energies

Article

Seaports' Role in Ensuring the Availability of Alternative Marine Fuels—A Multi-Faceted Analysis

Magdalena Klopott, Marzenna Popek and Ilona Urbanyi-Popiołek *

Faculty of Management and Quality Science, Gdynia Maritime University, Morska 81-87, 81-225 Gdynia, Poland
* Correspondence: i.urbanyi@wznj.umg.edu.pl

Abstract: In the effort to decarbonise shipping, a number of measures can be taken, one of which is to switch from conventional to alternative fuels. However, without an active role for seaports in providing adequate bunkering infrastructure for alternative fuels, these targets may not be achieved. Hence, the aim of this article is threefold: (1) to provide an overview of some of the emerging alternative fuel technologies that are being used or tested for further use in maritime transport, (2) to analyse the bunkering infrastructure in seaports, and (3) to assess the level of advancement of Polish ports in relation to the bunkering of alternative fuels by ships and to explore the ports' plans in this regard. To achieve these goals, several research methods were applied: a critical literature review, desk-study research, critical and comparative analyses, and semi-structured interviews with representatives of three major Polish seaports. The research showed that the level of advancement of Polish seaports in the construction of bunkering infrastructure for alternative fuels is relatively low, as they are still in the early stages of conversations with their stakeholders identifying which new fuels should be included in their plans. However, with the growing number of LNG-fuelled ships operating worldwide, Polish ports are being forced to prepare for LNG bunkering; however, it is on a small scale for now. They have to make a decision about what type of fuel their bunkering infrastructures should be for, and this constitutes the subject of a great deal of uncertainty. All this is even challenging when taking into account the fact that shipowners are also struggling to choose alternative fuels for their ships. This uncertainty could be reduced through closer cooperation between ports and shipowners, between individual ports, and between ports and other shipping stakeholders. Unfortunately, there is a noticeable lack of cooperation between Polish ports in this regard, as well as with the relevant government departments.

Keywords: decarbonisation; maritime transport; alternative fuels; seaports; bunkering infrastructure

Citation: Klopott, M.; Popek, M.; Urbanyi-Popiołek, I. Polish Seaports' Role in Ensuring the Availability of Alternative Marine Fuels—A Multi-Faceted Analysis. *Energies* **2023**, *16*, 3055. https://doi.org/10.3390/en16073055

Academic Editor: Dimitrios C. Rakopoulos

Received: 6 March 2023
Revised: 22 March 2023
Accepted: 22 March 2023
Published: 27 March 2023

1. Introduction

Although shipping is the most fuel-efficient mode of transport (per tonne-mile), it is a source of increasing greenhouse gas emissions and fossil fuel consumption, which contribute to climate change.

In early 2022, the world fleet totalled 102,899 ships of 100 gross tonnes and above, equivalent to 2,199,107 DWT of capacity [1]. Carrying about 11 billion tonnes of goods in 2021 [1], shipping, with an energy demand of nearly 8.7–9.2 oxyjoules (EJ) [2], consumes around 300–330 million mt per year [3], releasing a noticeable amount of greenhouse gases (GHGs). The impact of all shipping (international, domestic, and fishing) on greenhouse gas emissions is best illustrated by some of the figures from the Fourth IMO GHG Study [4]:

- The GHG emissions expressed in CO_2 increased by 9.6% from 977 million tonnes in 2012 to 1076 million tonnes in 2018;

- CO_2 emissions alone in 2012 accounted for 962 million tonnes, while in 2018, total CO_2 emissions increased by 9.3% to 1056 million tonnes (with 708 mt from international shipping). In 2021, international shipping was responsible for 667 mt of CO_2 emissions [2];
- International shipping contributes to global anthropogenic emissions; this contribution increased from 2.76% in 2012 to 2.89% in 2018, and experts say it could reach 17 percent or more by 2050, as global trade is expanding and other industries are reducing their fossil fuel consumption [5].

On the EU level, where data regarding GHG emissions from shipping have been collected since 2018 under the Monitoring, Reporting, Verification (MRV) scheme, shipping is also a significant emitter of CO_2, accounting for more than 144 million tonnes of CO_2 emissions in 2019; i.e., between 3 and 4 percent of the EU's total CO_2 emissions [6].

Unquestionably, these emissions must be addressed appropriately by the international shipping sector in order to keep it aligned with the temperature target set in the Paris Agreement (a legally binding international treaty on climate change adopted by 196 countries at the UN Climate Change Conference (COP21) in Paris in 2015); i.e., to maintain a global temperature rise less than 2 °C above pre-industrial levels and preferably limit it to 1.5 °C [7].

Nevertheless, there is a lot of debate, both in policy forums and within the industry, about how to tackle shipping emissions. The discussion is extremely complex and, unfortunately, very much permeated by politics, which often impedes debate.

However, there is a growing consensus that no single measure will be sufficient to achieve significant reductions in greenhouse gas emissions and that multidirectional approaches are needed. One of these is undoubtedly legislation, which, by setting clear standards, can drive the investment and innovation that the shipping sector needs in order to move towards a zero-carbon future. Some regulations to reduce GHG emissions from ships are already in the process of being implemented and others are still in the pipeline, all providing the basis for a radical shift towards reducing and ultimately removing carbon emissions from shipping.

In the international context, the goals and policy objectives for reducing GHG emissions from shipping were clearly defined by the International Maritime Organization (IMO), which has already been implementing a number of measures in this regard for a decade.

The first global IMO regulation setting CO_2 emission standards in shipping was the Energy Efficiency Design Index (EEDI) for newly built ships, adopted in 2011 as a mandatory measure under MARPOL Annex VI, requiring a gradual, three-phase reduction in carbon intensity [8]. It was accompanied by Ship Energy Efficiency Management Plans (SEEMPs) for all ships, which entered into force on 1 January 2013 and will be enhanced from 2023 [9].

Nevertheless, it was the landmark initial IMO strategy on the reduction of GHG emissions from ships (the initial strategy) adopted in April 2018 that started a real discussion on the topic [10]. The IMO's initial strategy sets very ambitious targets for international shipping and envisages:

- "a reduction of the average carbon intensity of international shipping by at least 40% by 2030, pursuing efforts towards 70% by 2050, as compared to 2008 levels; and,
- a reduction of total annual GHG emissions from shipping by at least 50% by 2050 compared to 2008, while pursuing efforts towards phasing them out entirely within this century".

The initial strategy is expected to be revised in April 2023, with the requirements possibly tightened and even more ambitious targets set. These targets are to be met by a basket of measures applicable in the short, medium, and long term. However, which measures should be included in the "basket" remains a topic under intense debate. So far, it has been agreed to include, as amendments to MARPOL Annex VI (regulation 23–25)

[11], the Energy Efficiency Existing Ship Index (EEXI) as a technical measure and a Carbon Intensity Index (CII) as an operational measure. However, these are only short-term measures.

