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An Overview on Zero-Emission Tugs (or Ships) in the Market

presented by

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Zero-emission vessels are among the promising solutions that might respond to the pressing demand of the global maritime industry to decrease greenhouse gas (GHG) emissions, thereby reducing the environmental deterioration caused by shipping.

Therefore, this study aims to give an overview of the current market situation of zero-emission tugs and ships. To achieve that, this study reviews the recent developments in zero-emission propulsion systems, focusing on hydrogen propulsion systems, battery-electric systems, and hybrid-based technologies. It also covers the regulatory frameworks and incentives that shape the adoption of zero-emission vessels, as well as the economic impact of zero-emission technologies on ports and shipping companies; hence, it gives reasons for challenges and opportunities on the pathway to a sustainable future for the maritime sector.

Furthermore, performances in real conditions are presented with case studies of some operating zero-emission tugs and ships in the market. Operational challenges faced by tugs and ships, like technical difficulties, high initial investments or operational costs, and infrastructure requirements are also touched upon in such a way as to try to underscore the economic feasibility of the transition towards zero-emission shipping solutions.

The present research study puts it in a nutshell that zero-emission tugs and ships are gaining greater importance in the maritime industry and emphasizes their role in achieving a sustainable and environmentally responsible future for global shipping.

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1 Introduction

1.1 Background

The maritime industry is among the backbones of trades and commerce in the world, transporting about 90% of goods in the world. It belongs to the most relevant sources of discharge of greenhouse gases in the atmosphere, caused mainly by the combustion of fossil fuels (Capasso et al., 2018). These emissions have a huge environmental impact in terms of warming and air pollution. Most common Greenhouse gas (GHG) emissions include CO2 from different sources, which, by performing a critical role in global warming, affects society and the environment. This has brought extreme weather conditions, rising sea levels and extinction of animal species (Doornebos et al., 2023). GHGs from the maritime sector are expected to rise substantially by 2050 (Brown and Aldridge, 2019). Having noticed this fact, ambitious goals for the reduction of emissions were set by international regulatory bodies like the IMO, and developed abilities for deployment in low- and zero-emission technologies in the shipping sector (Paul, 2020), (Kim et al., 2022).

Environmental concerns and strict regulations have been instrumental in compelling the sector toward transformation on an enormous scale. The earliest round of mandatory international measures aimed at enhancing ships' energy efficiency, were adopted by IMO on 15 July 2011 (International Maritime Organization, 2024). Thereafter, IMO acted to adopt further regulatory measures subsequent to 2011, adopt the initial IMO GHG strategy in 2018, and revise the strategy on reduction of GHG emissions from ships in 2023 (International Maritime Organization, 2024). A major development is the IMO revised GHG strategy, which has ambitious targets in terms of emission reduction. Under it, it has said, by 2050, net-zero from shipping would be achieved; with intermediate targets of 20-30% reduction by 2030 and a 70-80% cut by 2040. These goals cover the entire lifecycle of GHG emissions—from production to combustion—indicating very holistic thinking toward decarbonization (IMO, 2023), (Jegou et al., 2023).

Zero-emission tugs and ships are guaranteed in this scenario to transform the maritime scene and support the new era of sustainable transportation onto the high seas (Kim et al., 2023). These, powered by emerging alternative fuels in the main, hydrogen, biofuels, and advanced technology solutions such as full electric, hybrid power systems capable of transforming marine transportation, literally represent a technology that needs urgent deployment in order to meet ambitious targets laid down by the IMO for truly sustainable shipping operations globally (IMO, 2023), (Jegou et al., 2023). So far, all transition solutions available have very little time to become commercially viable (Forum, 2024). (Ünlübayir et al., 2024) emphasizes that there is currently no emission-free propulsion solution using advanced battery technology that would serve completely emission-free shipping.

Regardless, new propulsion systems are being developed to deliver strong emission reductions by minimizing or completely avoiding local greenhouse gas emissions (Ünlübayir et al., 2024).In fact, several alternatives have been developed for research and commercial application to extend the range of low-carbon emission SPS: namely, battery-electric, hybrid-electric systems powered by renewable energy sources, and FC-powered electric vessels (Anwar et al., 2024). Recently, GreenPlug, an innovative renewable energy technology company based in Hamburg, Germany, has planned on developing an hydrogen-powered pusher boat with the capability to propel 2,400 tons at a speed of 10 knots as part of its H2 Schubboot project (Hydrogen Hamburg, 2024).

Further, there is also interest in operational measures that may provide better energy efficiency or optimization of shipping routes. Just-in-time practices for arrival, for example, will doubtless save immense quantities of fuel and reduce emissions by cutting idle time at harbors (IMO, 2023).

Governments, international organizations, and private sector entities—some of the societal players—finance and support the processes of sustainable transition in the global maritime industry. This sends a very strong signal at a high policy level for a commitment of sea actors to reducing emissions from ships with projects for zero-emission fuels, such as through the Getting to Zero Coalition (Jegou et al., 2023).

Although emission-reduction technologies are increasingly available, particularly in the area of tugboats and other marine vessels, zero-emission solutions show very little uptake. Some major barriers are likely the high sunk costs associated with new technologies, an overall lack of infrastructure for alternative fuels, and uncertainty as to whether the operational efficiency benefits from zero-emission vessels will truly be realized. For example, hydrogen production cost by high-temperature electrolysis is also extremely dependent on the price of electricity (Thorson et al., 2022). Finally, while the regulatory regime is increasingly stringent, it still fails to create a clear set of incentives or to offer binding commitments with regard to the absolute transition to zero-excess technology.

The process toward addressing these challenges is far from being lost. For example, the First Movers Coalition is working on scaling up the zero-emission fuel supply, despite the fact that more than 95% of maritime fuel projects are still yet to reach the final critical investment phase. This slow progress underlines that much more by way of policy interventions and global cooperation needs to be effectively harnessed if there is to be any chance for expediting the process of adopting sustainable technologies for the maritime industry as a whole (Furusaki and Asmussen, 2024), (Lu et al., 2023), (Laffineur et al., 2023). Also marine areas, such as the Emission Control Areas (ECAs), apply strict measures by putting in place rules that reduce the airborne emission by ships. Overall, the Emission Control Areas set tighter limits on such pollutants as sulfur oxides, nitrogen oxides, and particulate matter in specific maritime zones (Sustainable Ships, 2024a). Furthermore (Zero-Emission Shipping Mission, 2022) defines green corridors as shipping routes between two or many ports where the demonstration and support of solutions of zero-emission shipping are facilitated through accelerated decarbonization efforts in overcoming technology, economic, and regulatory challenges by means of public-private collaboration.

This paper aims to fill the knowledge gap in the existing landscape of zero-emission tugboats and ships by providing an overview of available technologies and their adoption rate, along with related issues that must be considered for industry stakeholders. It aims to understand the main barriers to the wide diffusion of zero-emission vessels, with a close look at opportunities for innovation and policy intervention that may act as levers of change in this area toward an entirely sustainable maritime industry.

1.2 Focus of the Study and Addressed Key Questions

This study attempts to give the correct view of zero-emission tugs and ships available in the market with an analysis of the different technologies driving such vessels, including battery-electric propulsion, hydrogen fuel cells, and other emerging alternatives. The analysis of technological developments and operational performance is done with the purpose of investigating the adoption of zero-emission vessels across different regions and sectors within the maritime industry.

The findings will review barriers and challenges that, from a technical, economic, and regulatory standpoint, prevent the mass introduction of zero-emission technologies. It is very important to perceive those obstacles in order to define opportunities for innovation and policy interventions that will enhance the transition to zero-emission vessels. The study also aims to provide, through strategic recommendations to the industry's stakeholders and policy makers, additional support for wider diffusion of zero-emission tugs and ships, contributing to broader efforts at the reduction of environmental impacts from the maritime industry.

To achieve these objectives, the study seeks to answer several key questions:

- What are the current technologies driving zero-emission tugs and ships?
- What are the main barriers to the adoption of zero-emission vessels? These include technological, operational, and regulatory challenges.

- What strategic recommendations might be made to industry stakeholders and policy makers in order to expedite the transition to zero-emission vessels within the maritime sector?

