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Operational and Environmental Benefits of Shore-To-Ship Power Systems in Container Shipping

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Abstract

This study investigates the feasibility, environmental impact and financial implications of implementing shore-to-ship power (S2SP) systems in the container shipping industry. The study revolves around three main goals: looking at the advantages and disadvantages of S2SP, determining its environmental impact and investigating the possibility of retrofitting older vessels. Using cost-benefit analysis (CBA) and Comparative Analysis (CA), this analyses the financial and operational impacts of retrofitting existing vessels as compared to implementing S2SP on newly built vessels. The findings indicate considerable reductions in emissions, while identifying the high upfront costs and lack of availability of port infrastructure as a major challenge for implementation.

Keywords
Shore-to-Ship Power (S2SP), Carbon Emissions Reduction, Environmental Sustainability, Container Shipping, Retrofitting

1. Introduction
The maritime industry is crucial to global trade, with 90% of all goods and commodities transported by sea (ICS, 2024). Globally, 4.6 million port calls were recorded in 2022, with Norway leading in the number of port calls. The median time for cargo-carrying ships at Norwegian ports was 10 hours (UNCTAD, 2023). The expansive and vital network of marine transportation is highlighted by the hundreds of container lines that connect about 800 ports throughout the world (MoverDB, 2024). Many international organisations, including the International Maritime Organisation (IMO), Organisation for Economic Cooperation and Development (OECD), International Council on Clean Transportation (ICCT), United Nations (UN) have provided emission-reduction and scientific analysis guidelines for the maritime industry.

The amount and type of bunker fuel used determines the carbon dioxide (CO2) emissions from the vessel's main and auxiliary generators, which as seen in Figure 1. According to historical statistics obtained by the United Nations, shipping emissions are rising. Vessels consequently have a detrimental environmental impact on the surrounding natural ecosystem.

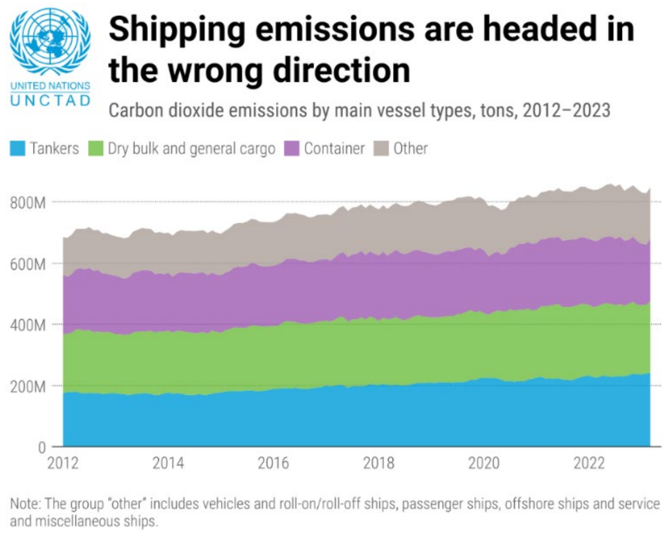

Figure 1. Shipping emissions are headed in the wrong direction

The shipping industry is currently at a critical juncture, addressing the complicated problem of lowering carbon emissions while simultaneously coping with economic and geopolitical issues. The industry's CO2 emissions contribute to 3% of the global total, have grown by 20% in the past 10 years (UNCTAD, 2023). If no immediate actions are implemented, emissions might rise to 130% of present 2008 levels by 2050 (UNCTAD, 2023). The fact that the world's fleet of vessels is ageing adds to the problem. In 2023, the vessel age was 22.2 years (Chambers, 2023). With more than half of vessels being over 15 years old, a substantial proportion of vessels are either unsuitable for modernisation or too young to be scrapped. (UNCTAD, 2023). The need to reduce carbon emissions is clear. However, the industry is confronted with the challenge of making multibillion-dollar expenditures while struggling with uncertainty on the most effective way of net-zero emissions by 2050.

While utilizing biofuels and liquefied natural gas (LNG) is considered more eco-friendly during transport compared to traditional fossil fuels and diesel. However, these alternatives still release CO2 at reduced levels (Cherylashton, 2023). Despite developments in cleaner fuel technology, emissions from vessels docked in port continues to be a major environmental issue.

As depicted in Figure 2, the average time vessels spend in port varies significantly across vessel types. Container vessels have an average port time of 1 to 0.7 days. This prolonged berthing period results in continuous fuel combustion for auxiliary generators, contributing to air pollution and greenhouse gas emissions.

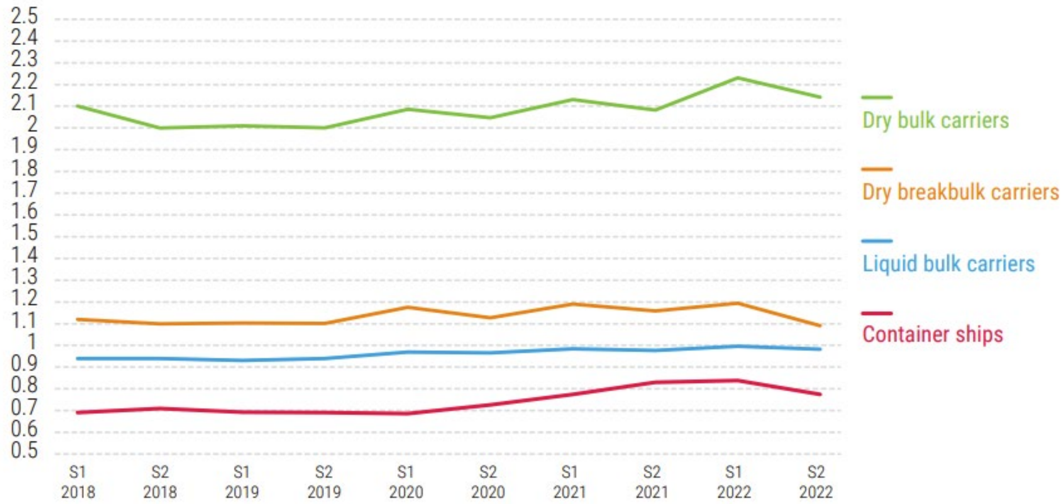

Figure 2. Average time vessels spend in port

1.1 Objectives

The research questions and the corresponding objectives of this study are as follows:

1. Advantages and Disadvantages of Shore-to-Ship Power (S2SP) Systems

The first objective is to examine the advantages and disadvantages of Shore-to-Ship Power (S2SP) Systems for ports and shipping companies by cutting operating costs and reducing their environment footprint. This objective involves an in-depth analysis of how S2SP systems improve emission savings and costs by providing a steady and high-quality power supply during berthing. By turning off their auxiliary generators (AG) and connecting to the local electricity grid, vessels can cut their fuel consumption.