In parallel with this legislation, even more ambitious regulations have begun to emerge in some regions of the world. The EU, for example, discouraged by the IMO's progress in reducing the carbon footprint from shipping, decided to create its own regulatory regime in this area. In July 2021, the European Climate Law was adopted, enshrining the EU's new climate targets of reducing GHG emissions by at least 55% by 2030 compared to 1990 levels and becoming carbon neutral (net zero) by 2050. To deliver these targets, a package of interrelated legislative proposals for various sectors of the EU economy, including maritime transport, known as the "Fit for 55" package was published. It encompasses both amendments to the existing regulations and new measures, goals, and tools. With regard to shipping, the package may be expected to include regulations aimed directly at reducing emissions from the sector, such as: (1) tightening the EU emissions trading scheme (ETS) and widening its scope to include shipping and (2) solutions to increase the use of alternative fuels in shipping and the development of infrastructure for bunkering these fuels, as will be discussed further below [12].

In July 2022, the Clean Shipping Act of 2022, the first stand-alone legislation to decarbonise shipping, was introduced in the US Congress. The act would require the carbon intensity of ship fuel to decrease progressively over time from at least 20% below baseline (2024) in the calendar years 2027 to 2029 to 100% below the baseline in 2040 and each year thereafter. In cases where the carbon intensity of a vessel is reduced to a greater extent, credit may be given for this amount in the future [13]. Should it happen that the IMO introduces more stringent carbon intensity reduction standards for a given year, these could be adopted as mandatory under this act.

There are many parallels between these regulations enacted by the IMO, the EU, and the US. Despite some differences, the important point is that all these efforts and regulations are moving in the same direction; i.e., towards decarbonisation of shipping.

However, there are different pathways for achieving reductions at a scale and with a timeliness consistent with these regulations. Shipowners may choose from a variety of measures, such as speed reductions (slow steaming), changes in hull and propeller designs, just-in-time arrival in ports, and alternative energy sources (e.g., wind). Moreover, each of these legislative frameworks explicitly emphasises the importance of developing alternative fuel technologies as a key pathway towards reducing GHG emissions, as it has particularly strong potential to achieve the levels of the goals outlined in the initial IMO GHG strategy, as well as other regulations. Indeed, it is anticipated that more than 60% of the reduction in CO_2 emissions by 2050 will be achieved through the use of zero-carbon and low-carbon alternative fuels [14]. However, for such fuels to become a viable option, they must be available, cost-effective, compatible with existing and future technology, and in line with current and future environmental requirements. Given high complexity of this challenge, there needs to be a concerted effort from all shipping-related sectors and stakeholders in the maritime supply chain, including seaports. Without their commitment, the decarbonisation goal may not be achieved.

Hence, the aim of this article is threefold:

1. To provide an overview of some of the emerging alternative fuel technologies that are being used or tested for further use in maritime transport, as well as their availability;
2. To analyse the bunkering and storage infrastructure available at seaports worldwide;
3. To assess the level of advancement of Polish ports in relation to the bunkering of alternative fuels by ships and to explore the ports' plans in this regard.

The introduction of alternative fuels in maritime transportation is an important global issue. There are few publications on the introduction of alternative fuels in Polish seaports. This article is the first analysis of the progress of Polish ports in the development of alternative fuel bunkering infrastructure.

The article is organized as follows: Section 2 provides a literature review of the research focusing on the main challenges and opportunities associated with alternative fuel bunkering in seaports. Section 3 describes physical and chemical properties of selected alternative fuels in maritime transport based on the latest scientific articles and the most current IMO documents on the safe use of these fuels. Section 4 presents the results of the analysis of bunkering infrastructures available at seaports worldwide. Section 5 provides an analysis of the results of interviews conducted with representatives of the three largest Polish seaports on the preparation of ports for bunkering ships with alternative fuels, as well as an assessment of the ports' plans in this regard. The final section summarizes the conclusions of this study.

To achieve these goals, several research methods were applied: a critical literature review, desk-study research, critical and comparative analyses, and semi-structured interviews with the representatives of three major Polish seaports. In Sections 4 and 5, selected methods are explained in more detail.

2. Literature Review

There are many types of alternative fuels available for shipping, such as gaseous fuels, which include liquefied natural gas (LNG), methanol, hydrogen, and ammonia. Since these fuels are currently being considered by various IMO committees and sub-committees, it is to these that further attention is given. Advanced biofuels will also soon be the subject of discussion at the IMO, but they have been omitted from consideration here, although they undoubtedly have great potential (this will be the subject of further research).

The literature on alternative fuels is extensive, but it is mainly focused on their physical and chemical properties, the costs associated with their production and use, or environmental aspects. Little attention is given to the important issue of ports' readiness to supply ships with alternative fuels. The following literature review outlines the challenges and opportunities associated with alternative fuel bunkering in ports. A summary of the literature review showing the main challenges and opportunities in bunkering alternative fuels in seaports is presented in Table 1.

Table 1. An overview of key issues regarding bunkering alternative fuels.

Fuel	Challenges and Opportunities in Bunkering Alternative Fuels	Reference
LNG	The authors indicated the main challenges related to bunkering LNG: *"investment costs and the lack of LNG infrastructure"* *"the investment costs, the required infrastructure and safety issues are major limitations"* *"if no effective infrastructure planning is implemented carefully"* *"the lack of LNG infrastructure in ports"* *"Investing in LNG infrastructure in the near term"* *"must be a global network of bunkering facilities for the fuel"* The authors point to the opportunities associated with bunkering LNG: *"the application of LNG leads to lower operating costs"* *"will increase the number of ports providing LNG bunkering services"* *"The fuelling infrastructure has widely developed beyond just a handful of key bunkering ports in recent times"* *"upscaling of bunkering infrastructure for LNG is growing"* *"the LNG bunkering infrastructure for ships is improving quite rapidly"*	[15–24]
Methanol	The authors indicated the main challenges related to bunkering methanol: *"further development of the bunkering infrastructure and distribution chains of methanol are required"*	[19,24–29]

	"it is thought that several more terminals will be needed" *"there may be a need for additional terminals for ship fuel"* The authors point to the opportunities associated with bunkering methanol: *"the infrastructure for methanol available today is based on the worldwide distribution of methanol"* *"best alternative fuel, use of existing infrastructure"* *"potential investments in methanol bunkering infrastructure are reasonably low, and retrofitting of currently functioning infrastructure is a possibility"*	
Hydrogen	The authors indicated the main challenges related to bunkering hydrogen: *"found a lack of reliable infrastructure"* *"infrastructure and bunkering facilities for hydrogen are not yet in place"* *"ammonia and hydrogen require the most new or modified infrastructure"* *"widespread utilization of clean fuels such as hydrogen and ammonia can be obstructed or delayed due to issues related to the underdeveloped infrastructure"* *"there is no distribution or bunkering infrastructure for ships"* *"hydrogen does not have a standardized design and fuelling procedure for ships and its bunkering infrastructure"* *"new infrastructure would costs over several billion dollars in the coming decade"* *"ammonia and hydrogen require the most new or modified infrastructure"*	[18,23,26–29,30–33]
Ammonia	The authors indicated the main challenges related to ammonia: *"found a lack of reliable infrastructure for the use of methanol, hydrogen ammonia and hydrogen require the most new or modified infrastructure"* *"Widespread utilization of clean fuels such as hydrogen and ammonia can be obstructed or delayed due to issues related to the underdeveloped infrastructure"* *"the existing bunkering and fuel infrastructure is not sufficient"* *"the development of bunkering infrastructure remains a barrier for the application of ammonia as a marine fuel"* *"ammonia and hydrogen require the most new or modified infrastructure"* The authors point to the opportunities associated with ammonia: *"a well-established global ammonia storage and distribution infrastructure"* *"ammonia has existing global logistics infrastructure for transport and handling"*	[18,21,27,30,34–37]

The cited authors highlight the current key challenges when adopting alternative shipping fuels. These are the cost of fuels, global availability, bunkering infrastructure, and technology readiness. It is emphasized that an important challenge is to facilitate access to alternative fuels through the development of bunkering infrastructure in ports.

