cost of Emission Saving 100% Elect Nordic mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission Saving Ton/year</td>
<td>Reduction Efficiency</td>
<td>2017</td>
</tr>
<tr>
<td>NOx 60.25</td>
<td>97.94%</td>
<td>NOx</td>
</tr>
<tr>
<td>PM</td>
<td>24.73</td>
<td>PM</td>
</tr>
<tr>
<td>SOx 5.5</td>
<td>94.40%</td>
<td>SOx</td>
</tr>
<tr>
<td>CO2 366.5</td>
<td>91.69%</td>
<td>CO2</td>
</tr>
<tr>
<td>Total Cost</td>
<td>1625813.5</td>
<td>€/year</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emission Saving 100% Elect from Wind</th>
<th>Price of Emissions</th>
<th>Cost of Emission Saving 100% Elect Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission Saving Ton/year</td>
<td>Reduction Efficiency</td>
<td>2017</td>
</tr>
<tr>
<td>NOx 64.76</td>
<td>99.72%</td>
<td>NOx</td>
</tr>
<tr>
<td>PM</td>
<td>2.83</td>
<td>PM</td>
</tr>
<tr>
<td>SOx</td>
<td>6.09</td>
<td>SOx</td>
</tr>
<tr>
<td>CO2 380</td>
<td>98.35%</td>
<td>CO2</td>
</tr>
<tr>
<td>Total Cost</td>
<td>16789865</td>
<td>€/year</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emission Saving 60% Elect Nordic mix</th>
<th>Price of Emissions</th>
<th>Cost of Emission Saving 60% Elect Nordic mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission Saving Ton/year</td>
<td>Reduction Efficiency</td>
<td>2017</td>
</tr>
<tr>
<td>NOx 49.55</td>
<td>58.76%</td>
<td>NOx</td>
</tr>
<tr>
<td>PM</td>
<td>1.45</td>
<td>PM</td>
</tr>
<tr>
<td>SOx</td>
<td>3.54</td>
<td>SOx</td>
</tr>
<tr>
<td>CO2</td>
<td>220.5</td>
<td>55.41%</td>
</tr>
<tr>
<td>Total Cost</td>
<td>975491.5</td>
<td>€/year</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emission Saving 60% Elect from Wind</th>
<th>Price of Emissions</th>
<th>Cost of Emission Saving 60% Elect Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission Saving Ton/year</td>
<td>Reduction Efficiency</td>
<td>2017</td>
</tr>
<tr>
<td>NOx 50.35</td>
<td>59.83%</td>
<td>NOx</td>
</tr>
<tr>
<td>PM</td>
<td>1.56</td>
<td>PM</td>
</tr>
<tr>
<td>SOx</td>
<td>3.65</td>
<td>SOx</td>
</tr>
<tr>
<td>CO2</td>
<td>258</td>
<td>58.95%</td>
</tr>
<tr>
<td>Total Cost</td>
<td>1006342.1</td>
<td>€/year</td>
</tr>
</tbody>
</table>
6.4. Investment, Operation and Maintenance Costs

The investment cost of installing OPS facilities can be broken down into capital and operational costs. The capital cost is divided also into two major parts, the grid connection and the OPS facilities costs. Onboard installations however are not included in this study due to the focus on only Port’s financial perspective.

For this case study, 5 connection points are considered to cover all port berths and be able to investigate the scenario where 100% of ships berthing might be able to connect to OPS facilities. Therefore, to ensure OPS connection in all berths, the port has to upgrade the distribution grid to be able to increase the capacity in the port area. However, referring to (Ports of Stockholm, 2017), the port of Kapellskär has recently renewed and extended the connection grid by building new connection lines to enable High-Voltage facilities. Thus, in our business case, the grid connection cost is estimated to be 2M€ for this port according to data from suppliers and other OPS projects. On the other hand, a general cost estimate of the components of Onshore power is provided as shown in (Table 16) stating the cost of Transformers, Frequency converters as well as cabling and the management system. As mentioned before, the E.U and the Swedish policy promote and facilitate the scale-up of OPS installations in Swedish ports. In this intention, incentives and subsidies have been introduced as variable input in the calculation (assumed to range between nothing and 3M€) to assess the change in assumptions applied in this model.