Additionally, this study will look at the possible cost reductions for shipping companies that have implemented S2SP and has seen cost reductions from lower fuel usage and maintenance expenses, highlighting the economic benefits of implementing S2SP technology. From a cost perspective, S2SP contribute to significant operational savings. By utilising shore power, vessels lessen their reliance on fuels and auxiliary generators, resulting in significant fuel cost reductions. The maintenance costs associated with AG are minimized as the generators will be used less frequently. These cost savings are especially important in today's economic context, as shipping companies are under pressure to reduce their environmental impact.

2. Retrofitting Older Vessels with Shore-to-Ship Power (S2SP) Systems

The final objective of this study is to explore the feasibility and benefits of retrofitting older vessels with S2SP. As a significant portion of the global shipping fleet consists of older vessels, many of which are not equipped with modern emissions-reducing technologies (KNEWS, 2024). According to a study done by Alphaliner, MSC Shipping Line owns roughly 25% of all container ships that are 20 years old or older, making it the world's largest operator of ageing vessels (Phaata, 2023). Retrofitting these older ships with S2SP is a great opportunity to for such company to enhance their operation sustainability (Phaata, 2023). Given that the challenges and solutions associated with integrating new technology into existing vessel infrastructures, this study would **show the cost of retrofitting** and demonstrate how retrofitting older vessels can significantly reduce their carbon footprint, as well as **potential incentives** that could facilitate widespread adoption of S2SP retrofits. This ensuring that even the fleet's oldest vessels can contribute to a cleaner, more sustainable maritime future.

2. Literature Review

There are limited studies on the utilization of shore-to-ship power since its acceptance by maritime companies is still minimal. This is mostly due to insufficient infrastructure and skepticism about the return on investment in this technology. The literature review for this study is as follows:

- Shore To Ship System – An Alternative Electric Power Supply in Port (Borkowski et al, 2012).

2.1 Shore To Ship System – An Alternative Electric Power Supply in Port

The paper by Borkowski highlights how important it is for ships to connect to the local power grid when they are in port to reduce the environmental impact. It emphasizes that the port must have existing flexible electrical equipment that can work with different vessels, as each ship has its own unique electric system. There is also a case study of a vessel that has been modified for shore power connections.

The paper explored the S2SP concept and explain the environmental impact when ships of current diesel generators are used during berthing operations. Currently, auxiliary diesel generators used to power vessels at ports are the part of the source for carbon emissions, noise and vibration (Borkowski et al, 2012). Connecting vessels to a shore-based electric grid rather than utilising diesel generators is an efficient approach to minimise pollutants, noise and vibrations at ports.

Referring to Figure 3 showcases the nitrogen oxides (NOx) restrictions set by the IMO: The Tier 1 limitations were established in the year 2000, while the Tier 2 limits were established in 2011. However, the Tier 3 restrictions, implemented in 2016, applies within **certain Emission Control Areas**. Vessels built prior to 2000 under the 2008 Annex VI amendment are not currently subject to the emission laws and will be classified under Tier 1 requirements (DieselNet, n.d.). This highlights a **gap** where older ships are not impacted by the more stringent restrictions set forward by the IMO on January 1, 2011.

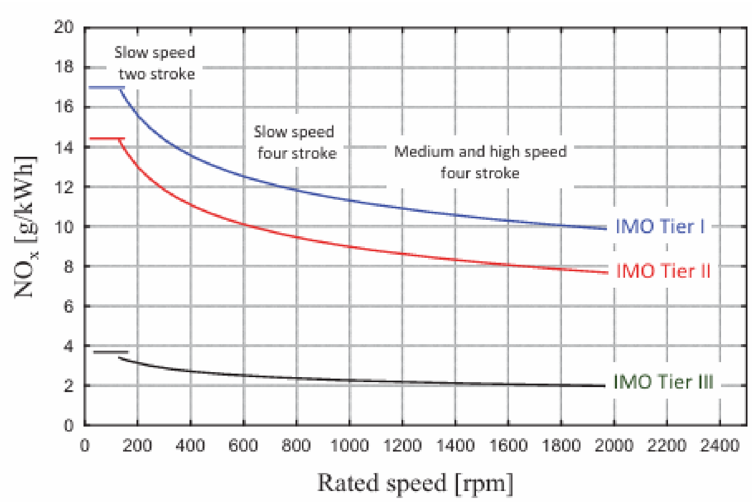

Figure 3. Nitrogen Oxides Emission Limits by International Maritime Organisation

<u>Introduction to Shore-to-Ship Power (S2SP) Systems</u>

This paper reflects the use of S2SP signifies that a substantial change in maritime operations with the objective of mitigating the environmental impact of vessels when they berth at ports. The implementation of these systems is filled with several obstacles that must be resolved to make them feasible on a worldwide level.

An important issue highlighted in the literature is the absence of **standardisation** in the electrical infrastructure among various ports and countries. Electrical grids will vary in voltage and frequency. Many countries in Europe, Asia and Africa operate at a frequency of 50 Hz, whilst others utilise a frequency of 60 Hz (Kraft, n.d.). In addition, ships have different voltage needs according on their classification, dimensions and the specific operating circumstances (Borkowski et al, 2012). The absence of standardisation in this gives rise to substantial compatibility challenges, resulting in a complex task that requires large modifications or specialised machinery.