It should be noted that research on the quality of conventional fuels continues, such as on the analysis of very low sulphur fuel oil (VLSFO) and ultra-low sulphur fuel oil (ULSFO), the introduction of components for the production of environmentally friendly high-octane motor gasoline, and the determination of the properties of isooctane in various gasoline bases [38–41].

3. Alternative Fuels for International Shipping

3.1. Characteristics of Selected Alternative Fuels

Currently, the dominant fuel in international shipping is heavy fuel oil (HFO), which accounts for 79% of the total fuel consumption by energy in 2018, according to voyage-based allocation. However, significant changes in the fuel mix have been observed in recent years; e.g., HFO consumption decreased by approximately 7%, while marine diesel (MDO) and liquid natural gas (LNG) consumption increased by 6 and 0.9%, respectively. This was due to the Annex VI MARPOL requirements for the use of fuels with sulphur content up to 0.5% and 0.1% in Sulfur Emission Control Areas (SO_x-ECAs), as well as further regulations on CO_2 emissions from ships. There has also been a significant increase in the consumption of methanol, which has become the fourth most widely used marine fuel [4].

To put shipping on the path toward full decarbonisation by 2050, scalable zero-carbon fuels must account for 5% of the fuel mix in international shipping by 2030 [42]. Further, a 2019 UMAS study estimated that, for full decarbonisation by mid-century, zero-carbon fuels would need to account for 27% of the shipping fuel mix by 2036 and 93% by 2046 [43]. Moreover, according to EU research, renewable and low-carbon fuels should represent 6 to 9% of the fuel mix in international maritime transport by 2030 and 86 to 88% by 2050 to contribute to the EU's economy-wide greenhouse gas reduction targets, but this will depend on the scenario adopted [44].

In the medium term, the primary strategy must involve progressive but rapid replacement of fossil fuels with alternative, and preferably renewable, fuels. Industry must select future marine fuels by evaluating factors such as environmental impact, technical performance, availability, cost, and infrastructure [18].

3.1.1. LNG

LNG is a colourless mixture of gases, mostly methane cooled to condense into a liquid. It typically comprises more than 95% methane and a mix of less than 5% of other hydrocarbons, such as ethane, propane, and butanes. It is sourced from natural gas, which is extracted from gas fields. LNG is a cryogenic liquid that rapidly evaporates when exposed to normal atmospheric conditions [45].

Methane can also be obtained from biomass. Biomethane has similar properties to fossil-based natural gas. However, it contains a large percentage of CO_2, which must be purified to achieve biomethane purity over 95% before it can be used as a marine fuel. The high cost of purification is one of the main barriers to the wide adoption of biomethane as a fuel [46].

LNG has been ranked highly as a fossil fuel-based alternative by the shipping industry. With the increasing trend for cleaner shipping, the environmental benefits of using LNG as a new source of marine fuel have proven significant compared to existing marine diesel fuels. LNG has become the most adopted alternative marine fuel as of 2020 [47].

LNG emits approximately 25% less CO_2 than conventional marine fuels [48]. LNG propulsion produces only trace amounts of SO_x and particulate matters, and NO_x emissions can be reduced by 91.4% [49]. LNG is the cleanest fossil fuel available, but methane slip could cancel out its beneficial effects in terms of GHG reductions [50].

Although LNG as a fuel itself does not decarbonize maritime transport, unlike carbon-neutral fuels, its contribution to the decarbonization process is not negligible. The results of an investigation showed that LNG can serve as such a transitional fuel only if it is combined with the best engine technology; e.g., diesel dual-fuel engines [51].

3.1.2. LPG

Liquefied petroleum gas (LPG) is mainly composed of a mixture of propane (C_3H_8) and butane (C_4H_{10}) and contains small amounts of propylene and butylene. LPG combustion results in CO_2 emissions that are approximately 16% lower than those of HFO. As far as the complete lifecycle is concerned, including fuel production, the CO_2 savings amount to roughly 17% [52].

The IMO has discussed the possibility of drafting guidelines for the use of LPG as a fuel for ships [53].

The use of LPG as a fuel has been restricted because LPG is heavier than air and the ventilation and dilution of the leaked gas are disadvantageous. Comparing the properties of LPG and LNG makes it possible to determine the risks associated with the use of LPG as a fuel. One of the most important risks associated with LPG is the fact that it is characterized by composition volatility; hence, a change of the properties based on the composition ratio may result. Other basic hazards in the exploitation of LPG as a fuel include the formation of a flammable atmosphere at lower concentrations of fuel components and possible autoignition at lower temperatures.

3.1.3. Hydrogen

There are three classes of hydrogen: grey hydrogen, produced from hydrocarbon-based fuel; blue hydrogen, where grey hydrogen is accompanied by carbon capture technology; and green hydrogen, produced from renewable energy [54]. Currently, the major share of the produced hydrogen is generated via methane reforming, with methane normally being obtained from natural gas, and in some cases, oil and coal are also used to generate hydrogen

Green hydrogen, which is produced by using renewable energy, is the cleanest marine fuel, with zero carbon emissions [22]. Hydrogen is considered to be more advantageous in comparison to other fuels due to its high energy content per unit of mass and the availability of its primary source (when produced from water) [55]. The energy density per mass is approximately three times the energy density of HFO. The volumetric density of liquefied hydrogen is only 7% that of HFO. This results in approximately five times the volume compared to the same energy stored in the form of HFO [23].

Nevertheless, due to its low volumetric energy content, efficient application requires its liquefaction at −253 °C or compression to 700 bars [31].

Currently, two types of hydrogen have been analysed as fuel options: compressed hydrogen and liquefied hydrogen. Various applications for hydrogen are under consideration, such as in gas turbines, fuel cells, or internal combustion engines in stand-alone operations. The direct use of fuel cells is considered to be the most economical and efficient method for extracting energy from hydrogen [56]. Furthermore, the combustion of hydrogen may result in the formation of NOx, which does not occur in fuel cells.