<table>
<thead>
<tr>
<th>Number Of Connection point</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPEX OPS from NORDIC MIX Energy</td>
<td>Euro €</td>
</tr>
<tr>
<td>Grid Connection</td>
<td>-2000000,00</td>
</tr>
<tr>
<td>Transformer Station</td>
<td>-1500000,00</td>
</tr>
<tr>
<td>Frequency Converter</td>
<td>-3600000,00</td>
</tr>
<tr>
<td>Cabling</td>
<td>-720000,00</td>
</tr>
<tr>
<td>Cable Management System</td>
<td>-2200000,00</td>
</tr>
<tr>
<td>Incentives and Subsidies for OPS installation</td>
<td>0,00</td>
</tr>
<tr>
<td><strong>Total CAPEX</strong></td>
<td>-10020000,00</td>
</tr>
</tbody>
</table>

*Table 17: Overview of OPS investment Costs (Author)*
In addition to Capital investment costs, operational and maintenance costs have been taking in consideration as well, consisting mainly of the cost of electricity purchased from the national grid and O&M costs which, referring to ongoing studies, have been assumed to be 5% of the total Capital costs annually (Table 17).

<table>
<thead>
<tr>
<th>OPEX 100% OPS from NORDIC MIX Energy</th>
<th>Euro €</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Operating &amp; Maintenance</td>
<td>501000,00</td>
</tr>
<tr>
<td>Electricity Purchase Price</td>
<td>291500,00</td>
</tr>
<tr>
<td>Total OPEX</td>
<td>792500,00</td>
</tr>
</tbody>
</table>

*Table 18: Operational and Maintenance costs of OPS facilities (100% used) (Author)*

If only 60% of the ships will be able to connect to OPS while at berth, we assume the O&M costs of this case equal to 60% of the O&M costs in the previous scenario as clearly pointed out in (Table 18).

<table>
<thead>
<tr>
<th>OPEX 60% OPS from NORDIC MIX Energy</th>
<th>Euro €</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Operating &amp; Maintenance</td>
<td>300600,00</td>
</tr>
<tr>
<td>Electricity Purchase Price</td>
<td>174900,00</td>
</tr>
<tr>
<td>Total OPEX</td>
<td>475500,00</td>
</tr>
</tbody>
</table>

*Table 19: Operational and Maintenance costs of OPS facilities (60% used) (Author)*

Concerning the other scenarios developed using Wind turbines and batteries for energy storage, the Capital and Operational Costs are assumed the same as the ones considered for the HOMER model calculation as shown in (Table 19).
Last and not least, the annual revenues provided from installing OPS facilities is breaking down in the calculation model developed stating mainly the annual emission saving cost mentioning above in addition to the fees required by the Port Authority related to the OPS connection which is fixed at 0.16 €/kWh by Stockholm Port (Port of Stockholm, 2015). For more flexibility, we assumed this OPS connection fee variable ranging from 0.12 €/kWh to 0.22 €/ kWh. However, when considering energy from Wind Turbines, the electricity generated might represent a surplus for the energy demand. Thus, the annual cost of the Wind surplus energy sold back to the national grid has been calculated and considered in this study contrary to the model developed by HOMER software where this annual cost is not included.

### Table 20: Overview of Component properties and costs of the hybrid system

<table>
<thead>
<tr>
<th>Components</th>
<th>Wind Turbine</th>
<th>Storage Battery</th>
<th>Converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type/Size</td>
<td>Vestas V47/ 660 kW</td>
<td>Generic Li-Ion</td>
<td>Eaton Power Xpert</td>
</tr>
<tr>
<td></td>
<td>(Vestas Wind Systems, 2011)</td>
<td>4hr 1MW</td>
<td>2250kW (HOMER)</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>2009 €/kWh</td>
<td>381 €/kWh</td>
<td>330 €/kW (Solutions, n.d.)</td>
</tr>
<tr>
<td></td>
<td>(Gupta et al., 2020)</td>
<td>(Kendall Mongird et al., 2020)</td>
<td></td>
</tr>
<tr>
<td>Replacement Cost</td>
<td>1738 €/kWh</td>
<td>270 €/kWh</td>
<td>178 €/kW (Solutions, n.d.)</td>
</tr>
<tr>
<td></td>
<td>(Gupta et al., 2020)</td>
<td>(Kendall Mongird et al., 2020)</td>
<td></td>
</tr>
<tr>
<td>O&amp;M Cost</td>
<td>74 €/kWh/year</td>
<td>9 €/Kw/year</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>(Gupta et al., 2020)</td>
<td>(Gupta et al., 2020)</td>
<td></td>
</tr>
<tr>
<td>Lifetime</td>
<td>20 years</td>
<td>10 years</td>
<td>15 years (HOMER)</td>
</tr>
<tr>
<td></td>
<td>(Vestas Wind Systems, 2011)</td>
<td>(K Mongird et al., 2019)</td>
<td></td>
</tr>
</tbody>
</table>
6.5. Sensitivity analysis and Results discussion

All facts considered and calculations done, a Monte Carlo simulation is performed with 50,000 iterations in which all input data subject to uncertainty are simultaneously varied in order to get a large number of observations in terms of Net Present Value NPV computed for the 3 scenarios described in the previous part of the study.