2 Literature Review

In this section, the development of ship propulsion technologies and the current status of zero-emission solutions in the market are explored. This section also examines international and national regulations driving the adoption of zero-emission vessels, such as IMO regulations and national clean energy initiatives.

2.1 Evolution of maritime propulsion technologies

In the maritime world, propulsion has been subjected to a radical change according to the different eras. The early maritime propulsion methods included human-powered oars followed by wind-powered sails (Chang, 2012). The Egyptians and the Phoenicians used oars to propel their vessels while various other types of populated sailors began to utilize the wind with primitive sails that allowed them to travel across water with greater efficiency. Wind power would remain a dominant force in maritime propulsion for many centuries. The sails turned into designs where larger ships, inclusive of galleons and frigates that had been fitted with multiple masts and sails, enabling the technology to achieve longdistance exploration and trade during the ages of discovery (Tunis, 1952).

By the early 19th century, steam power came of age, and so did the first significant turning point in maritime propulsion. Steam engines started substituting the sails in many vessels, providing a reliable and controllable source of power. Steamships revolutionized both transoceanic travel and trade by greatly reducing the length of voyages and increasing cargo capacity (Tunis, 1952). The first vessel powered by batteries was the Russian tanker MV Vandal, which was launched in 1903 (Jeong et al., 2022).

In the mid-19th century, the screw propeller was developed as an alternative to paddlewheels, greatly improving propulsion efficiency. Ships equipped with screw propellers could navigate more easily and with less vulnerability to damage. This technology became the standard for maritime propulsion (Larrabee, 1980). The moderately efficient steam engine was in wide use at this point. But then, during the latter part of the 19th and early 20th centuries, work began on the internal combustion engines that ran on diesel, gasoline, and other types of fuel. Compared to the steam engine, these were far more efficient and flexible. They thus soon found applications on everything from small boats up to the largest cargo vessels (Stone, 1999).

Starting in the mid-20th century, the invention of nuclear propulsion systems introduced a new era in maritime technology. The work originally began in the context of nuclear propulsion on submarines and aircraft carriers. Such nuclear-powered submarines and aircraft carriers enjoyed advantages in extended operational ranges and capability to stay submerged for extended spans of times- labyrinths (Paul, 2020). However, the technology was confined to military and some research vessels. The first-ever nuclear-powered submarine commissioned was the USS Nautilus in 1954. A wide application of power electronic devices was carried out in naval vessels during the latter half of the 20th century. The RMS Queen Elizabeth 2 started its service in 1987 as the first ever to introduce an integrated diesel-electric propulsion system (Paul, 2020). The 21st century has therefore placed greater emphasis on the development of hybrid and alternative propulsion systems as ways of reducing environmental impact, such as electric drives and hydrogen fuel cell technology.

2.2 Current Zero-Emission Technologies in the Maritime Industry

Hydrogen fuel cells, battery-electric propulsion systems, and hybrid systems are some of the most discussed zero-emission technologies in the maritime sector. Recently, a great interest has been focused on battery-electric propulsion systems as a clean and efficient alternative method of propulsion besides conventional internal combustion engines (Programme, 2023), (of the European Union, 2022). Hydrogen fuel cells represent another very promising technology in order to achieve zero-emission marine transportation (of the European Union, 2022). Hydrogen fuel cells may play an important part in shipping decarbonization (Bach et al., 2020). In this respect, one of the ways to make such a significant elimination of greenhouse gases emissions from ships is the use of the hybrid propulsion system related to fuel cells in combination with batteries (Ünlübayir et al., 2024).

Other alternatives include ammonia propulsion, wind-assisted propulsion, biofuels, and solar power. One of the most manufactured chemicals in the world is ammonia (Xing et al., 2021). Similar to fuel cells, ammonia offers longer endurance than batteries. Indeed, according to (Julian Atchison, 2023), Pherousa - an independent technology developer from Norway - has just presented a validated propulsion system making use of the ammonia cracking for application to ocean-going vessels. Among these, wind-assisted propulsion technologies, mainly in the form of wind sails and rotor sails, can help assist vessels by using the wind as their propelling power.

Biofuels such as biodiesel, methanol, GLEAMS glycerine fuel, and algal biofuels are also considered a more sustainable alternative to traditional fossil fuels. When used in conjunction with advanced engine technology, biofuels can reduce greenhouse gas emissions and air pollutants (Bioenergy, 2023). Since most biofuels can be run in a wide selection of existing engines, their transition would also be largely seamless; hence they are also viable options for tugs and ships which are considering ecological concerns. As an example, a joint venture between Qatar and Royal Dutch Shell was undertaken to develop LNG for the express purpose of providing the largest container shipping company in the world with a marine fuel.

In the not-so-distant past, Lloyd's Register led a two-year project on the evaluation of biodiesel use as a marine engine fuel. Onboard the container ship Maesk Line, Maesk Kalmar is where the feasibility study was conducted. Collaboration included other institutions such as Maersk Line, Maesk Tankers, Maersk supply service, Maersk drilling, Maesk ship management, strategic research Lloyd's Register, and a consortium of Dutch subcontractors (Bioenergy, 2023). The principle of solar-assisted propulsion can be highly effective in tugs and smaller vessels operating in sunny regions. For instance, EMP is a Fukuoka Japan-based revolutionary marine renewable energy technology company that has developed an advanced integrated maritime solar power package. The integrated package comprises of a marine computer, battery chargers, ocean-going class solar panels, batteries and interfaces allowing it to be connected to other equipment and sensors across vessels (Institute, 2023).

Zero-emission technologies are among the fastest-evolving and most relevant technologies currently being taken up by the maritime industry in its effort to decrease environmental footprint. Each technology, as earlier mentioned, has several advantages and challenges, and their applicability may change with the specific operational needs or geographical conditions of a vessel. As the legislation gets stronger and awareness is raised with the involvement of people on environmental concerns, zero-emission technologies in tugs and ships are likely to see wider applications. The different technologies discussed herein could provide the pathway to a greener and cleaner maritime sector.

3 Methodology

3.1 Research Design

A qualitative research design was applied in this study to capture the nuances of zero-emission technologies in vessels. This review provides a comparison of technological advancement, operational challenges, and regulatory impacts arising from selected case studies. This study further identifies commonalities and differences based on recurring themes and significant findings from literature and case studies. For example, generally high costs and technical limitations have been highlighted in several case studies. Finally, it offers an comprehensive understanding that allows detailed insight into challenges and opportunities related to zero-emission vessels, based on integrated insight from the literature and case study findings.

3.2 Data Collection

This analysis uses a combination of primary and secondary data collection methods, specifically, literature review and case studies to gather and analyze data on zero-emission tugs and ships. These methods will provide a comprehensive understanding of the current state of zero-emission technologies, their market adoption, and the challenges and opportunities associated with them.

3.2.1 Literature Review

The literature review involved analyzing sources from academic journals, industry reports, and policy documents related to zero-emission vessels. By doing so, relevant information on zero-emission technologies, market trends, and regulatory frameworks were extracted. The goal was to gather broad insights into technological advancements, operational challenges, and regulatory impacts based on published studies and industry reports. Table 3.1 summarizes the key sources used and Table 3.2 shows the process followed for the literature review.

Type	Source	Description
Academic Journals	• Ocean sustainability • Journal of marine science and engineering • Journal of Cleaner Production, etc.	• Provide articles and write-ups about sustainability and clean technologies in addition to covering the latest developments in zero-emission technologies. • Provide technical insights into maritime technology that will enable zero-emission propulsion systems.
Industry Reports	• International Maritime Organization (IMO) • DNV • Lloyd's Register	• Publish findings on the latest trends both in maritime technologies and in the adoption of zero-emission technologies • Research with a view on maritime safety, new technologies, and zero-emission vessels.
Policy Documents	• IMO Regulations • European Union Maritime Strategy • National Policies	• Include international standards and guidelines allowing for emission reductions within the maritime sector • Detail EU policies aimed at reducing maritime Emission and the Code of Good Practice for Sustainable Shipping,- country-specific regulation, and incentives to adopt zero-emission maritime technologies.