Current trends indicate a growing adoption of standardized configurations and technologies that support the wider implementation of S2SP. Regulatory authorities, such as the IIMO and the EU, have progressively required the utilisation of shore power in specified Emission Control Areas (ECAs) to reduce emissions. EU regulations have established specific criteria and standards for the implementation of shore power systems as seen in Figure 4 (European Parliament, 2017).

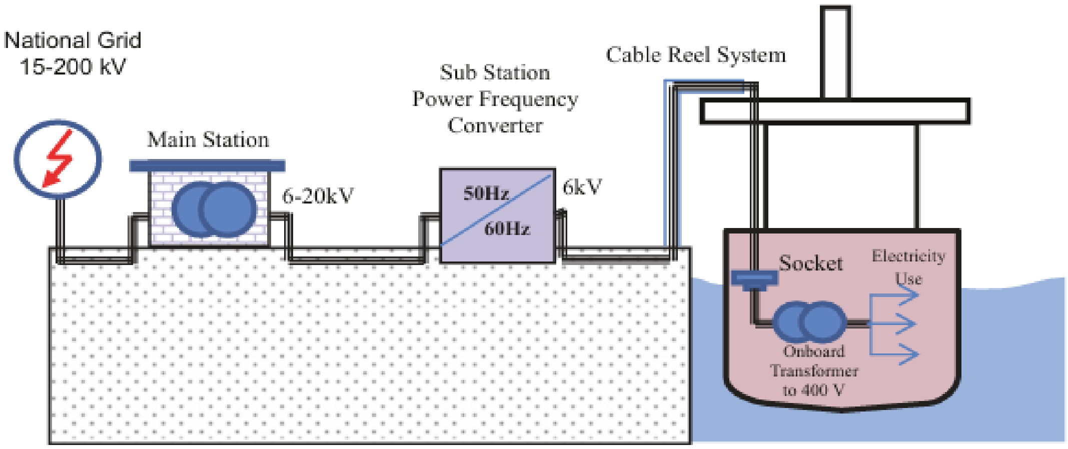

Figure 4. Vessel Electric Supply system configuration by European Union

<u>The impact on the natural environment while berthing</u>
This section explores the adverse environmental impact of vessels during berthing operations. It emphasises that even while stationary, vessels depend on onboard diesel generators to supply electricity for crucial operations such as powering reefer containers, leading to substantial environmental impacts. These generators emit huge amounts of pollutants, which add to air pollution, pose health risks to individuals living nearby (Saksa et al, 2022).

This study claims that switching to shore-based electricity for vessels, rather than their existing reliance on onboard diesel generators, is a practical and effective way to mitigate these negative environmental impacts.

<u>Relevance:</u>
The paper by Borkowski et al. (2012) on S2SP system as an alternative electric power supply in port is **highly relevant** in pointing out the advantages and disadvantages of this study. This literature review provides insights to the S2SP concept and addresses the environment impact that ships would have when berthing at ports in the container shipping industry.

The success factor pointed out a clear need for standardization of electrical infrastructure across different ports and countries. It also highlights the disadvantages such as a need for investment in S2SP infrastructure to support the diverse power needs of different ship types.

The paper **addresses two objectives** of this study: *<u>Advantages and Disadvantages of Shore-to-Ship Power (S2SP) Systems</u>* and *<u>evaluating environmental impact of S2SP systems</u>*. This research shows that S2SP is a viable and successful approach for reducing environmental impact, as proven by a real-world study on the Ro-Pax passenger ferry Skania. The results revealed a 140% reduction in operational expenses compared to the average fuel cost.

3. Methods
This study would use a two-research design: **Exploratory and case study approach**. This combination would evaluate how the S2SP system would impact the container shipping industry.

Exploratory Research
This would allow us to look at the study in a wider view to better understand the use of S2SP system and identify general concerns or trends within the data. Information would be obtained from various stakeholders such as Port authorities, Shipping research companies pertaining to the research questions in the objective of this study.

Case Study
To gain a more comprehensive understanding, case studies methods to examine specific cases of ports and shipping companies that have previously implemented S2SP. This will look at real-world examples to better understand how

these systems operate. The geographical location will be considered while selecting case studies. This helps in forming a holistic perspective and avoiding bias.

Limitations of Exploratory Research and Case Study

One disadvantage of exploratory research is the lack of clear conclusions and the possibility of bias due to the lack of preexisting knowledge. Since exploratory research focusses on topics that have not been previously investigated, the results may be more speculative and less precise. Similarly, case studies are susceptible to researcher bias since they focus on cases chosen by the author. This focus may lead to a bias towards outcomes that support the intended outcome, potentially overlooking other relevant variables.

4. Data Collection

For this study data collection will be from existing research and case studies, interviews, surveys and observations with stakeholders for primary data collection. Secondary data collection would be from government and shipping company publications.

Existing Research and Case studies

Primary data would derive from existing research and case studies showing the implementation of S2SP technologies on ships and ports. These cases serve as a supporting factor in the feasibility of using S2SP for vessels and ports worldwide. This approach aims to provide different strategies that were used during implementation. As mentioned above in the *literature review 2.1* electrical grids will vary in voltage and frequency across different countries.

Interviews, surveys and observations with stakeholders

Surveys and interviews will be conducted with stakeholders. These stakeholders would include port officials and representatives from shipping companies and industry experts. These stakeholders would give useful information about the real-world advantages and limitations of S2SP. The emphasis will be on how these solutions lower environmental impact. Stakeholders will also be questioned about their perception of retrofitting older vessels with S2SP or using alternative fuels which are widely available.

However, there will be limitations such as access to stakeholders. One mitigation would be to build connections early through professional networking events, industry events or academic contacts to establish rapport before requesting interviews.

Publications

Shipping companies that have implemented the S2SP system would publish annual and sustainability reports outlining their efforts to decrease their environmental footprint. These publications would aid in the data collection. Another useful data collection would be to use automatic identification system (AIS) tools such as Marine Traffic AIS. This allows us to determine how much time these vessels spend berthing for port operations.