Hydrogen in its natural state is colourless, odourless, and non-toxic. Due to hydrogen's properties, leakages can be difficult to detect. The hazards of hydrogen as a fuel include its low ignition energy and wide flammability range of between 4% and 77% when mixed with air. In the event of a fire, additional hazards are associated with the poor visibility of the flames and high flame velocity, which can lead to shockwave detonation [57].

Liquid hydrogen is costly and difficult to produce, transport, and store [58].

Several important aspects related to the transportation of hydrogen in bulk need to be considered to facilitate the further use of hydrogen as a fuel, in a similar way to what has been undertaken with other fuels, such as liquid natural gas (LNG) [59].

3.1.4. Ammonia

As mentioned in the Full Report of the Fourth IMO GHG Study 2020, ammonia is one of the promising alternative fuels [4].

Ammonia is a flammable gas but, while its lower flammability limit is high, its flammability range is not wide. Its spontaneous ignition temperature is 651 °C, which is higher than other conventional fuels, and the minimum ignition energy is 2000 times higher than methane. The most dangerous property of ammonia is its toxicity. Ammonia can be fatally toxic for humans depending on concentration and exposure time. Nevertheless, due to its unique smell, ammonia can be easily detected at 1.5 ppm, which is much lower than the level of 30 ppm at which it can harm the human body [60]. Although ammonia has a low risk of explosion, it is considered the first fuel to be labelled with the risk of explosive toxicity because its toxicity is fatal. Ammonia in the liquid phase is strongly corrosive, especially if mixed with water [61].

The maritime industry of today has experience in transportation of ammonia in gas carriers and using it as a refrigerant for cooling [30].

Due to its high hydrogen content, ammonia could be a future fuel option for shipping [56]. Similarly to hydrogen, ammonia can either be burned or used in a fuel cell. Additionally, a third option would be to use ammonia as a hydrogen carrier.

Ammonia has high hydrogen content but does not contain any carbon or sulphur molecules. As a result, combustion of ammonia does not emit any carbon dioxide or sulphur oxide. It has been estimated that, depending on the propulsion type and ammonia production method used, ammonia-fuelled ships could reduce GHG emissions by approximately 83–92% [62]. In particular, N_2O requires significant attention as it is a GHG with a higher global warming potential, almost 300 times greater than that of CO_2 [63].

Ammonia is currently mostly produced through the high-energy and carbon-intensive Haber–Bosch process. Current production accounts for 2% of global energy consumption and 1% of CO_2 emissions [64].

Another advantage of using ammonia is that its synthesis is relatively energy-efficient and, in contrast to hydrogen carriers, it can be used directly in a high-temperature fuel cell or burned in ICE without the need to carry out costly dehydrogenation steps on board [65].

LNG, liquefied ammonia, and liquefied hydrogen have different physical properties. Analysis has shown that liquefied ammonia and liquefied hydrogen are disadvantageous as far as maritime transportation costs are concerned due to their calorific values and densities per unit [66].

3.1.5. Methanol

Methanol has been gaining increasing attention in the shipping industry over the past decade. The main raw material in methanol production is natural gas. However, it can be produced from a variety of renewable feedstocks or as an electro-fuel. The data prove that methanol from organic sources is a feasible alternative for substitution, and it emits less CO_2 compared to methanol produced from natural gas [67]. In order to utilize methanol as an alternative fuel for marine use, current research and testing in the industry are focused on the use of agricultural waste and forest biomass as feedstocks for methanol production [68].

Methanol is the simplest alcohol, and it is a toxic, volatile, and flammable liquid. The flammable limits of methanol are between 6.7 and 36% vol. of methanol in the air. Compared to common fluids, such as diesel fuel, the fire risk is much higher. Methanol is classified as a category-three toxic substance and as a category-one hazardous substance for health.

However, its high oxygen content is conducive to more efficient combustion in engine systems [69]. Methanol is regarded as a pure fuel because consumption in internal combustion engines generates nearly zero SO_x and delivers reductions in CO_2. One of the key advantages of methanol fuel is its lower emission of NO_x [70].

Tables 2–6 provide an overview of the advantages and disadvantages of selected alternative fuels.

Table 2. An overview of the advantages and disadvantages of LNG as an alternative fuel for the shipping sector [45,47,48,51,52].

Advantages	Disadvantages
The cleanest fossil fuel available today	40% lower volumetric energy density than diesel; increases injection time when used in internal combustion engines
No SO_x emissions, particle emissions are very low	Twice the volume compared to the same energy stored in the form of HFO; requires more fuel tanks
The NO_x emissions are lower than those of MGO or HFO	The storage temperature is −160 °C; requires an additional cryogenic plant
High energy density: approximately 18% higher than that of HFO	Risk of fire and explosion

The technology required to use LNG as a ship fuel is readily available	Methane release (slip); requires the installation of an additional ventilation system
Available worldwide and investments are underway in many places to make LNG available to ships	Reduction in CO_2 is limited; limits the decrease in the Energy Efficiency Design Index
Bunkering infrastructure for ships is improving quite rapidly	Treated as a short-term solution, especially when targeting zero-emission shipping

Table 3. An overview of the advantages and disadvantages of LPG as an alternative fuel for the shipping sector [48,65,71].

Advantages	Disadvantages
More expensive than LNG but cheaper than traditional marine fuel (HFO)	Fuel tanks are larger than oil tanks due to the lower density of LPG Lack of bunkering infrastructure
Relatively easy to develop bunkering infrastructure at existing LPG storage locations or terminals by adding distribution installations	Reduction in CO_2 is limited
Fuel supply system is technically simple, so the construction costs are relatively low compared to those of LNG	Formation of flammable atmosphere Risk of autoignition
	Methane release (slip); requires the installation of an additional ventilation system

Table 4. An overview of the advantages and disadvantages of hydrogen as an alternative fuel for the shipping sector [31,55,56,58,72].

Advantages	Disadvantages
No emission of CO_2, particulate matter (PM) or SO_x	Low volumetric energy density, large fuel volume
High energy content per unit of mass	No distribution or bunkering infrastructure for ships
Suitable for relatively short distances	High flammability NO_x emission during combustion

Table 5. An overview of the advantages and disadvantages of ammonia as an alternative fuel for the shipping sector [30,61–63,66,73].

Advantages	Disadvantages
No emission of CO_2	Low volumetric energy density, large fuel volume
Already produced in substantial amounts	Release of high levels of NO_x during combustion of ammonia
Handling issues in maritime transport are already well-understood	N_2O emission
	Highly toxic and requires careful handling Strongly corrosive in its liquid state

Table 6. An overview of the advantages and disadvantages of methanol as an alternative fuel for the shipping sector [67,70,74].