Table 3.1.: Summary of Sources for Literature Review

Step	Description
Search Strategy	• **Databases:** Scopus, IEEE Xplore, ScienceDirect, JSTOR, etc • **Keywords:** "zero-emission tugs and ships," "hydrogen fuel cells," "battery-electric propulsion," "hybrid propulsion systems," "sustainable shipping" • **Filters:** Limited to publications from the last 5-15 years for relevance
Selection Criteria	• **Relevance:** Focus on sources discussing zero-emission technologies, market trends, and regulatory frameworks • **Quality:** Prioritize peer-reviewed journals and authoritative industry reports • **Breadth:** Include sources on technological innovations, market trends, and regulatory impacts
Data Extraction	• **Technological Insights:** Document technologies such as battery-electric systems and hydrogen fuel cells • **Market Trends:** Record adoption rates and regional differences • **Regulatory Framework:** Summarize relevant policies and regulations
Synthesis	• **Organize Findings:** Group information by themes like technological advancements, market trends, and regulatory impacts • **Identify Patterns:** Highlight recurring themes and significant findings • **Highlight Gaps:** Note areas needing further research and propose future study directions

Table 3.2.: Summary of the Literature Review Process. Based on (Brereton et al., 2007) and (Mazo et al., 2014)

3.2.2 Case Studies

Case studies provide specific deep insights into the existing, practical applications of zero-emission technologies in maritime industry. By examining specific examples, this approach aims to illustrate the practical implementation, performance, and challenges associated with these technologies. Selection of case studies was ensured based on the relevance of the technology applied, the level of innovation involved, geographical diversity, and quality of detailed performance data available.

Selection Criteria

Target selection was based on the following criteria in order to make the case studies as valuable and representative as possible:

- Technological Innovation: Vessels with unprecedented technological developments or novel applications of zero-emission technologies.
- Operational Relevance: Vessels with detailed data on performance, efficiency, and operational challenges.
- Geographic diversity: Inclusion of vessels from different regions to provide a broader perspective on global advancements.

3.3 Case Studies of Zero-Emission Vessels

Case Study	Vessel Name	Current State	Country	Technology	Literature/Source
1	Dynamo and Dynamo II	Operating since 2024	Canada	Battery-electric propulsion systems	(SAAM Towage, 2024)
2	Energy Observer	Operating since 2017	France	Hydrogen fuel cells, solar panels, wind turbines, battery storage	(Energy Observer, 2024)
3	H2 Pusher Tug (H2SB)	Under development	Germany	Hydrogen fuel cells	(Hydrogen Hamburg, 2024)
4	ELEKTRA	Operating since 2021	Germany	Hybrid propulsion systems	(EST Floattech, 2024)
4	MF Ampere	Operating since 2015	Norway	Battery-electric propulsion systems	(Corvus Energy, 2024b)
6	Yara Birkeland	Operating since 2022	Norway	Battery-electric propulsion systems	(Yara International, 2024a)
7	MF Hydra	Operating since 2023	Norway	Liquid hydrogen	(Norled, 2024)
8	Condor H2	Under development	The Netherlands	Hydrogen fuel cells	(The Port of Rotterdam, 2024)
9	E-Pusher type M	Operating since 2022	The Netherlands	Battery-electric propulsion systems	(KOTUG, 2024)
10	Sea Change	Operating since 2024	United States	Hydrogen fuel cells	(Switch Maritime, 2024)

Table 3.3.: Selected Case Studies of Zero-Emission Vessels

4 Analysis and Findings

4.1 Emerging Technologies

Zero-emission technologies for maritime vessels have seen significant advancements in recent years. These advancements primarily include battery-electric propulsion systems, hydrogen fuel cells, and hybrid systems combining multiple technologies. This section throughly discusses these technologies, highlighting recent developments, and illustrates their application through selected case studies.

4.1.1 Hydrogen Fuel Cells

1. H2 Pusher Tug (H2SB)
2. MF Hydra
3. Condor H2
4. Sea Change

H2 Pusher Tug (H2SB), MF Hydra, Condor H2 and Sea Change are among the most prominent hydrogen powered tugs and ships trying to make a change in the maritime sector and foster the development of new green maritime solutions. Although the H2 Pusher Tug (H2SB) is still under development, the company GreenPlug's CEO Dr. Agnus Cassens has already expressed some optimism about the possibility to give a boost to the market in terms of infrastructure for inland waterway vessels, with a particular focus on those using hydrogen and fuel cell technology (Hydrogen Hamburg, 2024). The H2 Pusher Tug (H2SB) will have the ability to move 2,400 tons at 10 knots (Hydrogen Hamburg, 2024).

On the other hand, MF Hydra is already making an impact as a significant advancement in reducing greenhouse gas emissions after being put into operation in March 2023 (Ballard Power Systems, 2024). (Norled, 2024) states that the establishment of MF Hydra had great implications in both technological development and changes in regulations to enable hydrogen-powered passenger ships in Norway. Before this, Norled, the company behind MF Hydra had developed MF Ampere, the first electric and propeller-driven ferry in the world. As the world's first hydrogen ferry, MF Hydra project shows that Norled is leading in the development of green maritime solutions (Norled, 2024). According to (Riviera Maritime Media, 2024), Ballard Power Systems fitted the MF Hydra with two 200 kW fuel-cell modules in November 2022, sufficient to keep it sailing for about 12 days at an average speed of 9 knots, covering some 1,000 nautical miles.

Along with countries like Germany and Norway, The Netherlands also has notable developments in zero-emission vessels and is hence contributing greatly at an international level to sustainable maritime technologies. With that being said, (Inland Waterway Transport, 2024) reports that the port of Rotterdam has initiated the ambitious project with the Province of Zuid Holland and over 40 partners-DCFCA aiming to give a new face to inland and coastal shipping while introducing hydrogen-powered vessels, in this case, the "Condor H2 project". Condor H2 is a ground-breaking project: emission-free inland and near-shore shipping powered by hydrogen. Adopting modular "tanktainers" for flexible hydrogen storage combined with fuel cells and battery packs, the system allows the owners to operate on a pay-per-use model that keeps upfront costs to a minimum. Part of RH2INE network, Condor H2 unites over 40 partners from the complete hydrogen supply chain to make the world's first hydrogen inland shipping begin in 2025, and it should avoid 100,000 tons of CO2 emissions annually before 2030 (The Port of Rotterdam, 2024).

Sea Change is another significant advancement towards green maritime transition as the the United States' first fuel cell powered vessel (ZeroEI, 2024). The vessel, owned by SWITCH Maritime, was designed and built to demonstrate a path toward commercializing zero-emission hydrogen fuel cell technologies for marine applications (Cummins, 2024). Sea Change is powered by 360 kW of PEM fuel cells,including 100 kWh of Li-Ion battery storage, as well as 600 kW of electric propulsion. That gives the vessel an estimated speed of up to 15 knots and a service speed in the range of 8 to 12 knots (San Francisco Bay Ferry, 2024). Interestingly, the only thing the vessel emits is warm water vapor, not´forgetting clean water that passengers are able to drink (ZeroEI, 2024).

Hydrogen is currently the only energetic vector that can replace fossil fuels with very low environmental impact (Observer, 2023). In recent years, fuel cells have been progressing rapidly by their advantage of low emission and high energy efficiency to meet ever-stringent maritime emission regulations (Ma et al., 2021). Actually, fuel cells can be regarded as one of the most promising technologies for maritime purposes (Xing et al., 2021).

According to (European Maritime Safety Agency, 2023), hydrogen fuel cells generate electricity through a chemical reaction between hydrogen and oxygen, emitting only water vapor and heat. This technology eliminates emissions of NOx, SOx, and particulate matter (PM), making it an environmentally friendly alternative, however hydrogen has a low energy density, which requires larger storage volumes compared to conventional fuels. This limitation makes it more suitable for short-sea shipping rather than deep-sea applications. Hydrogen leakage and slip can occur, contributing to indirect greenhouse gas emissions.