4.1 Analysis

This study implements exploratory research which is supported by Cost-Benefit Analysis (CBA) and Comparative Analysis (CA) of case studies and publications regarding the application of S2SP. The operational and environmental benefits of S2SP will be analysed using CBA, while the retrofitting of older vessels will be addressed using CA. Although each method has its own set of limitations. For example, CBA may be difficult to implement due to its inability to consider all variables that could affect the outcomes (Stobierski, 2019). CA is restricted by the case studies objective, which only offers insights within a specific timeframe (Capital, 2024). The accuracy of the analysis can be influenced by the availability, quality and reliability of the data and requires a substantial time, effort and resources (RCM, 2023).

The objective is to gather a variety of perspectives that will facilitate a thorough analysis from experts who have conducted vessel research using S2SP. The foundation of this study will be from the data gathered from these interviews and cross-referenced research papers.

The primary objective of S2SP is to minimise emissions during berthing, which necessitates an extensive investigation of port emissions and the possible impact of S2SP. The evaluation of auxiliary generators is critical since they contribute significantly to emissions. Auxiliary power utilization, load factor, berthing time and fuel type are all important factors that should be taken into consideration.

Using CBA to determine the economic feasibility of S2SP. It investigates scenarios such as fluctuating fuel costs to provide a complete perspective of the financial implications, offering **actionable insights** and recommendations for ports and maritime companies seeking economic and environmental benefits.

CA is an important component of this study, which involves comparing the long-term financial impact of retrofitting older vessels to keeping traditional fuel-based systems or implementing S2SP in new vessels. Its goal is to explore the real-world advantages, obstacles and implementation experiences of S2SP in ports and maritime companies. The insights obtained will result in suggestions such as **maintaining current emissions or retrofitting older vessels**. This analysis contributes to the study's aims by providing practical insights, making the findings more relevant to ports and maritime companies.

5. Results and Discussion

This study investigates three key objectives for S2SP. First, it examines the **advantages and disadvantages of Shore-to-Ship Power (S2SP) Systems** for container vessels by substituting fuel-based auxiliary generators with S2SP based on the cost involved. Second, this study investigates the viability of **retrofitting older vessels with S2SP technology**, considering the technical and economic challenges as well as the significant emission reductions that such retrofitting provides.

5.1 Findings and Discussion for Advantages and Disadvantages of S2SP Systems

Before executing the CBA to implement the S2SP system for ports and shipping, an in-depth interview was conducted with port workers, industry experts and company A. The purpose was to better understand the challenges of implementing the system and to see whether any incentives may help offset the costs involved. This would examine the cost reductions from lower fuel usage and maintenance expenses from stakeholders who have implemented S2SP. The key findings and collective perspectives from these interviews are analyzed in **Appendix A**

5.1.1 Recognizing Shore-to-Ship Power (S2SP) Systems

The implementation of S2SP systems provides significant operational benefits, including reduced emissions and cost savings, yet is hindered by substantial upfront costs and limited infrastructure availability. Insights gathered through interviews with industry stakeholders indicate that while S2SP has the potential to revolutionize the maritime industry's sustainability practices, its widespread adoption necessitates coordinated efforts among regulatory authorities, port operators, and shipping companies.

5.1.2 Cost-Benefit Analysis

A detailed Cost-Benefit Analysis (CBA) reveals that the adoption of S2SP systems offers substantial cost reductions primarily through decreased fuel consumption and maintenance expenses. For example, a vessel that typically consumes 2 metric tonnes of Marine Gas Oil (MGO) per day while berthed could save approximately $140,000 annually by using shore power. Additionally, maintenance costs for auxiliary generators can be reduced by up to 20%, contributing an extra $10,000 in yearly savings per vessel. However, the limited availability of ports equipped with S2SP infrastructure—currently only 3% globally—poses a significant barrier to realizing these benefits universally. Table 1 displays declarations showing a trend towards S2SP infrastructure at ports.

Table 1. Declaration of Shore Power Targets

Ports with Carbon Neutral / Shore Power Ambitions or Targets			
Port	**Carbon Neutral**	**Shore Power**	**Area**
Shanghai Port	2060	-	China
Shenzhen Port	2060	-	China
Port of Singapore	2050	-	Singapore
Port of Rotterdam	2050	2028	Netherlands
Port of Amsterdam	2050*	2028	Netherlands
Port of Antwerp-Bruges	2050	2028	Belgium
Port of Hamburg	2040	2028	Germany
Port of Los Angeles	2050	2028	US, California
Port of Le HAROPA	-	2028	France
Port of Marseille	-	2028	France
Port of Dunkerque	-	2028	France
Aqaba Container Terminal	2040	-	Jordan

The cost data in this finding is mostly derived from two sources: Environ's cost-benefit analysis of onshore electricity (Environ, 2004) and the California Air Resources Board's analysis (CARB, 2007). Detailed data and assumptions on CBA are available in **Appendix B.**

5.1.3 Results

Return-On-Investment based on Fuel Savings

<u>A simple ROI payback formula is used to compute based on fuel savings</u>. It is important to note that this computation does not take into consideration a variety of other aspects, as data can differ dramatically between vessels based on their size, electrical power requirements and variations in energy and fuel costs. The calculation is computed as follows:

$$ROI\ Payback\ Period = \frac{Initial\ Investment}{Net\ Annual\ Savings}$$

$$ROI\ Payback\ Period = \frac{\$500{,}000}{\$140{,}000} = 3.57\ Years$$

This computation suggests that the investment in S2SP retrofitting for container vessels could be paid back in around **3.57 years** based only on fuel savings. Other observations from various studies performed for particular ports are suggests that shore power becomes economically attractive when bunker fuel costs rise.