Advantages	Disadvantages
Liquid at ambient temperature	40% lower volumetric energy density than diesel oil
Easy to store and handle	Methanol fuel tanks have sizes approximately 2.5 times larger than oil tanks for the same energy content
Lower emissions of NO_2 and CO_2 than the corresponding emissions with oil-based fuels	Low-flashpoint fuel that represents fire risk
Minor modifications to existing storage and bunkering facilities needed	Toxic when inhaled
Already available in some port bunkering infrastructures	
Readily biodegradable	

All the types of alternative fuels analysed are accompanied by both benefits and challenges. The transition to alternative fuels is very complex and requires in-depth economic, environmental, and technical analyses related to fuel production, transport, and bunkering infrastructure. In summary, each of the alternative fuels analysed has promising properties, but there are some significant challenges, particularly engineering challenges, that need to be addressed before their widespread implementation.

To comply with the environmental regulations and reduce costs, shipowners must evaluate alternatives to traditional fuels and technologies and decide which option is the best for a ship's actual operating conditions.

3.2. Lifecycle of Marine Fuels

When evaluating the environmental impact of a fuel, effects relating to the energy conversion in the engine are not the only important issues. Although the fuel may be compliant with the emission regulations for the engine, there may be adverse environmental effects that occur during production.

Some studies have focused on assessing the environmental impacts of different fuels used in sea transportation. When determining the benefits of different fuels from an environmental and cost perspective, it is very important to conduct an assessment spanning the fuel's lifecycle. Lifecycle assessment (LCA) addresses the environmental facets and potential environmental impacts of a particular product system throughout its lifecycle [30].

Lifecycle assessment is used for the assessment of the environmental impact of a fuel throughout its lifecycle, from fuel production to fuel consumption for ship operation (well-to-wake). In an LCA, the emissions contributing to environmental and health impacts, as well as the energy and resource use, are assessed. The potential contributions to different categories of the environmental impact, such as global warming and acidification, are thus predicted. LCA is a tool that is standardized in ISO 14040 [75].

Analyses indicate that the combustion of conventional fuels is responsible for about 80% of well-to-wake greenhouse gas emissions, while their production, or well-to-tank (WWT) phase, is responsible for about 20% of their emissions and energy consumption [26].

With so-called zero-GHG fuels, the picture becomes more complicated. In maritime transportation, the tank-to-wake (TTW) phase is responsible for the most significant influence on the total lifecycle performance. This phase accounts for 50–90% of the total lifecycle performance, depending on the impact of the fuel alternative. Greenhouse gas emissions (GHEs) are measured as CO_2 equivalent emissions. Figure 1 illustrates the CO_2 emissions of selected fuel alternatives.

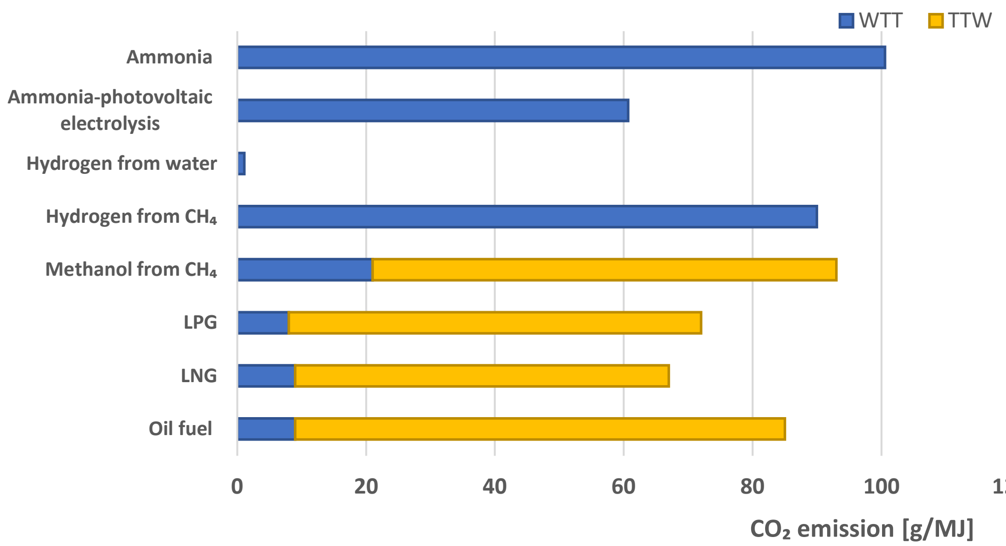

Figure 1. The CO_2 footprints of selected fuel alternatives [23].

Of all the relevant fossil fuels, LNG produces the lowest CO_2 emissions. However, the release of unburnt methane (so-called methane slip) can reduce the benefits compared to HFO and MGO. Hydrogen does not emit any GHGs when the power for propulsion is released in a fuel cell or engine, but large amounts of energy are needed to produce it. Ammonia forms no CO_2 when combusted but is characterised by higher N_2O emissions (a powerful GHG gas) than conventional fuels. Large amounts of energy are needed to produce ammonia [76]. When comparing the lifecycle impacts from different marine fuels in an LCA, it is usually concluded that the cleanest fuel is hydrogen produced using renewable energy (hydrogen from water). This parameter is also an important indicator of the possibility of producing a fuel at a competitive price [77].

The above considerations indicate that, at present (and probably also in the future), it is impossible to point to a one-size-fits-all solution, and the selection of an appropriate fuel option by shipowners and ports requires a great deal of in-depth consideration based on vessel type and age, trade routes, retrofitting costs, operating budget, safety issues, fuel price and availability, bunkering and storage infrastructure development, etc.

The question is what can be done to make these alternative fuels, assuming this is the desired pathway for reducing GHG emissions, a viable alternative to conventional fuels? A multifaceted approach seems to be key and, in particular, the inclusion of measures such as:

- Increasing the availability of marine alternative fuels in ports to provide bunkering options for shipowners;
- Introducing market-based measures to reduce the price differential between the marine alternative fuels and conventional fuels;
- Establishing a mechanism to fund both research and development (R&D), incentivize the "first movers", and ensure a fair and equitable fuel transition.

It should be emphasized that all three areas of action are equally important; however, in the remainder of the article, due to its subject matter, only point one will be discussed in more detail.

4. Development of Alternative Fuel Infrastructure in Ports

4.1. Ports on the Path to Decarbonising Shipping

Ports have often been overlooked when discussing the decarbonisation of shipping, as more attention has been given to the actions of shipowners. However, it should be recognized that ports, as transhipment hubs, can play an important role (and even be leaders) in the energy transformation of maritime and maritime-related transport [78]. Port authorities understand perfectly well that they cannot be passive in the decarbonisation process. This is reflected by, among other things, the conclusions of the recent ESPO Environmental Report 2022, which, for the first time since the start of monitoring, ranked "climate change" at the top of ports' environmental priorities [79]. Previously, from 2013, this place was held by "Air Quality", and it was treated more as a local pollution issue (emission of PM, NO_x, SO_x, and VOC), since many ports operate in close proximity to urban areas [80,81].