Nevertheless, shipping companies are modernizing their vessels by going full-on electric vessels, while others are integrating hydrogen fuel cells in ambition to meet the IMO's goals for reducing the amount of greenhouse gas emissions (Thorson et al., 2022). Fuel cells can be used for long-haul operations and offer a far higher power density of 1550 W/L compared to general power densities of other chemical power sources, which lie between 30 and 45 W/L (Ma et al., 2021). The production cost of hydrogen by high-temperature electrolysis is highly dependent on the price of electricity. Low-price electricity, for instance from renewables or off-peak grid electricity, is thus a prerequisite to make hydrogen production less expensive (Thorson et al., 2022). Considering the tankers, super trawlers, and cargo ships that spend a great deal of time at sea, the size of hydrogen fuel tanks would be impractically large (Thorson et al., 2022). This indicates that hydrogen storage in its current technological state might not apply to long-duration voyages on large vessels due to space and practicality concerns.

These storage devices are needed based on the hydrogen production scale, energy converter configuration, and power electronics interfacing.

In the general case of combining marine energy with hydrogen, electrical energy storage systems like hydraulic systems or batteries is likely essential in dealing with intense fluctuations from the marine energy system. These types of storage devices become necessary based on the scale of the hydrogen production, the power electronics interfacing, and the energy converter configuration (Thorson et al., 2022). Hydrogen is energy-dense and, therefore, can be a good candidate for various applications that demand a high-energy source. It has many uses, from blending with conventional fuels. Production of hydrogen can be done using electricity from renewable sources to help reduce emissions. It will also play a very important role in lowering the emissions from sectors that are difficult to decarbonize like shipping (DNV, 2023). On the other hand, handling hydrogen requires a great deal of energy, and further technological development is also required. Advancements in technology and manufacturing are needed for efficient use (DNV, 2023).

4.1.2 Battery-Electric Propulsion

1. Dynamo and Dynamo II
2. MF Ampere
3. Yara Birkeland
4. E-Pusher type M

Some of the tugs and ships using battery propulsion as the main source of energy include Dynamo and Dynamo II, MF Ampere, Yara Birkeland, and E-Pusher type M. The Dynamo and Dynamo II are tugboats built by Sanmar Shipyards for Saam Towage, with all-electric propulsion systems. These two tugboats joined the fleet at SAAM as part of its fleet sustainability effort and were fitted with advanced technology to offer zero-emission towing operations-an important milestone of a reduced carbon footprint in maritime logistics (SANMAR SHIPYARDS, 2024). According to (SAAM Towage, 2024), this initiative, supported by partners from both private and public sectors, should be able to cut down on carbon dioxide emissions by 2,400 metric tons per year. (SAAM Towage, 2024) continues that both Dynamo and Dynamo II powered with clean energy from BC Hydro represent a major step in making maritime operations sustainable. Conversely, the MF Ampere is a Norwegian pioneering commercial electric vessel project-a ferry intended to increase energy and environmental efficiency by at least a factor of 20% compared to traditional propulsion vessels (Kolodziejski and Michalska-Pozoga, 2023). Being the world's first all electric-powered vessel, MF Ampere's propulsion system includes Siemens BluDrive PlusC technology featuring two 450kW electric motors, one for thrusters, allowing this vessel to operate at a speed of as much as 10 knots (Technology, 2015). Interestingly, MF Ampere has seven crew cabins and 140 seats and a capacity for 120 cars and 360 passengers. The project to build the ferry emerged from competition started in 2011 by the country's Ministry of Transport and Communications for a design on environmental-friendly ferry between two villages, and following that, Norled won the tender competition and thus the concession for carrying the ferry on this route up to 2025 (Technology, 2015). As part of their study of electrification of ferries in Norway, through the conducted interviews, all interviewees marked MF Ampere tender as the point initiating the transition to ferry electrification in Norway (Sæther and Moe, 2021).

Yara Birkeland, another Norwegian electric vessel is the first full electric, autonomous container vessel with zero emissions in the world according to (Yara International, 2024a), (Leclanché SA, 2021). It is capable of carrying 120 TEUs, features a deadweight of 3,200 tons, and has propulsion via twin 900kW Azipull pods with twin 700kW tunnel thrusters for up to 15 knots (Yara International, 2024a), (Leclanché SA, 2021). While the vessel indeed comes with clear advantages, including a drastic reduction in emissions and eventually a zero-emission status, it also presented a few challenges. According to the Senior Advisor of the Yara Birkeland project, the investment in Yara Birkeland has a long payback period. The vessel, while generating quite a lot of publicity, pressed hard to be converted into financial benefits. In addition, the vessel is not in full operation yet (previously scheduled to end its trial period towards the end of 2024, this vessel's trial period is now extended to 2026), and some operational bottlenecks are still being worked on by the Yara Technology and Projects team (Yara International, 2024b).

Alternatively, the E-Pusher type M is the world's first zero-emission electric pusher tug, realized through a joint effort between Cargill and Kotug according to (Cargill, 2023). Operating such vessels fully electrically, there would not be any discharge or noise to disturb the environment during transportations from Amsterdam to Zaandam, Netherlands according to (Cargill, 2023). It features a modular and scalable design with swappable energy containers for diesel, biogas, hydrogen, or battery power. The thinking here is that this would greatly reduce the emissions of the most problematic compounds, including CO2, SOx, NOx, and particulate matter, to help move toward greener maritime operations according to (Offshore Energy, 2024). Additionally, (KOTUG, 2024) mentions that this tug boat is propelled by two variable electric azipods-a setup that provides great flexibility to any operation and is very environmentally friendly.

Battery-electric propulsion systems have emerged as a leading technology for reducing emissions in maritime transport. (European Maritime Safety Agency, 2023) states that battery-electric propulsion involves using electric energy stored in batteries to power ship engines. This technology is primarily suited for short-range vessels due to current battery capacity limitations, although he energy density of batteries is low compared to traditional marine fuels, necessitating frequent recharging or larger battery sizes that may not be feasible for longer voyages. The battery-electric vessels rely exclusively on the battery packs, whose capacities are within the range of 50-500 kWh (Cha et al., 2024). Aside from the early pilot projects such as the likes of Yara Birkeland, battery-electric propulsion has remained a relatively unexplored low-emissions option in marine shipping (Kersey et al., 2022). This happens notwithstanding the fact that this is an area with really great potential for emission reduction, accompanied by recent battery price decreases and advances in battery energy density, greater availability of increasingly affordable renewable electricity, and some striking efficiency advantages over e-fuels like green hydrogen and ammonia (Kersey et al., 2022).

The electrification of ships propulsion systems is customized to each application due to the different sizes and range requirements that exist in ships (**?**). (Lee and Kim, 2021) reports that the global trend is now focusing on the completely electric ship powered by a friendly energy source like a battery since electric propulsion reduces environmental pollution and noise during operation, allowing more flexibility in designing the ships. However, there exists a number of disadvantages, including high costs and low density in energy within the batteries (Lee and Kim, 2021). (Brown and Aldridge, 2019) adds that while battery electric vessels are perfect for lightweight, short-distance marine transportation; several hydrogen systems are in place, offering great opportunities for longer-distance, heavy-duty shipping vessels.

This therefore means that research and development of technologies that enhance energy efficiency should be advanced in order to advance ship electrification (Lee and Kim, 2021).

Generally speaking, battery systems are larger and heavier compared to internal combustion engines and fuel tanks. Their capacity is limited by the specifications of individual cells and is not independently scalable. Moreover, for open sea transport, operational and economic limitations become significant due to cargo and volume limits (Kistner et al., 2024). Findings from (Kistner et al., 2024) indicate that while it is theoretically better for the environment to shift from fossil fuels to batteries, doing so may not be economically practical, even with potential taxation in the future on greenhouse gas emissions. Although (Kistner et al., 2024) conclude that the annualized cost of battery systems is lowest when distances are short. The performance of the battery cells and the storage systems' costs are in conformance with the data provided by the manufacturer, which allows clarity between cell and system specifications. The evaluation also covers an environmental assessment (Kistner et al., 2024). Also, results from (Ivanov, 2022) indicate that for short trips, battery propulsion is economically viable than conventional combustion power systems. Moreover, forecasts predict that energy density will improve on the back of advances in cell structures, designs, and materials (Kistner et al., 2024). Battery-fitted electric vessels have a number of drawbacks in view, since special charging stations are required while batteries are heavy and bulky to carry-a far cry from the space diesel engine propulsion systems take up (Anwar et al., 2024)

4.1.3 Hybrid Propulsion Systems

1. Energy Observer
2. ELEKTRA

Energy Observer is a pioneer in testing the energy system that will link different kinds of renewable energies with hydrogen right to its diffusion for individual users, neighborhoods, and even whole cities (Observer, 2023). The vessel features a PEMWE-assembled system that can produce hydrogen by using renewable energy obtained from onboard solar panels and wind turbines, with seawater purified directly on the vessel (Bacquart et al., 2021). According to (Observer, 2023), it is the first catamaran in the world fully self-sufficient in energy, powered by the combination of renewable sources: solar, wind, and hydraulic energy. It also employs a complete hydrogen system, resulting from seawater electrolysis, to store surplus energy and compensate for the variability of renewable energy generation.