6.5.1. Scenario 1: OPS installations and energy supplied from Nordic Mix

First things first, (Fig 29) clearly highlights through the 2 scenario graphs that the more ships are able to connect to the OPS facilities, the more the investment is cost-effective. For this case, the profitability of the project proportionally depends mainly on 3 variables: the average lay-time of ships, the average energy consumed while at berth and the number of port calls per year with respectively 47.6, 25.8 and 8.9%. However, the investment becomes less and less profitable with the increase of the interest rate value.

Figure 29: Sensitivity analysis of Onshore Power from Nordic Mix Energy (Author)
6.5.2. Scenario 2: OPS installations and energy supplied from Wind power

Unlike the previous one, the input data that influences the investment in this scenario changes with the percentage of ships able to connect to the OPS installations. As (Fig 30) shows, the NPV in the first graph where 60% of ships might use OPS facilities proportionally depend with almost 36% on the average lay-time. However, the second most crucial factor is the interest rate that if it increases, the NPV of the project drops automatically with 20.5% and this is explained by the considerable Capital cost of the investment. Contrarily, if 100% of ships are connected to OPS while at berth, the Capital cost of the project is rapidly covered by the annual revenue. As a result, the interest rate is less important than the average energy consumption per ship at berth in this case.

Figure 30: Sensitivity analysis of Onshore Power from Wind Energy (Author)
6.5.3. Scenario 3: OPS installations and energy from Wind power & Batteries

The probability that this investment results in negative NPV is almost 10% in the first scenario (60% of ships connected) which is notably high due to the additional Capital cost of the energy storage system. This percentage drops to only 1% in the 2nd scenario (100% of ships connected) due to the extra revenue achieved by emissions saving and OPS connection fees. Additionally, the dependence on the average lay-time and the energy consumed per vessel increase from 36.9% and 21.5% to respectively 43.2% and 25.1% if the percentage of ships connected raise by 40% from the first to the 2nd scenario. Whereas the dependence on the interest rate value fell from -17.8% to only -12.9% (Fig 31).

Figure 31: Sensitivity analysis of Onshore Power from Wind Energy & Batteries (Author)
6.5.4. Overview of the Results obtained

The final results illustrated in the graph (Fig 32) clearly point out the high cost-effectiveness of producing the shore power electricity from the Wind power which gives this solution more credits when decisions have to be made exactly as the results provided from HOMER software. However, adding batteries to store the surplus of wind energy is obviously less interesting if only 60% of the vessels calling the port are able to connect to shore facilities.

![Figure 32: Overlay of the 3 project models when 60% of ships connected to OPS](Author)

This difference in terms of NPV values decreases with the increase of the percentage of ships connected to OPS at berth. The graph in (Fig 33) shows that installing Wind Turbines with batteries becomes as cost-effective as supplying the OPS electricity from National Grid during the 20 years’ lifetime of the investment. However, in any case it exists profitable solution than installing Onshore Wind Turbines to supply renewable energy to the Port.

![Figure 33: Overlay of the 3 project models when 100% of ships connected to OPS](Author)
Chapter VII: Conclusion and Recommendations

The continuous increase in maritime traffic has highly raised the issue of environmental pollution in Port areas especially when they are located within stone’s throw from urban areas making hence precautions much needed and wanted. It is worth mentioning that a huge amount of this pollution originates from ship power generation based on diesel combustion while at berth. The options to overcome this issue are strongly influenced by the international, national and local regulations imposed in those areas. Therefore, this study provided in the first part an overview of the regulations and incentives in Nordic countries and Sweden specifically. Those regulations represent the most effective drivers creating a “level playing field” to reduce air pollution, GHG emissions and improve energy efficiency in the maritime sector in general and Port sector in particular (International maritime organization, 2015).

In this context, Onshore Power Supply represents an effective method that when implemented in Ports, can significantly mitigate in a short period not only GHG emissions and air pollution, but also vibrations and noise pollution.

However, even though this technology has been available in some Ports in the Nordic countries for more than a decade, the uptake is still facing a slow pace due to several factors. Thus, this research has presented a SWOT analysis breaking down the benefits and concerns of speeding up the adoption of Shore Power facilities in the port of Stockholm as a case study in the Nordic region. As a result of this analysis, the benefits and opportunities of implementing Cold Ironing in this Port have obviously outweigh the concerns and threats.