For the cost for adopting S2SP was based only on vessel retrofit costs, disregarding port infrastructure. However, the cost would varies depending on the region, type and age of vessels. The summary of CBA would be an initial investment needed to convert a vessel for S2SP to be valued at around **$500,000**. As for electrical cost for a 6,000 TEU container vessel needed **1,307 kWh** at a price of **$0.15 per kWh** for 100 days at **$19,600.**

Annual savings as shown in Table 2 and similar case study on Port of Rotterdam mentioned in **Appendix D**, shipowners are mostly attributable to **reduced fuel usage** while at berthed, as well as **lower maintenance costs** owing to less reliance on auxiliary generators. Fuel savings are predicted at **$140,000** per vessel year, with an extra **$25,000** saved on port fees and maintenance saving on auxiliary engine at **$10,000** for a total adjusted annual savings of **$175,000.** The savings from reduced emissions are significant, but they cannot be expressed in monetary terms, making it difficult to attach a specific monetary value to emissions savings.

Table 2. Estimated Cost and Savings

Tangible Savings	
Port Fees	$ 25,000
Fuel	$ 140,000
Maintenance on Auxiliary Engine	$ 10,000
Total	**$ 175,000**
Intangible Savings	
Emissions	**Up to 90%**
Cost	
Retrofitting Cost	$ 500,000
Electricty Cost	$ 19,600
Maintenance on S2SP	$ 60,000
Total	**$ 579,600**

In conclusion, the Cost-Benefit Analysis (CBA) shows that the **primary benefits of S2SP** are overall emission reductions of **28% to 93%** with **short payback period based on fuel savings**.

However, the **disadvantages are the significant upfront costs** required by shipping companies at the start of S2SP implementation and the small number of ports that currently have shore power infrastructure.

5.2 Findings and Discussion for Retrofitting Older Vessels with S2SP Systems

The findings focus on the feasibility and financial costs associated with retrofitting older vessels with S2SP. A significant number of ageing vessels lacking modern emissions-reducing technologies. Data from prior retrofitting projects are used as benchmarks, offering significant insights into associated costs and serving as a reference point for future retrofitting initiatives. Figure 4 shows the cost involved.

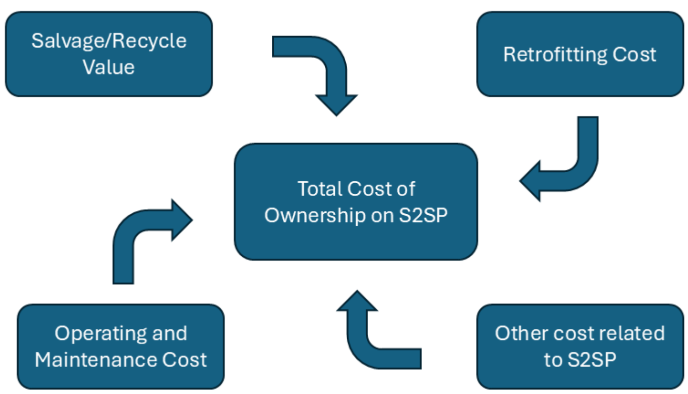

Figure 4. Total Cost on S2SP

Table 3. Upfront Cost Estimation

Total Upfront Cost Estimation

New build capex	**Small**	**Medium**	**Large**
Transformer capex (€)	78,050	114,478	203,889
Equipment lifespan (year)	10	10	10
Annualised costs (€/year)	9,623	14,114	25,138
Cable installation capex	2,740	2,740	2,740
Equipment lifespan (year)	25	25	25
Annualised costs (€/year)	175	175	175
Total Capex new build (€)	**80,790**	**117,218**	**206,629**
Annualised capex costs new build (€/year)	**9,798**	**14,289**	**25,313**
Capex per kW AE installed (€)	153	80	55
Retrofit capex (€)			
Transformer capex (€)	111,500	163,540	291,270
Equipment lifespan(year)	10	10	10
Annualised costs (€/year)	13,747	20,163	35,911
Cable installation capex (€)	3,906	3,906	3,906
Equipment lifespan (year)	12.5	12.5	12.5
Annualised costs (€/year)	403	403	403
Total Capex retrofit (€)	**115,406**	**167,446**	**295,176**
Annualised capex costs retrofit (€/year)	**14,150**	**20,566**	**36,314**
Capex per kW AE installed (€)	**218**	**114**	**78**

Table 3 shows the total upfront cost estimate for retrofitting older vessels and installing on newly built ships. The total cost of newly built ships is €80,790 for small vessels, €117,218 for medium vessels, and €206,629 for large vessels.

Retrofitting older ships has significantly higher costs. Retrofits cost €115,406 for small vessels, €167,446 for medium-sized vessels, and €295,176 for larger vessels. The yearly costs are significantly greater, ranging between €14,150 for small vessels and €36,314 for larger vessels.

This clarifies that retrofitting older vessels is more costly than installing S2SP in new vessels. Larger vessels would benefit from lower costs per kilowatt of electricity, leading to a higher ROI.

Total Cost

The total cost of implementing S2SP includes both retrofitting and operating costs. According to Directive 2005/33/EC, berthed vessels at EU ports is required to use marine fuels with a sulphur level not exceeding 0.1% from 2010 onwards (Damgaard, 2020).

Table 4. Total Life Cycle Cost

	Vessel		
New build capex	**Small**	**Medium**	**Large**
Transformer capex (€)	78,050	114,478	203,889
Equipment lifespan (year)	10	10	10
Annualised costs (€/year)	9,623	14,114	25,138
Cable installation capex (€)	2,740	2,740	2,740
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Capex per kW AE installed (€)	218	114	78
O&M costs			
O&M costs excluding tax (€/year)[15], low/high fuel price	**1,445 / -6,500**	**5,997 / -16,200**	**17,216 / -40,400**
Opex per MWh (€/MWh)	9.8	14.6	16.3
O&M costs including tax (€/year), low/high fuel price	**2,900 / -5,100**	**10,000 / -12,200**	**27,400 / -30,200**
Total annual costs - new build (€/year) (excluding tax)	**11,243 / 3,298**	**20,286 / -1,911**	**42,529 / -15,087**
Total annual costs - retrofit (€/year) (excluding tax)	**15,595 / 7,650**	**26,563 / 4,366**	**53,530 / -4,086**

The data in Table 4 shows that new builds are lower in both capital and operating costs than retrofitting older vessels. While **retrofitting has higher upfront and annualized costs**, the choice between retrofitting or new built will be affected by governmental policy, subsidies, vessel size, fuel price and operational challenges which will be touched on in Chapter 5, 6 and **Appendix C**.