ELEKTRA is a hybrid push boat, the first in the world, and a result of pioneering work by the German consortium under the leadership of Prof Gerd Holbach from Technischen Universität Berlin-TU Berlin (EST Floattech, 2024). Indeed, the consortium in Germany has been dealing with the emission-free hybrid experimental vessel "ELEKTRA" to be operated in the Berlin-Brandenburg area as well as in commercial service on the route between Berlin and Hamburg (Energy, 2024). (E4ships, 2024) explains that the ELEKTRA project researches hydrogen due to its very special characteristics for the supply of energy. In addition, infrastructural variants for the charging of batteries with onshore-produced electricity and the supply of hydrogen to the fuel cell are surveyed. Furthermore, an energy management system will be elaborated which, based on the given onboard energy sources limited in their capacity, optimizes the use of energy and deploys it effectively among all producers and consumers. The project partners expect Elektra to play the role of a pioneer for zero-emission ships, whose energy system is intended to subsequently be applied to different inland and coastal ship categories (Energy, 2024).

Unlike hydrogen fuel cells, battery-electric propulsion, hybrid propulsion systems use more than one type of energy source. Hybrid systems combine multiple propulsion methods, such as internal combustion engines with batteries or fuel cells. This approach optimizes fuel efficiency and reduces emissions by switching between power sources as needed as discussed by (European Maritime Safety Agency, 2023). (Cha et al., 2024) states that hybrid vessels integrate batteries with other power sources such as a diesel engine or renewable energy in sizes ranging from 500 to 5000 kWh depending on vessel size (Cha et al., 2024). Moreover (Jiang and Ding, 2024) refers hybrid-power propulsion system to an optimized integration of multiple main engines or power sources improved from different marine engines and power sources, respectively, for a mixed-use operational profile.

Indeed, hybrid power and propulsion systems have been promising in showing their potential to improve fuel efficiency and safety in marine operations, thereby serving as an alternative to traditional mechanical propulsion (Gao et al., 2024). It is about operational flexibility given by an efficient hybrid propulsion system, exceptional maneuverability, combined with high levels of redundancy for ensuring the vessel's operation under safe conditions (Kolodziejski and Michalska-Pozoga, 2023). Hybrid systems contribute to a very significant saving in fuel consumption, reducing hence greenhouse gas emissions and noise pollution thanks to the use of electric propulsion for low-speed operations and in maneuvering conditions for docking-Power Take-In, PTI (Gao et al., 2024). Furthermore, these systems can be tailored for various operational profiles, allowing ships to use electric power in emission-controlled areas and switch to conventional fuels or hydrogen in other zones (European Maritime Safety Agency, 2023), however managing the complex integration of multiple power sources and ensuring reliability remains a key challenge. Hybrid systems require sophisticated control systems to balance power distribution efficiently (European Maritime Safety Agency, 2023).

The fuel cell-battery hybrid power system turns to the low energy conversion efficiency of a single power source and severe air pollution problems of the conventional engine (Ma et al., 2021). It is well recognized that hybridization, a process putting two or more units together, may help to overcome the limitations in batteries and fuel cells. Lately, this strategy has gotten significant attention from international automotive and shipbuilding companies (Ma et al., 2021).

4.2 Operational Challenges of Zero-Emission Tugs (or Ships) in the Market

There are a number of operational challenges that need to be solved in order to make implementation and efficiency go hand in hand in the fast-evolving field of zero-emission vessels. These challenges range from technical limitations, high costs, and infrastructure requirements too, among others. Each peculiar challenge is due to the different types of vessels: For example, technical limitations often involve developing and integrating new technologies that can be quite complex and untested. Besides the issues mentioned, other concerns have to do with rapid technological advances that this new system would require and/or a current technological infrastructure unable to accommodate new demands. High costs are another major bottlenecks, normally driven by the high level of investment required for new technologies and infrastructures. These involve very high production costs, heavy financing of innovative solutions, and high economic impacts linked to adaptation in already existing systems. Finally, infrastructure requirements underline the needs for supportive infrastructure to be in place for zero-emission vessels to be feasible, understand what new supply chains are to be laid out, establish all necessary charging or bunkering facilities, and adapt on-shore infrastructure to new demands.

Table 4.1 outlines each case study's response to technical limitations, high costs, and infrastructure requirements based on the available literature. In case, where there was no available information regarding operational challenges, "Not Applicable (N/A)" was applied.

Vessel	**Technical Limitations**	**High Costs**	**Infrastructure Requirements**
Dynamo and Dynamo II	N/A	N/A	N/A
Energy Observer	Premature aging of materials in extreme heat, the need for constant optimization of the vessel's solar technology, limited hydrogeneration due to lack of wind in certain regions (Observer, 2023)	N/A	Maintenance and replacement of photovoltaic panels needed (Observer, 2023)

Vessel	Technical Limitations	High Costs	Infrastructure Requirements
H2 Pusher Tug (H2SB)	N/A	High costs for hydrogen production and infrastructure (Hamburg, 2024)	Need for green electricity, infrastructure development, and regulatory changes (Hamburg, 2024),
ELEKTRA	Weight and space challenges, new technology with limited supplier base, testing new strategies required (Holbach, 2022)	High cost for green hydrogen and green electricity (Holbach, 2022)	Energy provision from shore (bunkering and charging), regulatory framework for vessel approval (Holbach, 2024)
MF Ampere	Challenges in extending power grid (Husjord, 2023), quick charge challenge (Corvus Energy, 2024a)	Significant investments required (Husjord, 2023), cost-prohibitive upgrades due to grid capacity limitations (Corvus Energy, 2024a)	Need for careful planning of infrastructure and additional land for technical facilities, and grid extensions (Husjord, 2023), grid capacity limitations (Corvus Energy, 2024a)
Yara Birkeland	Delays in the development of robust technical solutions (Yara International, 2024b)	Long payback period and high initial investment (Yara International, 2024b)	Regulatory requirements and alignment with authorities (Yara International, 2024b)
MF Hydra	Absence of hydrogen supply chain and bunkering hubs (Østvik, 2021)	High initial cost for hydrogen fuel and mechanisms like CfD (Østvik, 2021)	Requires development of hydrogen supply chain and bunkering hubs (Østvik, 2021)
Condor H2	Layout issues, impact on load capacity (Boersma and van Loenhout, 2023)	Higher conversion costs, increased day rates, and handling costs (Boersma and van Loenhout, 2023)	N/A
E-Pusher type M	N/A	N/A	N/A

Vessel	**Technical Limitations**	**High Costs**	**Infrastructure Requirements**
Sea Change	Rapid technological changes, complexity of new technology (Murphy and Ralli, 2023)	Capital Expenditure (CAPEX) Premium, financing challenges (Murphy and Ralli, 2023)	Hydrogen supply chain development, regulatory approval (Murphy and Ralli, 2023)

Table 4.1.: Operational Challenges of Selected Case Studies of Zero-Emission Vessels

5 Strategic Drivers of Zero-Emission Adoption and the Involvement of Regulatory Forces

Driven by increasing concern for environmental sustainability and reductions of greenhouse gas emissions, governments and international organizations have taken proactive actions in promoting sea transport that is cleaner and more efficient.

For example, the International Maritime Organization (IMO) was established as one of the specialized agencies of the United Nations (UNs) with the set objective of providing influence in developing global maritime regulations. IMOs have already set up a number of key initiatives to decrease the shipping industry's environmental footprint through reduced ship emissions.