Due to hesitation, uncertainties and lack of standard concepts, a feasibility study has been conducted in the port of Stockholm specifically the port of Kapellskär in order to establish a deep knowledge and thorough insight of deploying OPS facilities and provide a methodological framework that can be useful for other Ports not only in the Nordic region. In addition, a more effective solution consisting of combining OPS with renewable energy from
wind with a possibility of storing the surplus of wind power using batteries has been
investigated in order to promote a new zero emissions port concept as well as contributing in
the Swedish energy target to produce electricity from 100% renewable sources by 2040
(Energimyndigheten, 2019).

The outcome from the approach conducted to assess the potential of emission reductions has
revealed 1.5, 3.6, 50.8 and 2358 tons per year of respectively PM, SOx, NOx and CO2
emissions saved when 60% of ships calling the port of Kapellskär connect to shore side
electricity generated from wind Turbines. The total cost of those emissions saved is estimated
to be almost 1 million Euro annually. However, around 3900 tons of CO2, consisting around
98% of CO2 emitted by ships if they are using auxiliary engines at berth, has been avoided in
addition to 2 tons of PM, 6 tons of SOx, and 84 tons of NOx if 100% of the vessels calling
berth use shore electricity from wind turbines leading hence to a 1.67 M€ of benefits each and
every year in this case.

By studying the economic aspect of various scenarios using both HOMER and Crystal ball
software, another important fact has been outlined, is that although the emission reductions
from Nordic Energy Mix and Wind energy are almost the same, but when considering a 20
years’ project lifetime, the cost-effectiveness of the proposed solution including 3 onshore
wind turbines of 660 Kw blended with National grid is the optimum source of shore power for
ships berthing in term of Net Present Value NPV and Levelized Cost of Energy LCOE due to
the possibility of sellback of the excess of energy to the grid making the revenues for this
option higher. Moreover, the fact that this model consisting of wind turbines is profitable in
Sweden where the cost of electricity from the national grid is one of the lowest in Europe
(0.0583 €/kWh) makes it undoubtedly more profitable in other ports in different European
countries. Consequently, the higher the price of electricity purchased by the port, the more
including Wind Turbine to the grid becomes economically beneficial. Over and above, Wind
turbine technology is becoming nowadays more mature with an ongoing fall in the Capital
and Operational Cost and hence lower Levelized Cost of Energy (Elia et al., 2020). Thus, it is
recommended for future research to investigate the influence of low expenditures and high
lifetime Wind turbines in the financial and operational verdict of such proposals when
integrated within the Port grid.

On the other hand, the installation of Batteries to store the surplus of Wind Energy seems
from the HOMER and Crystal ball analysis not a cost-effective proposal for several reasons.
First things first, this energy storage system is not yet mature in large scale installations in
addition to the massive Capital and Operational cost as well. Besides, the lifetime of the Li-ion batteries which have been chosen in this project is quite low and require additional replacement cost after 12 years. As a result, the NPV and LCOE of the given option cannot compete with the base case or the other options. Besides, as highlighted above in the analyses of the results, the energy generated by the wind turbines present an excess that can be stored by the batteries and reinjected in the grid only in the off-peak period. Whereas between May and September, the scarcity of wind source and the huge demand of power result in a situation where the storage batteries are almost useless in this period. Therefore, it is recommended for future effective proposals to investigate the installations of a suitable number of wind turbines that will be able to off-set the peak of power demand around the year and allow the excess to be stored and reused afterward in a more effective way. Moreover, several studies show that other energy storage systems might present a good alternative to the Li-ion batteries for large scale installations in the future with high effectiveness and less cost such as the power to hydrogen storage system.

It is recommended from the sensitivity analysis that the average Lay-time and the average energy consumption per ship and per call are the two crucial criteria when those hybrid energy solutions have to be implemented within the Port. As a consequence, we can conclude that cruise and passenger terminals are the most concerned and present the best case in terms of cost-effectiveness of Shore side electricity from renewable sources. However, we cannot turn a blind eye toward the importance of subsidies and incentives not only for Port Authority but also for ship owners in order to encourage and boost the installation of onshore connection onboard ships. The Port Authority of Stockholm emphasizes the fact that collaborating and sharing knowledge with all stockholders and partnership such as other neighbor Ports is at the same importance of the investments in OPS projects. In this context, the Port of Kapellskär have been awarded for instance a funding from the Swedish Environmental Protection Agency and E.U of around 1.6 M€ which help to boost the investments in OPS projects with cooperation with the port of Naantali in Finland in order to be able to attain the port environmental targets (Ports of Stockholm, 2017).

Last and not least, although this study does not touch upon the ship owner’s perspective in the investigation and research of OPS projects, but it is worth mentioning that the port of Stockholm is one of the few ports that provide incentives to ships calling the port in order to speed up the adaptation between the shore power facilities and the vessels calling those berths.
in a regular traffic which is obviously considered as one of the vital factors of scaling up this technology in the future.

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