For more than a decade, many ports have been taking measures to contribute to decarbonisation, implementing changes affecting the ports themselves; the ships calling at ports (ships' movements in ports, ships' activities in the hoteling phase); the connection to the hinterland; loading and unloading operations, including storing and warehousing; and industries settled within the port area [82–84]. Hence, these are multidirectional activities, the most widespread of which are listed below, and numerous ports around the world have enjoyed many successes in this field:

- Reducing speeds in fairway channels [85,86];
- Incentive schemes for ships (e.g., differentiation of port dues) [87];
- More automated and effective cargo-handling operations; e.g., [88];
- Improved coordination and synchronization between ships and ports [87], such as just-in-time arrival for ships;
- On-shore power supply for ships;
- Reduced turnaround times at berth [89];
- Implementation of incentive programmes that facilitate fuel savings within the port area [90];
- Investment in green handling technologies and handling equipment, such as cranes, straddles, and truck trailers [91];
- Development of intermodal connections to and from the hinterland [85].

Currently, the role of ports is perceived as being more broad than just that of transhipment hubs since their importance as so-called "energy hubs" is increasingly recognised. This new role is also highlighted in the EC's new approach to the "blue economy": "…their future lies in developing their key role as energy hubs (for integrated electricity, hydrogen, and other renewable and low-carbon fuels systems)" [92]. Indeed, ports can also manage and administer the supply of alternative fuels [83] and provide the necessary infrastructure for their bunkering.

As shipping decarbonisation progresses, regular facilities for bunkering conventional fuels will gradually be supplemented by or replaced with facilities for bunkering and loading liquefied gases or hydrogen-based fuels over the next 25 years. This will require additional investment in storage facilities and infrastructure, as the lower energy density of alternative fuels may also require a higher number of bunkering facilities, since ships will have to refuel more frequently.

The International Association of Ports and Harbours (IPAH) has noticed that this may lead to the decentralisation of bunker fuel hubs, creating opportunities to modernise or develop bunkering infrastructure in the countries and ports that have so far not had a significant (or any) stake in this. With new business and development opportunities related to the energy transition in shipping, such ports can enter the global market for zero-emission bunker fuels [93].

It seems obvious that the decarbonisation of maritime transport without the active participation of ports is impossible to achieve, as both ports and shipping are inherently intertwined.

With the adoption of the IMO initial strategy, the role of ports in the decarbonisation process has been further emphasised. In addition to setting out the objectives of the strategy, as mentioned in Section 1, the strategy calls for, among other things, the promotion of port development to facilitate reductions in GHG emissions from shipping, including provisions for "infrastructure to support supply of alternative low-carbon and zero-carbon fuels" [10].

This call continued with the invitation for IMO member states to encourage voluntary cooperation between ports and shipping sectors to contribute to reducing GHG emissions from ships in resolution MEPC.323(74) 2019 [94] at IMO MEPC 74. Among other things, the resolution calls for the involvement of states in order "to promote the consideration and adoption by ports—within their jurisdiction- of regulatory, technical, operational, and economic actions to facilitate the reduction of GHG emissions from ships". One action explicitly highlighted is "safe and efficient bunkering of alternative low-carbon and zero-carbon fuels". In this regard, much attention has been given to facilitating the uptake of these fuels through cooperation between "ports, bunker suppliers, shipping companies and all relevant levels of authority in addressing the supply and availability of alternative low-carbon and zero-carbon fuels, including the legal, regulatory and infrastructural barriers to the efficient and safe handling and bunkering of alternative low-carbon and zero-carbon fuels".

However, there are no international binding regulations regarding the obligation for ports to invest in marine alternative fuel bunkering infrastructure, which does not mean that states are unable to independently establish such regulations for application in their territories.

For example, at the EU level, the 2014 Clean Power Transport Directive (2014/94/EU) provides for the building of, inter alia, LNG refuelling infrastructure. Article 6 of the directive stipulates that Member States should ensure an adequate number of LNG refuelling points at maritime ports by the end of 2025 to enable ships to circulate between seaports of the TEN-T core network. However, this provision is not mandatory; hence, the "Fit for 55" package mentioned in Section 1 includes a proposal to revise the 2014 directive and transform it into a regulation [95]. The proposed regulation establishes a number of mandatory, binding, and enforceable targets for the deployment of alternative fuel infrastructure in the EU for vehicles used in different modes of transport, including ships, and it is only a matter of time before this new piece of legislation is adopted.

4.2. Existing and Planned Alternative Fuel Bunkering Infrastructure

4.2.1. Research Methodology

A desk-research method was used to analyse alternative fuel bunkering infrastructure. Data were collected from databases provided by the recognized classification society Det Norske Veritas (DNV), the multi-industry coalition Sea-LNG, and the Methanol Institute, the most reliable institutions with information on vessels using these fuels and bunkering infrastructure. In addition, reports on the available infrastructure and scientific articles were used for the analysis. In order to find the most up-to-date information, seaport websites and reliable maritime portals were also analysed; in particular, the multimedia platform for port managers www.portstrategy.com/greenport. However, it should be noted that the data in the available databases varied and were incomplete and, in addition, sometimes inconsistent.

4.2.2. Research Findings

Infrastructure for ship bunkering is an important element of port infrastructure that relates to the storage and refuelling of ships. Currently, the ports with the largest bunkering capacities in the world are Singapore, Fujairah (United Arab Emirates), and Rotterdam (the Netherlands), the latter being the largest bunkering port in Europe [96]. On the path to decarbonisation, enabling shipowners to bunker alternative fuel is crucial, and this requires adequate bunkering infrastructure, which should be available in a sufficiently large number of ports [23]. Therefore, there are now a growing number of projects around the world involved in the development of such infrastructure.

Technically, ship bunkering can be achieved in a variety of ways—from waterside and landside—and the most common include [97]:

- Ship-to-ship (STS);
- Truck-to-ship (TTS);
- Port-to-ship (PTS).

Ship-to-ship bunkering involves the use of a barge or bunker ship, which is a vessel specifically designed to supply other vessels with fuels. Bunker barges have no propulsion and require tugboats to tow them to the vessel, and they are designed for use in port areas only. Bunker vessels, on the other hand, are propelled units and can be used in port areas and on the open seas as anchorage. The use of this method enables smooth loading and unloading operations in the port without any interruption, which is a definite advantage.

The truck-to-ship solution is based on the use of a tractor and a tank trailer equipped with hoses and a refuelling connection. The road tank trailer is positioned alongside the ship in the port and connected to it with a flexible hose, so it is a simple method that does not require a particularly sophisticated infrastructure. However, this method can be used for ships with relatively small power plants. Large ship power plants require several tractors and tank trailers.

The port-to-ship method, also known as shore-to-ship, requires dedicated infrastructure, such as storage, pipes, hoses, arms, and couplings, to connect a vessel. The advantages of this method are that the larger storage tank facilitates the bunkering vessels, which require a considerable amount of fuel. The fixed loading arm allows the use of a larger hose, thus enabling a higher flow rate and a shorter bunkering time [98].