The IMO is also extending its umbrella of regulation by adopting new emission control areas and considering the impacts that mid- and long-term measures will have on states, particularly developing countries. Other initiatives, such as Green Voyage 2050, are supporting the introduction of low-carbon technologies in both ports and ships, especially in developing regions (IMO, 2021).

The revised IMO strategy, therefore, put a stronger focus on the application of life cycle assessment methods as a means of analyzing the GHG intensity of marine fuels during their production to end-use. This strategy also supported hydrogen, biofuels, and ammonia as alternative fuels for use; however, such fuels will be in need of strict international rules with the view of ensuring that their supply is environmentally sustainable (IMO, 2023).

The 2023 IMO GHG Strategy separately pursues an average reduction in carbon intensity of international shipping, intended to ensure a total reduction in CO2 emissions per unit of transport work of at least 40 percent by 2030 compared with a 2008 baseline. In addition, the strategy enumerates that zero or near-zero GHG emission technologies, fuels, or energy sources should be at least 5 percent-aspirational goal of 10 percent-of the energy used in international shipping by 2030 (Organization, 2023). It has sensational effects on the development and the adoption of zero-emission tugs and ships around the world.

The most prominent of them is the International Convention for the Prevention of Pollution from Ships-the so-called marine pollution (MARPOL). Annex VI of MARPOL is the annex that deals with air pollution and emissions from ships, setting limits on sulfur and nitrogen oxide emissions; it also sets EEXI and CII as the allowance index for monitoring and improving vessel efficiency (IMO, 2024).

New regulations will eventually call for new technologies and alternative fuels to be installed in order to cut emissions. At the same time, decarbonization in shipping would dramatically change how ship fuel is produced and supplied to the market (Kolodziejski and Michalska-Pozoga, 2023).

Some of the projects on zero-emission maritime technologies have faced or are facing the implications caused by the involvement of regulatory forces as the development and adoption of zero-emission tugs and ships continues. On this, with reference to the H2 Pusher Tug (H2SB) project, (Hamburg, 2024) underlines the fact that top politics from both federal and EU levels need to embody regulations into laws that will make investment economically viable over a long-term perspective. The identified regulatory gaps in the MF Hydra alternate design process are effectively dealt with based on the risk-based approach outlined in IMO Circular 1455 (Østvik, 2021). At the moment, some regulatory restrictions have forced the Yara Birkeland's current onboard crew to a minimum of 3 employees for safety and monitoring (Yara International, 2024b). "The regulatory aspects are also difficult since no regulations exist," says Knut Midtsian, Interface Manager for Yara Birkeland. "Alignment between technology development and authorities has had an effect on project progress, and the slow development pace compared with 'off-the-shelf projects can be frustrating at times," he adds (Yara International, 2024b). Relating to Sea Change, (Murphy and Ralli, 2023) brings to notice that project timelines have to be aligned with how regulatory agencies work: "regulatory agencies' timelines do not follow commercial timelines, plan ahead.". On the same note, (Holbach, 2022) comments on the challenges facing ELEKTRA in that "rules and regulations enabling economic use of the technology need to be created", again stressing a reliable regulatory framework as the basis upon which future investments may be made.

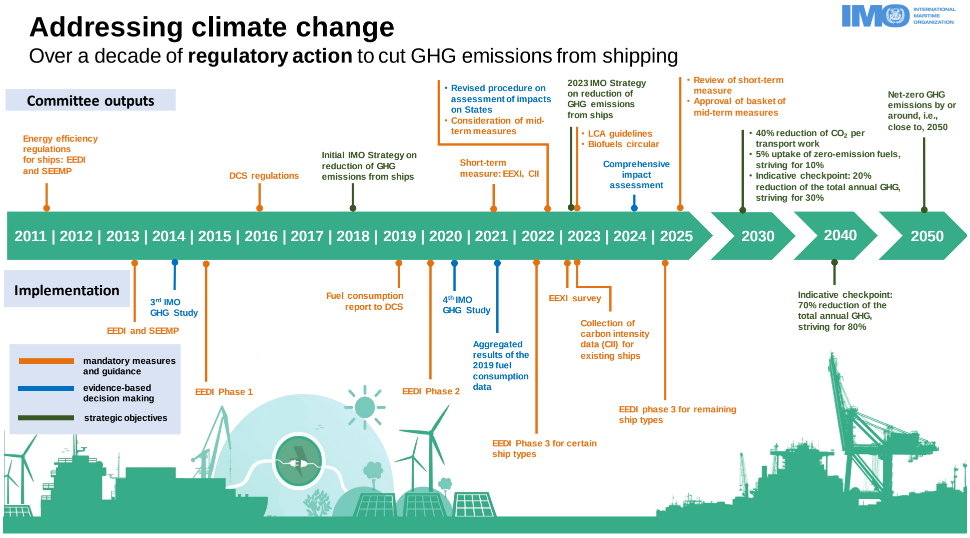

Figure 5.1.: The IMO's Vision on Cutting Greenhouse Gas Emissions from the Maritime Industry based on (Organization, 2023)

Most countries have already identified their regulatory and incentive frameworks to promote zero-emission vessels within their territorial waters, including financial incentives, tax breaks, and emission reduction targets. For example, the European Union Green Deal has, among other things, included "Fit for 55" to reduce EU greenhouse gas emissions by 55% by 2030.This includes plans for facilitating zero-emission shipping and investing in engineering sustainable infrastructure. Under the National Hydrogen Strategy (NHS) Target Vision 2030, the Federal Ministry for Economic Affairs and Climate Action in Germany - BMWK - intends to significantly accelerate the development and uptake of hydrogen, its derivatives, and related technologies, with substantially increased ambition along the entire value chain (BMWK, 2023). Moreover, the United States has also brought into practice the Clean Maritime Transportation Act elaborating on some ambitious targets for cutting GHGs in the domestic maritime sector. In particular, the funding provided is intended to cover research and development related to zero-emission vessels and infrastructure and it encourages the deployment of such vessels in U.S. ports (Sustainable Ships, 2024b).

In addition, CCS had developed the "i-Ship" notation, which was a classification notation related to intelligent ships. These notations are designed to certify and standardize the use of advanced technologies and intelligent systems in ships. The requirements for the class notation "i-Ship" among others require compliance with environmental regulations, including making use of technology to minimize the environmental impact of the ship (China Classification Society, 2023).

Another important factor as far as the development of regulatory for zero-emission tugs and ships is concerned includes classification societies such as Lloyd’s Register and DNV. These are responsible for setting the standards and maintaining them with regard to vessel design, construction, and operation (Bennett, 2022), (DNV, 2023). For instance, one of the oldest classification societies, Lloyd’s Register, has been actively involved in the decarbonization process of the shipping industry through its Maritime Decarbonisation Hub. This focuses on the development of future maritime fuels, based on collaboration across industries to develop such fuels. The expertise of LR goes beyond classical services in classification into advisory services with regard to fleet optimization, compliance, and sustainable maritime technologies. Thus, the organization is closely cooperating with the industry stakeholders for better development of zero-emission vessels and innovative ship designs by including alternative fuels such as ammonia (Bennett, 2022). Similarly, on the other side, DNV has been updating its rules of classification according to the latest technological and environmental standards. For example, the July 2023 version of DNV’s rules introduced new requirements that were in line with newly developed international regulations toward better safety and reliability of zero-emission vessels. DNV provides detailed battery and hybrid ship-related services, from independent analysis and validation to advisory services that support the transition of shipowners and operators to cleaner energy solutions. The services range from supporting battery retrofits, including battery operation, covering all technical, economic, and environmental maritime battery system issues (DNV, 2023).

In a context of developing environmental concerns, classification societies are increasingly working upon developing rules and guidelines concerning zero-emission propulsion systems and their related emission-reduction technologies. These rules and guidelines will be important in view of safety and compliance for zero-emission vessels.

Finally, matters of regulatory framework regarding zero-emission tugs and ships would be dynamic, in continuous evolution, induced from a variety of stimuli such as international organizations, national governments, and classification societies. Adhering to these regulations will be crucial both during the entry into the market and for success applied to the long term in the zero-emission maritime business. With environmental sustainability topping the priority chart, stakeholders in industry must be properly informed and adapt to the evolving regulatory landscape that will help ensure the market growth and acceptance of zero-emission vessels.