5.3 Proposed Improvements

Retrofitting older vessels is certainly more expensive than installing S2SP systems in newly built vessels. Furthermore, the required infrastructure at ports for S2SP is not widely available. Emerging technologies such as the integration of renewable energy with S2SP systems and the use of digital twins to improve system efficiency has the potential for further adoption and optimization of S2SP solutions. The two recommendations are as follows:

5.3.1 Policy Shift to Mandate Shore Power Usage

The high upfront costs of retrofitting vessels and the limited availability of shore power infrastructure at ports are major obstacles to adopting S2SP. Implementing a **policy mandating** that vessels with **long berthing durations** utilize shore power. This would create a clear legal framework, encouraging shipping companies and ports to prioritize S2SP. It is important to note that this mandate could accelerate the adoption of S2SP, and it should be phased accordingly. This policy should allow for ports and maritime companies to invest and plan progressively to limit the supply chain disruption.

5.3.2 Partnership and Monetary Incentive

The high cost of retrofitting vessels is an important challenge, fueled with a shortage of shore power infrastructure. Establishing **Public-Private Partnerships (PPPs)** allows for the pooling of resources and promotes joint investments in shore power infrastructure. Government **Subsidies, Carbon Credits, Incentives, Tax breaks or reduced electricity prices** can significantly reduce the initial costs, making retrofitting older vessels more cost effective. Furthermore, reduced energy prices for vessels that use shore power creates a long-term economic incentive. Creating a structured carbon credit trading system where shipping companies earn credits for using S2SP that can be sold or offset against emissions-related costs. This approach not only reduces the financial burden on individual stakeholders but also speeds up the development of S2SP.

6. Conclusion

In conclusion, **using S2SP is recommended in container shipping despite the cost**. The results of Chapter 5 clearly show that **S2SP systems significantly reduce carbon emissions**. Real-world studies undertaken in the ports of Rotterdam, Guangzhou, Los Angeles and Long Beach support these findings. Furthermore, power supplier ABB's assessments suggest that **S2SP adoption in the container industry is both feasible and beneficial**.

6.1 Advantages and Disadvantages of S2SP

The findings concluded that S2SP had substantial advantages, particularly in terms of environmental benefits. Connecting shore power reduces NOx, SOx and PM emissions significantly. Additionally, companies can save significantly on fuel consumption and maintenance expenses since auxiliary generators are utilized less frequently when vessels are connected to shore power.

Despite its advantages, S2SP implementation brings multiple challenges. The high initial cost of retrofitting vessels. These costs include the installation of specialised electrical equipment such transformers and switchgear. The limited availability of S2SP infrastructure at ports, restricts its usage in ports.

6.2 Retrofitting Older Vessels with Shore-to-Ship Power (S2SP) Systems

Retrofitting costs for older vessels are high, owing to the complexity required in integrating modern electrical systems. The cost of implementing S2SP on newly built vessel are much lower. The cost of retrofitting vessel is between $300,000 to $2 million depending on its size and age. However, the long-term benefits such as lower fuel and maintenance costs make retrofitting a feasible choice.

Despite its cost retrofitting is doable. Previous retrofitting initiatives have been successful, providing a foundation for future deployments. The problem is to balance the cost against operational savings and environmental advantages which can be mitigated by government subsides.

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Appendix A:

Key Findings and Collective Perspectives from Interviews

A Feasible Implementation for Reduction in Emission

A shared observation from the interviews recognised the advantages of S2SP. The implementation of S2SP would result in a substantial reduction in carbon emissions for container vessels. Currently, smaller vessels such as electric tugboats and certain passenger liners are using S2SP. This strengthens the idea that S2SP may serve as a feasible alternative for container shipping to reduce emissions in port.

Unified Stakeholder Efforts for S2SP

The main concern is the collaboration between stakeholders for the needed to address the infrastructure, regulatory and financial challenges associated with S2SP adoption. There needs to be a joint initiative to establish clear standards, cost-sharing and incentives to promote S2SP adoption.

ROI Uncertainty

A common uncertainty revolves in the ROI when implementing S2SP as a huge upfront cost would be needed and there are not many studies that show favourable returns as compared to LNG fuels.

Infrastructure Gaps Limiting S2SP Adoption

The limited availability of existing port infrastructure capable of supporting S2SP continues to be an important obstacle to wider deployment. It recognised that just a few ports worldwide had the necessary infrastructure to provide S2SP. This gap restricts the practical benefits of S2SP for shipping companies, as vessels equipped with S2SP may only be able to utilize it in certain ports. Due to the lack of S2SP infrastructure, companies may be unwilling to take part in equipping vessels for shore power when only a few ports have the required infrastructure.

Appendix B:
Retrofitting Cost for Shore Power Integration

Existing vessels are required to be retrofitted with specialised electrical equipment such wire, connections, transformers and switchgear as shown in Figure 5. Many new vessels are currently being designed with S2SP system. Environ and the CARB estimate that the cost of retrofitting a vessel for shore power is between **$500,000 and $2 million**. Another study done by Dagkinis estimated retrofitting costs for vessels range from $300,000 to $2 million. More examples such as infrastructure cost

Figure 5. Shore Power Overview

Infrastructure Cost

Expenditures on infrastructure and retrofitting for the implementation of S2SP requires considerable investment in both port and vessel infrastructure (Bakar, 2023). Implementing S2SP at ports incurs costs **ranging from up to $300,000**. This cost will vary on the infrastructure and complexity of linking the port electrical grid with S2SP (Zhou et al, 2023). As indicated in Table 5, Sweden experts assessed the S2SP installation costs for the Port of Rotterdam in 2008.