4.2.3. LNG Bunkering Infrastructure

LNG-fuelled vessels represent the largest group of units using alternative transition fuels. According to available data, 320 vessels are already in service, and 518 units have been ordered [99]. In addition, there are 600 LNG carriers in service, the majority of which use the cargo as fuel [100]. LNG-powered passenger/car ferries and ro-ro-pax vessels lead the way, with 59 of such vessels in operation. The active fleet also includes 41 oil/chemical tankers, 40 container ships, and 41 crude oil tankers. Among the newly built units, container ships are the largest group with 178 in operation, followed by car carriers with 104. All PCTCs in yards' portfolios are LNG-fuelled [101].

The increasing number of LNG-fuelled ships has led to the development of suitable bunkering infrastructure. LNG as a fuel is currently available in 141 ports worldwide, with investments being made or planned in a further 55 ports [102]. Europe leads the way in LNG bunkering infrastructure, with the majority of prime ports offering access to bunkering services, followed by the major ports in Asia and North America.

Supply of LNG fuel to ships can be carried out with all three methods described above. As far as the ship-to-ship method is concerned, most bunker vessels are small LNG tankers, designed solely to provide fuel delivery services. However, there are also a few dual-purpose vessels in operation; i.e., delivering as well as bunkering LNG. There are an estimated 38 LNG bunker vessels in operation worldwide [103]. Their number has increased dramatically over the past three years: in 2019, there were only six bunker vessels in service, while a year later, their number had already doubled.

Europe and Asia are the regions where the ship-to-ship method is most developed. The largest number of bunker vessels, around 21, operate in Europe, with 5 bunker vessels operating in the Baltic Sea, 9 in the North Sea, and the rest in the Mediterranean (5) and Norway (2). In addition, ten small gas carriers with bunkering capabilities occasionally perform LNG bunkering operations in the region. Asia is the region with the highest number of bunkering vessels to have entered service since September 2021. There are an estimated ten bunkering vessels operating in the region. The others supply ships with LNG fuel at the US ports.

The order book includes 18 vessels that are expected to enter service by 2025, with a further 17 currently under discussion. These are to operate in Northern Europe, the Mediterranean, North America (the US and Canada), South Korea, Japan, Malaysia, China, Singapore, Brazil, and South Africa [102].

The PTS bunkering method is generally available in ports with LNG storage facilities. Bunkering takes place using LNG storage facilities, cryogenic tanks, and LNG export or import terminals located in the port area. The tanks are thermally insulated to maintain the storage temperature of −162°C. Larger volumes are usually stored in tanks with over 200,000 m^3 capacity located in prime LNG hubs [104].

The quay must be equipped with hoses, arms, and couplings to connect the vessel, as well as a pipeline connecting the quay to the supply facilities. The availability of this method of ship bunkering is not as widespread as bunkering with other methods due to infrastructure deficiencies. Infrastructure for PTS bunkering is primarily available in ports serving liner shipping (e.g., container or ro-pax vessels), as ships are berthed at fixed and dedicated berths. Examples of this are the large container hubs in Rotterdam and Antwerp and the ferry ports serving ro-pax vessels, such as Hirtshals and Klaipeda. According to the DNV database, the PTS method is available in 14 ports in Northern Europe and the Baltic Sea region and another 11 are under discussion, while very few PTS facilities are available in the Mediterranean (4), North America (2), and the Far East (1) [99].

The most popular method of LNG bunkering, since it requires the lowest investment, is TTS bunkering. A truck with a cryogenic tank with a capacity of 40–80 m^3 can be loaded with LNG directly from storage terminals located in seaports or on the mainland and can refuel vessels using a flexible hose supported by a mechanical arm or crane. This method of bunkering is considered a flexible solution because it can be used in any port without fixed infrastructure. However, it is necessary to maintain the temperature regime during TTS bunkering.

TTS bunkering is provided in the largest number of ports worldwide, primarily in Europe, Asia, and North America. It is available in both large and local ports and mainly serves LNG-fuelled liner vessels. In addition, it is offered in ports where LNG-fuelled ships enter occasionally, such as those operating in tramp shipping. The DNV reports 88 harbours in Europe, Asia, and America that offer this bunkering method [99].

4.2.4. LPG Bunkering Infrastructure

There are 28 active LPG-fuelled vessels and 93 on order. Nearly all of these are LPG carriers using cargo as fuel [99]. As with LNG, the network of LPG import and export terminals is well-developed worldwide. It is relatively easy to develop bunkering infrastructure in the existing LPG storage locations and terminals by simply adding distribution installations. Distribution to ships can occur either from dedicated facilities or from special bunker vessels. LPG can be effectively supplied as bunker fuel for ships using the existing facilities, such as terminals and refineries. The most important terminals where ships can be bunkered are located in major seaports, such as Singapore, Shanghai, Hong Kong, Busan, Rotterdam, Antwerp, Algeciras, Gibraltar, Fujairah, Houston, Panama, and Los Angeles.

All the methods are suitable for refuelling LPG-fuelled ships. Small LPG tankers are used for STS operations as bunker vessels, mainly in the world ports listed above. TTS bunkering is the best solution to refuel smaller vessels, such as ferries or offshore supply vessels. However, supplying LPG using trucks may involve capacity limitations due to semitrailer size and road limitations. PTS is the least commonly used method, as it requires permanent onshore infrastructure: tanks and fixed hoses or dedicated bunkering arms. The two latter methods are used in smaller local ports [105,106].

4.2.5. Methanol Bunkering Infrastructure

With 22 vessels in operation, the number of methanol-fuelled vessels is not very high. Among them is the first ro-pax ferry, "Stena Germanica", which was introduced into service in 2015 after conversion from HFO to methanol. The largest group, however, is currently made up of oil/chemical tankers (20), which were introduced by Methanex Waterfront Shipping between 2016 and 2019. As of 15 November 2022, the order book comprises 58 vessels [107]. The container segment leads the way with 47 orders. Most of the vessels ordered are dual-fuel vessels to be used in ocean services.

The infrastructure for the use of methanol as a fuel is based on the distribution of methanol to the chemical industry, which provides access to the fuel worldwide. According to the Methanol Institute, methanol was available at more than 100 ports in 2020, and 47 of these had storage facilities in excess of 50,000 metric tonnes [108]. Methanol terminals at seaports can be used for loading both bunker ships and tanker trucks for onward road distribution. There are fewer challenges in adopting methanol as a marine fuel compared to LNG or hydrogen. Investigations show that the handling and installation of a liquid such as methanol has clear advantages over gas or cryogenic fuels regarding fuel storage and bunkering. As methanol is a liquid, it is very similar to marine fuels, such as heavy fuel oil (HFO). This means that the existing storage, distribution, and bunkering infrastructure could be used for handling methanol. Only minor modifications of infrastructure are required [24].

For methanol-fuelled vessels, the truck-to-ship method is the most common, and virtually the only method, for bunkering ships other than methanol tankers. Methanol, as a product used in various areas of the economy, is transported by road to consumers in tanker trucks. In Europe, such transport is carried out under the provisions of the ADR international agreement. These tanker trucks are used for refuelling ships and must, therefore, be equipped with flexible hoses and arms. In general, the TTS method is considered suitable for bunkering smaller vessels, as well as for the delivery of relatively small quantities of fuel. However, larger ships are also currently refuelled using this method [109].