6 Economic Impact of Zero-Emission Technologies on Ports and Shipping Companies

Interest in hydrogen and zero-emission technologies is bringing a set of profound economic implications for Shipowners and Ports. The section is a discussion on the costs, infrastructure, and collaboration required by such challenges.

6.1 Hydrogen Production Costs and Investment Challenges for Shipowners

Hydrogen-powered vessels, like the Hydrogen-Project H2 Pusher Tug - H2SB, demand huge investments. In particular, for developing supply chains and infrastructure related to hydrogen production. For example, the analysis from (Consulting and BV/SRL, 2023) suggests that hydrogen production is expected to be far more expensive compared to conventional fuels, whose prices fluctuate from 2.9 to 5 €/kg in the Duisport area by 2030. This, hence, creates a massive barrier in terms of entry cost, mainly during the beginning period of technology deployment, and adds to total cost of ownership (TCO) for shipowners. The report from (International Renewable Energy Agency (IRENA), 2021) also points out that green hydrogen production is a costly affair currently but will see a significant drop by 2030 due to electrolyser and renewable energy costs going down. (International Renewable Energy Agency (IRENA), 2021) continues that by 2050, the steadily falling production cost of green e-methanol is forecasted to range from $ 107/MWh to $ 145/MWh.

Moreover, it is indicated that TCO of hydrogen and battery-electric vessels would be about two to four times higher compared to traditional diesel-powered vessels in BAU scenarios. This is primarily driven by high Capital Expenditure (CAPEX) associated with the adoption of zero-emission technology (Dahlke-Wallat et al., 2021). Although Operational Expenditure (OPEX) for such vessels is expected to come down after 2035 due to increased energy efficiency, the initial capital outlay remains the biggest hurdle for first movers (Dahlke-Wallat et al., 2021).

Besides the price of hydrogen production, the retrofitting of vessels or construction of new hydrogen-powered ships requires very high CAPEX. For instance, by 2030, the cost difference to decarbonize container transport would be in the range of $90/TEU and $450/TEU for zero-emission vessels compared with conventional LSHFO-fueled vessels on the Shanghai to Los Angeles route, while in the range of $30/TEU and $70/TEU on the Chinese coast (Perico et al., 2023). In the majority of scenarios, TCO estimates are projected to be from 2 to 2.5 times that of conventional fuel by 2040, and to narrow further to 1.5 to 2 times by 2050 (Perico et al., 2023).

6.2 Infrastructure Investment by Ports

Retrofitting vessels with zero-emission technologies, including the developing hydrogen refueling station and power grid extensions for battery-electric vessels, will be pretty costly for the ports. Shared hydrogen infrastructure options were given to contain a number of specific ports such as AntwerpBruges and Duisport that support the emergent hydrogen economy (Consulting and BV/SRL, 2023). That is supported by (Zero-Emission Shipping Mission, 2022) where a conclusion has been made that hydrogen and ammonia will require comparably much more expensive storage than conventional fuels since refrigeration is necessary with special equipment for handling.

Hydrogen demand at Duisport for 2050 is calculated as 0.8 million tonnes (Consulting and BV/SRL, 2023), for which substantial upscaling of the inner storage facilities and distribution systems will be inevitable. This is further supported by the report by (International Renewable Energy Agency (IRENA), 2021), according to which investment in hydrogen refueling stations, cryogenic storage tanks, and safety systems should also be made. Otherwise, without such upgradations, supply systems for hydrogen are underdeveloped and state-of-the-art vessels powered with hydrogen will fail in efficient operation performance.

Nevertheless, (Dahlke-Wallat et al., 2021) also emphasizes that it is necessary for the ports to invest in structural improvement in order to be able to receive the coming zero-emission vessels. Hydrogen bunkering facilities, and electric grid extensions for battery-powered ships are reflecting high costs. It costs much money to develop hydrogen refueling station and integrate it into existed port infrastructures (Dahlke-Wallat et al., 2021).

6.3 Cost Categories for Ports and Ship Operators

6.3.1 Costs Borne by Ship Operators

Capital Expenditure (CAPEX):

The transition from vessels running on fuels and emitting harmful gases to zero-emission vessels is actually very CAPEX-heavy on the part of ship operators. According to the report, one of the key drivers is that newbuilding costs for zero-emission vessels-particularly those powered by hydrogen or battery-electric propulsion systems-can be considerably higher than for traditional diesel vessels. For the bigger transpacific vessels, this could be around 2.4 to 2.7

times higher, while for vessels of smaller sizes, it's an increase of about 1.8 times (Perico et al., 2023).

The estimated incremental CAPEX for building zero-emission vessels in China within the period 2025-2050 stand within the range of $125 billion to $444 billion, depending on the fuel and propulsion technologies. CAPEX components are an ensemble of various costs, which relate to the ship hull, propulsion machinery, tank and fuel system, efficiency improvements, among others. Among these two scenarios, one believes in low CAPEX ammonia and the other in high CAPEX Hydrogen fuel cells (Meng and Rutherford, 2024).

(Dahlke-Wallat et al., 2021) also adds that the estimated overall CAPEX gap for the transition to zero-emission inland waterway vessels under a conservative pathway is between €3.42 billion and €4.51 billion, while the innovative pathway is projected at a gap of approximately €5.35 billion to €7.80 billion over the 30-year period. This means that the CAPEX stands at around 1.5 times higher for the conservative pathway, while the innovative pathway would need approximately 2.5 times more over and above the Business-as-Usual (BAU) scenario.

According to (Hoffmann et al., 2012), the additional capital expenditures related to CO2 reduction in shipping are implied below: the estimated 6% for the new ships according to a measure-by-measure approach and 27% according to a set-of-measures approach, regarding various levels of CO2 reduction by 2030 from a BAU scenario.

For ammonia-powered zero-emission vessels, the CAPEX includes costs related certain components such as processing and combustion equipment, structural reinforcements of the main engine, containment systems, and so on. This greatly increases the financial cost of adopting ammonia as a fuel in shipping and underlines the main economic challenges facing vessel operators (Nikolopoulos and Boulougouris, 2023).

Operational Expenditure (OPEX):

Recently (Mojarrad et al., 2024) explored the Operational expenditure (OPEX) for modernizing high-speed ferries from diesel to green hydrogen and concluded that the Compressed Hydrogen (CH2)-fueled ferry is the most economical, whereas the Liquid Hydrogen (LH2) ferry, though technically efficient, currently sustains higher costs due to the price of liquid hydrogen.

In the analysis from (Abma et al., 2019), OPEX considered of the Gouwenaar II battery-electric powertrain includes the cost of electricity, cargo loss due to space taken up by the battery container, time loss for battery exchanges, grid connection costs, and calculated maintenance expenses at 1% CAPEX. Furthermore, income from Frequency Containment Reserve (FCR) was considered.

The annual variable OPEX for the BAU scenario is between €26.8 billion and €34.6 billion in 30 years, while in the conservative pathway, the estimate is €25.3 billion-€35.9 billion, and in the innovative pathway, it is €23.6 billion-€33.6 billion. Basically, the OPEX of pathways that tend to decrease after 2035 because of a larger share of battery-electric sailing, meaning greater efficiency and lower energy costs (Dahlke-Wallat et al., 2021).

Furthermore, (Perčić et al., 2022) compared the life-cycle costs of various fuel cell types on ships using hydrogen and ammonia as zero-carbon fuels with those of conventional diesel systems. While blue ammonia is cheaper as a fuel, the total operating cost-be it investment or replacement of equipment-stands at 27-43% over conventional diesel ship operations with fuel cells, mainly due to larger initial investments and the setup of these systems with fuel cells, batteries, and hydrogen crackers.

The operating cost of the ammonia-based propulsion system for ships varies in the range from 210 €/MWh at 100% engine load up to 243 €/MWh at 25% engine load, where most of the OPEX is contributed by fuel costs, around 80-90% of the total operating cost depending on the load, while the remaining cost is due to amortization of the capital cost and maintenance expenses (Sánchez et al., 2023). A sensitivity analysis clearly reveals that ammonia's fuel cost is a main driver in determining the value of OPEX, which could decrease further to 150 €/MWh when production technologies for ammonia improve (Sánchez et al., 2023).