Table 5. Estimated Cost of S2SP Installation in Port of Rotterdam

Installation Cost for Port	**Cost ($)**
Electrical Connection to local grid	7,000,000
Sub-Power Station Construction	1,500,000
Main Power Station Construction	2,000,000
Convertor (Frequency)	2,500,000
Power Cables	2,000,000
Power Outlets	3,000,000
Transformers	3,000,000
Electrical Tubes	5,000,000
Project Cost	2,500,000
Total	**28,500,000**

Operations and Maintenance Costs

In addition to the retrofitting, ports and vessels face yearly operational and maintenance expenses to maintain S2SP infrastructure. This could amount to up to 12% of the overall capital investment annually (Wang et al, 2021). In this study we will use a **$500,000 retrofitting cost** with 12% on Operations and Maintenance which amounts to **$60,000**.

Electricity Costs During Berthing

Electricity costs account for a part of S2SP operating expenses. Since auxiliary generators are shut off when ships connect to shore power (Environ, 2004). Electricity costs vary by region, this study will take average cost ranging between \$0.10 and \$0.20 per kWh which is **\$0.15 per kWh** based on Environ findings.

Formula: $Average\ cost = \frac{Cost\ A + Cost\ B}{2}$

Bigger container vessel with daily power requirements similar to 1.5-3 metric tonnes of fuel (Zis & Psaraftis, 2017). This cost emphasizes the need of a reliable and affordable power supply to keep S2SP commercially viable for ports and shipping companies. As noted in Chapter 1, the average time container vessels stay in port ranges between 0.7 to 1 day or 16 to 24 hours.

International Council on Clean Transportation released the data for this study, which was carried out in partnership with the Shenzhen Human Settlements and Environmental Committee and the Port of Oakland (Wang et al, 2015). The estimations of auxiliary generators power depending on vessel as shown in Table 6.

Table 6. Estimation of Auxiliary Generators Power

Ship size (TEU)	Auxiliary engine (kW)	Boilers (kW)
0-1,000	300	136
1,000-2,000	388	232
2,000-3,000	650	232
3,000-4,000	913	313
4,000-5,000	643	393
5,000-6,000	1,307	534
6,000-7,000	1,307	393
7,000-8,000	1,320	586
8,000-9,000	1,488	586

Fuel Costs During Berthing

Using shore power instead of auxiliary generators allows vessels to save a significant amount on fuel. As shown in Figure 6, Singapore has an average MGO price of \$600 to \$700 per metric tonne. In this study we would use the last known MGO fuel price of **\$700 per tonne**. Assuming a vessel that uses around 2 metric tonnes of MGO per day estimated to save **\$1,400 per day using S2SP**. For vessel that berthed an average of 100 days per year (Zhou et al, 2023), this equates to **\$140,000 in yearly fuel savings per vessel.**

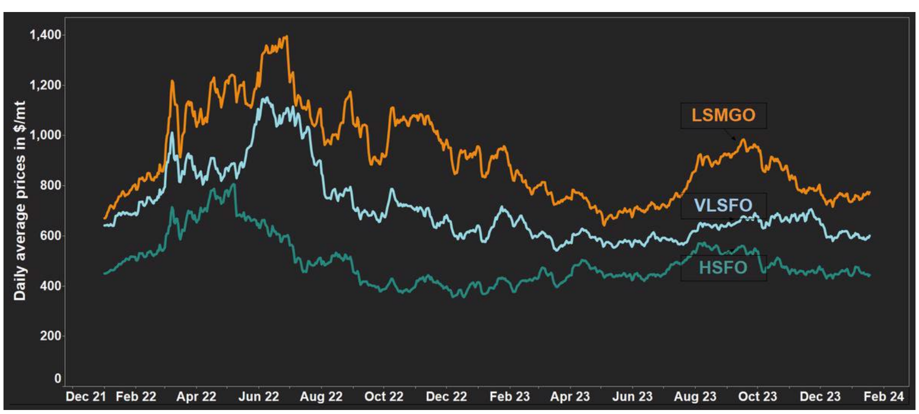

Figure 6. Average MGO Prices in Singapore 2024

Benefits

Environmental and Compliance Benefits

S2SP has the potential to reduce emissions by **28% to 93%** (Wang et al, 2024) which threatens both human health and the environment (Zis & Psaraftis, 2017). Compliance benefit could result in cash incentives or reduction of fees. For example, incentives imposed by the MPA's Green Ship Programme (GSP) offers 50% reduction on the Initial Registration Fees (IRF) is to reward ship owners that voluntarily implement solutions that allow vessels to exceed the IMO's environmental regulatory criteria by 10% or more (Safety4sea, 2022). The 50% savings on the IRF can provide up to $25,000, as illustrated in Table 7.

Table 7. MPA Initial Registration Fees

Initial Registration Fees	$2.50 per NT subject to a min - $1,250 (500 NT) max - $50,000 (20,000 NT)

Maintenance Cost Reduction on Auxiliary Generators (AG)
S2SP reduces fuel and the demands on auxiliary generators, resulting in lower maintenance costs. Auxiliary generators require frequent maintenance, which usually costs approximately **$50,000 per year**. S2SP reduces dependency on auxiliary generators potentially saving up to 20% on maintenance expenditures, this amounts to an **extra $10,000 in yearly savings per vessel** (Dagkinis & Nikitakos, 2015)**.**

Appendix C:

Container vessels would maintain their auxiliary generators even while using shore-side power when at berth. Auxiliary generators are required for electricity at sea and as a backup if shore power fails or is unavailable at certain ports. Thus, auxiliary generators' cost is not included in the calculations as there are no savings or additional costs involved. The estimated costs are shown in Table 8, 9 and 10.

Table 8. Estimated Cost of Transformer

Equipment Type	Estimation
Onboard transformer (0.5-4 MW):	€40,000 – 106,400;[9]
Installation cost, new build:	75% of equipment cost;[10]
Retrofitting installation:	150% of equipment cost;
Transformer lifetime:	10 years in a marine environment;
Unsheltered transformer:	10% equipment cost premium;
Unsheltered transformer lifetime:	10 years in a marine environment;
Multiple supply voltage transformer	50% equipment cost premium;
Multiple supply voltage transformer lifetime:	10 years in a marine environment.