6.3.2 Costs Borne by Ports

Infrastructure Investment Costs:

One of the major investments at the ports for reducing vessel emissions is the installation of relevant CI infrastructure. As estimated, the cost for installing one CI berth in Rotterdam was $ 4.7 million, while in the Port of Gothenburg, this was roughly $ 955,000 (Ssali, 2018). (Zero-Emission Shipping Mission, 2022) indicates that major global trade ports should be in a position to provide zero-emission fuels by 2030 to ensure reliability for ship owners. Major investment in the fuel infrastructure is needed to achieve this.

Moreover, infrastructure development pertaining to green shipping corridors, such as production and supply facilities for alternative fuels, will require a substantial amount of investment. Investments in infrastructure that develops the requirements for the safe storage and bunkering of these fuels involve huge money infusions (Webb and McMillan, 2023). The estimated CAPEX for bunkering facilities in certain specific ports involved in some of the well-known green corridor initiatives stands between $ 42-72 million. Once more, while this investment is small in proportion with the overall needs of producing fuel, it is essential to determine costs for the ports. Again, moving into green corridors will bring along opportunities for investment by both public and private players, which highlights the need for agreements among different stakeholders (Webb and McMillan, 2023).

Maintenance and Operation:

The annual maintenance cost for systems normally comes as a percentage of capital expenditure. For H2 internal combustion engines, it is approximately 2% of CAPEX. For hydrogen fuel cells, the cost is higher, being about 10% of CAPEX, because some parts like membranes have relatively shorter lives and would have to be replaced. For general internal combustion engines, the maintenance costs are about 7% of CAPEX (Dahlke-Wallat et al., 2021). Whereas OPEX for the hydrogen systems may decrease over time, initial maintenance costs can be high as special equipment and training are needed. Discussions hereof indicate that, in general, no return on investment is expected from near-zero-emission technologies for ship operators in any compared BAU scenarios. This is largely due to higher capital and maintenance costs (Dahlke-Wallat et al., 2021).

6.4 Shared Economic Burden and Collaboration Between Ports and Shipowners

Both shipowners and ports have to work together on the high upfront investment costs associated with zero-emission vessels. (Perico et al., 2023) estimate that in 2030, the TCO of zero-emission container freight shipping would be two to four times higher than conventional fuel vessels, which means the cost gap requires coordination on various fronts/shared investment models and public-private partnerships-so the financial burden falls fairly.

According to (Zero-Emission Shipping Mission, 2022), it will be necessary to collaborate among ports and shipowners, and having common rules at ports would reduce part of the costs as well, and may invest together in bunkering infrastructure. The same thing is explained in the (Webb and McMillan, 2023): green corridors introduction will take a lot of investment in infrastructure and should be made in close collaboration among the relevant actors, including ports, shipping companies, and governments. Public support in the form of tax credits and subsidies is critical to tight the cost gap between conventional and zero-emission fuels.

7 Discussion and Conclusion

7.1 Summary of Findings

This study aimed to give an overview of zero-emission tugs and ships in the market by exploring the recent activity regarding hydrogen fuel cells and battery electric propulsion systems, including hybrid implementations, in zero-emission maritime transportation developments. From the literature review of zero-emission tugs and ships, it can be ascertained that significant developments in furthering decarbonization in the maritime industry, besides the analysis of relevant case studies provided useful information on technological development, operational challenges, and regulatory impacts associated with such technologies.

Despite the fact that the project is still in the development process, the Hydrogen-Project H2 Pusher Tug (H2SB) showcases the potential of hydrogen fuel cells in maritime applications. In return, the project faces considerable challenges when it comes to the high production cost of hydrogen and building respective infrastructure. Similar to the H2 Pusher Tug (H2SB), Condor H2 is another ongoing project which encounters substantial costs of hydrogen. By contrast, Yara Birkeland embodies developments in battery-electric propulsion and exhibits benefits towards autonomous shipping. The vessel yet faces the slow pace of development and the regulatory hurdles hindering the overall application. Energy Observer and ELEKTRA illustrate the implementation of hybrid technologies. Hybrid systems-most promising in view of increasing flexibility and efficiency-do face their own set of challenges such as the necessity for constant optimization or testing new strategies which can be time-consuming.

7.2 Comparative Analysis

Comparing the case studies reveals several common themes and differences across hydrogen, battery-electric, and hybrid systems. All of the selected case studies in this study demonstrates promising technologies, yet each has specific problems. Hydrogen fuel cells are advanced but costly with infrastructural demands, especially in the cases of the H2 Pusher Tug and MF Hydra. Battery electric systems have operational efficiency issues, with range and charging infrastructure being specific bottlenecks, while a good example is the case of MF Ampere. Hybrid systems give flexibility but bring several integration problems and complexity for the side of owners, as in the cases of Energy Observer and ELEKTRA.

The general challenges observed in all projects are costs and infrastructure. The main complexities for hydrogen-based systems are fuel production and infrastructure; for battery-electric systems, it is the limitations of charging and building up infrastructure, while for hybrid systems, it is issues related to technology integration and dealing with a complex system.

Not least, there is a regulatory framework that also plays a not-unimportant part in the deployment of zero-emission technologies. Much of Yara Birkeland's progress will depend on regulatory alignment, while Sea Change has operations influenced by regulations with regard to the integration of renewable energy. ELEKTRA and H2 Pusher Tug also need to navigate regulatory landscapes related to new technologies and infrastructure requirements.

7.3 Implications and Recommendations

It is important to underline that the transition to zero-emission technologies does have a great impact on the economic aspect. The initial CAPEX and OPEX, in other words, the costs derived from hydrogen production plants including maintenance and operational costs for electric charging infrastructure, are higher compared to traditional options using diesel as noted from several reports on retrofitting the maritime industry.

The findings clearly indicate that while each of these zero-emission technologies has its particular advantages, they are also faced with significant barriers that must be addressed for widespread adoption. Overcoming various obstacles in terms of high costs and infrastructure challenges will need further investment in hydrogen production technologies, green electricity sources, and infrastructure development. That being said, further refinement of battery technology, along with building out the charging infrastructure, remains important for wider feasibility and efficiency in the use of battery-electric tugs and ships. Also, the development of hybrid systems will have to forcefully address multifaceted integration issues with various technologies and develop new design strategies. Lastly, the regulatory environment has to be more supportive; it needs to facilitate faster adoption of these zero-emission technologies. Regulation simplification and the provision of incentives by governments and industrial stakeholders together are needed globally in relation to technological development.

7.4 Conclusion

Zero-emission technologies hold much promise for a lesser environmental impact from maritime transport. The case studies analyzed have demonstrated very important advances related to hydrogen, fully electric batteries, and hybrid propulsion. Wide-scale adoption, however, would involve addressing major issues in terms of infrastructure development, supporting regulations, and technology optimization. The transition to zero-emission vessels, mainly hydrogen-powered vessels, poses significant challenges from a financial perspective for shipowners and ports alike. Early movers have to cope with much higher TCOs, while the investment costs for ports in hydrogen infrastructure and grid extensions are very high. Collaboration efforts of the stakeholders themselves, facilitated by regulatory frameworks, therefore mitigates this cost, as incentives stimulate and enable this transition to unfold toward sustainable maritime operations. According to the (International Renewable Energy Agency (IRENA), 2021) and (Perico et al., 2023) reports, green hydrogen will decrease in production cost over the coming years and hence make the transition economically more viable. The way ahead lies in finding innovative financing models, shared infrastructure, and public-private partnerships that can bring down economic barriers to adoption of zero-emission vessels. Hence, this research provides additional evidence that continued innovation and coordination among stakeholders should facilitate progress toward the greening of the maritime industry that is sorely needed.

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A Appendix

Abbreviation	Full Name
BMWK	Federal Ministry for Economic Affairs and Climate Action
BAU	Business as Usual
CAPEX	Capital Expenditure
CCS	China Classification Society
DNV	Det Norske Veritas
ECA	Emission Control Area
GHG	Greenhouse Gas
IMO	International Maritime Organization
MARPOL	marine pollution
NHS	National Hydrogen Strategy Update
OPEX	Operational Expenditure
TCO	Total Cost of Ownership
UN	United Nations

Table A.1.: List of Abbreviations

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