Table 9. Transformer Cost on Newly Build Vessels

New build ships	Small	Medium	Large
Onboard transformer (€)	40,000	59,200	106,400
Unsheltered onboard transformer (€)	44,000	65,120	117,040
Multi-voltage transformers (€)	60,000	88,800	159,600
Fraction of ships without shelter room for transformer (%)	40%	30%	20%
Fraction of ships needing a multi-voltage transformer	5%	5%	5%
Weighted average transformer cost (€)	44,600	65,416	116,508
Construction, installation and engineering costs (% of equipment)	75%	75%	75%
Transformer equipment and installation costs (€)	78,050	114,478	203,889
Annualised costs (€/year)	**9,623**	**14,114**	**25,138**

Table 10. Transformer Cost on Retrofitting Vessels

Retrofitting	Small	Medium	Large
Weighted average transformer cost (€)	44,600	65,416	116,508
Construction, installation and engineering costs (% of equipment)	150%	150%	150%
Transformer equipment and installation costs (€)	111,500	163,540	291,270
Annualised costs (€/year)	**13,747**	**20,163**	**35,911**

Connecting Electrical Supply

The cost of connecting the ship to the electrical supply is determined by the feasible configuration and the distance required to attach the cables. The projected costs for cables and installation distances are shown below in Table 11.

Table 11. Estimated Cost for Connecting Ships to the Electrical Distribution System

	New ships all AE sizes	Retrofitting all AE sizes
Low voltage cable (400V) (€/m)	12.5	12.5
Average distance from transformer to distribution system (m)	125	125
Construction, installation and engineering costs (% of equipment costs)	75%	150%
Total cable installation cost (€)	2,740	3,900
Lifespan (years)	25	12.5
Annualised costs (€/year)	**175**	**403**

Fuel Cost

The primary operational cost for AG is fuel. Although fuel and electrical prices vary across the EU and globally, this study references Jiven's 2004 analysis. To preserve consistency in LCCA, this study will stick to the 2004 cost structure for both fuel and electrical prices. The current MGO price in the Port of Rotterdam for 0.1% low-sulphur fuel is **€662 per tonne** as shown in Table 12 as of January 2025. This rise is likely due to inflation throughout the years. Examples of fuel usage and cost are displayed in Figure 7.

Figure 7. Current MGO Prices across the world

Table 12. Estimated Annual Fuel Usage of Ships at Berth (tons/year per ship)

	Small	Medium	Large
Fuel Saved per ship (t/year/ship)	32	89	230
Cost per tonne 0.1% MD (€/tonne), low / high fuel price	249 / 500	249 / 500	249 / 500
Fuel costs saved (€/year/ship), low / high fuel price	8,000 / 16,000	22,300 / 44,500	57,400 / 115,000
Fuel Saved per berth (t/year/berth) (70% berth utilisation)	282	781	2,013

Appendix D:
Case Study on Port of Rotterdam

A similar CBA study on the Port of Rotterdam co-funded by EU found a Benefit-Cost Ratio (BCR) of 1.23 and a positive net present value. This means that the economic benefits are greater than the costs without taking into consideration of upfront and maintenance costs (Table 13).

Table 13. SCBA results of Stolt Breland shore power 2024

	Present value 000s Euro
Ship Benefits	295
Emission Benefits	2,167
Project Investment Costs	(1,868)
Project O&M Costs	(382)
Net Present Value (NPV)	**453**
Benefit Cost Ratio (BCR)	**1.23**

The CBA for the Port of Rotterdam assesses the environmental consequences of building and operating a S2SP. These effects could include both positive and negative as shown in Table 14. The building phase is predicted to have short-term environmental impact. However, these effects can be minimized by using electric or hydrogen-powered equipment. Once operational, the S2SP is expected to provide considerable environmental advantages, such as improved water and air quality, decreased noise and odors, and lower nitrogen deposition in vulnerable natural regions within a 25-kilometer radius. Furthermore, it will help to reduce CO2, PM10 and SOx emissions. Therefore, improving the ecological balance in the surrounding regions.

Table 14. Findings of preliminary environmental impact assessment (PEIA)

	Impact during construction	**Impact during operation**
Water quality	Limited negative impact, but possible to mitigate with electric or hydrogen fuel propelled equipment.	Substantial positive impact
Air quality	Limited negative impact, but possible to mitigate with electric or hydrogen fuel propelled equipment.	Substantial positive impact
Noise	Limited negative impact, but possible to mitigate with electric or hydrogen fuel propelled equipment.	Substantial positive impact
Odour	Limited negative impact, but possible to mitigate with electric or hydrogen fuel propelled equipment.	Substantial positive impact
Flora and fauna	Possible limited negative impact due to habitat disturbance of local flora and fauna, possible to mitigate with appropriate measures. The deposition of nitrogen in N2000 areas during construction is expected to be limited.	- (Limited) negative impact due to occupation of the land surface and the riverbed. - Positive impact due to a decrease in nitrogen deposition in N2000 areas.

Biographies

Javier Gan Kuan Qi is a student in the Supply Chain Management programme with a minor in Analytics at the School of Business, Singapore University of Social Sciences (SUSS), Singapore. With a strong foundation in logistics and operations, Javier has honed his expertise through internships and professional experiences at organizations such CMA CGM and Tee Hai Chem (Brenntag Group). His roles have included spearheading automation projects, communications, optimizing administrative workflows, and coordinating operations to achieve greater efficiency. Javier's accomplishments include achieving 1st Runner-Up in the Maritime One Case Challenge and participating in the Impact Start-Up Challenge in Vietnam. His contributions reflect a passion for innovation and sustainability, further demonstrated by his involvement in environmental conservation initiatives like WildsMarines.

Peter Sundara Swamickannu is an Associate in the Supply Chain and Logistics programme at the School of Business, Singapore University of Social Sciences (SUSS), Singapore. With 27 years of experience in container shipping and logistics, he has held key roles at leading companies, including P&O Nedlloyd, Maersk Line, Agility Logistics, Flexport, Scan Global Logistics and LF Logistics. His expertise spans operations, trade management, and global business system projects, with professional stints in Australia, Taiwan, Hong Kong, the UK, and Vietnam. Passionate about technology and digitalisation, Peter Sundara brings a future-focused perspective to ocean freight and supply chain management.