The expected increase in demand for this fuel has prompted projects using the ship-to-ship method. In May 2022, the methanol dual-fuel chemical tanker Takaroa Sun, owned by NYK Bulkship, was refuelled using this method for the first time in the world. The ship was refuelled directly from a barge and the operation was carried out in the port of Rotterdam. It is expected that the STS method of bunkering will be further developed in this port [110]. Moreover, in January 2023, the aforementioned ro-pax "Stena Germanica" became the first non-tanker vessel in the world to be ship-to-ship bunkered with methanol, as methanol was previously bunkered solely from trucks [111].

Two methanol bunkering vessel projects are currently being developed. The first, a 4000 DWT IMO type 2 chemical-oil tanker, will operate in Singapore. The other project is a 2000 DWT vessel with a cargo capacity of 2100 cubic metres. This project is a joint venture between OljOla Shipping, the owner with full technical management; Stena Oil, the commercial operator; and Stena Teknik, the project and newbuilding manager. The bunker vessel will operate in Northern Europe, with the port of Goteborg being the home harbour [112]. It is expected that Rotterdam and Goteborg will become bunkering hubs for methanol in Northern Europe.

4.2.6. Hydrogen Bunkering Infrastructure

The era of the use of hydrogen as a marine fuel began in 2021, when the first vessel entered service. The MF Hydra, a small car–passenger fjord ferry, became the world's first ship powered by liquid hydrogen. Currently, there are six hydrogen-powered units in service: small off-shore supply vessels, passenger boats, and a tug. There are 19 vessels with hydrogen systems in the order book, which are scheduled for introduction by 2028. Among these orders are seven cruise ships with dual-fuel LNG and hydrogen propulsion.

Here, hydrogen will be used primarily in ports for on-board hotel operations. The others include off-shore vessels, hydrogen tankers, and coastal passenger ships.

The infrastructure for hydrogen-powered vessels is currently less developed. Ustolin et al. report that there are only two facilities in the world: in the port of Hastings in Australia and in the Japanese port of Kobe. The former is for loading hydrogen tankers, the latter for unloading the same vessels. Both ports are equipped with loading and unloading pipes and storage tanks [113].

It is estimated that new infrastructure would cost over several billion USD in the coming decade [58]. However, several hydrogen bunkering projects have recently emerged in ports; they are likely to increase in number and are linked to newly built hydrogen-fuelled vessels.

In the Netherlands, the first hydrogen bunkering licence this year (2022) was granted at the port of Ijmuiden. It allows Windcat Workboats to bunker their Hydrocat 48 hydrogen-powered vessel, used to transport crew to and from offshore wind farms for construction and maintenance work [114].

Pilot studies are also being conducted in other European ports. For example, the port of Amsterdam signed a memorandum of understanding with tank storage company Evos and a liquid organic hydrogen carrier LOHC Maritime to develop large-scale hydrogen import facilities at the port of Amsterdam. These facilities will include an LOHC dehydrogenation plant with a final release capacity of up to 100–500 tonnes of hydrogen per day, as well as associated storage and handling facilities. Another example is the port of Hamburg, where the first large-scale green energy import terminal is planned [115].

Gaseous hydrogen should be bunkered for a relatively short period of time, requiring less time than loading and discharging of cargo [56]. Liquid hydrogen may be bunkered similarly to LNG. Hydrogen refuelling and bunkering infrastructure must be approved by the relevant authorities, including regional authorities, governments, and fuel suppliers. In addition, it must meet the requirements stipulated in the forthcoming road transport regulations and also match the fuel arrangements for individual vessels [116]. The choice of bunkering method (STS, TTS, PTS) depends on the number of vessels using the fuel and calling at the port and the profitability of the investment.

4.2.7. Ammonia Bunkering Infrastructure

Currently, no ships are in service that use ammonia as fuel. However, the first ammonia fuel-ready vessel was delivered in 2022. It is a tanker currently operating on conventional fuel that meets the ABS Ammonia Ready Level 1 requirements and is designed to be converted to ammonia use in the future. The DNV reports that the first ammonia vessel will be a tanker carrying this cargo. There are currently around 200 gas carriers that can carry ammonia, which are deployed both for both short-haul operations and worldwide. In the near future, ammonia may enter other market segments, such as bulk and container shipping [117].

Terminals serving the ammonia seaborne trade are located in 132 ports around the world. Of these, 38 are export and 88 are import terminals, including six ports with both export and import terminals [118]. Where ammonia or fertilizer factories are located within a port area, the terminals are part of the plants and are equipped with ammonia loading and unloading facilities. Some factories are situated in the hinterland, in which case the terminals or ammonia quays are part of the commercial ports and are equipped with, in addition to handling facilities, ammonia storage. The storage space generally includes isothermal tanks and spherical pressure storage tanks, pipes and valve systems are used in liquid ammonia discharging arms for pumping ammonia in and out of ships [118].

The global distribution of ammonia sea terminals and cargo storage is relatively dense, with locations in ports situated along prime shipping routes. In Northern Europe, there are terminals, primarily import terminals, located in major harbours, including Rotterdam, Antwerp, and Le Havre; however, most are in smaller regional ports; e.g. on the Baltic and North Seas, such as Police (Poland), Venspils (Latvia), Rostock and Brunsbuttel

(Germany), and Ambes and Rouen in France [118]. The numbers of terminals in the Mediterranean are lower compared to Northern Europe, and they are located in small ports; e.g., in the ports of Sagunto and Castellon (Spain), Annaba (Algeria), Gabes (Tunisia), and Ali Aga (Turkey). In general, there is a lack of terminals in southern France, Italy, and the Adriatic ports. There is a dense grid of terminals located in the Mexican Bay, primarily in the US ports, and in Asia, with India, China, Singapore, Japan, and South Korea dominating [118].

These terminals are equipped to store this product and may in future be used as suppliers for ship bunkering. The transfer of ammonia for bunkering purposes is similar to that of LNG. Moreover, recent research has shown that converting LNG storage tanks and the corresponding technology to ammonia storage technology is possible without any extensive adjustments, since the materials used for full-containment and single-containment LNG tanks are generally compatible with the refrigerated ammonia tanks [119]. Liquid ammonia allows for storage of more energy per cubic meter than liquid hydrogen and, moreover, without the need for cryogenic temperature storage, as is needed with liquid hydrogen. Storing ammonia at −33.4 °C is technologically easier and cheaper than storing hydrogen at −252.9 °C [120].

As far as the port-to-ship method is concerned, there are only two ports currently bunkering ships in this way, which are located in Norway. There is no information available on the possibility of bunkering using the truck-to-ship method.

A number of projects have been developed to meet future demand for ammonia bunkering. One example is the Green Ammonia mega-project off the Suez Canal. The project is led by the Green Fuel Alliance consortium, which signed a memorandum of understanding with Egyptian institutions to develop infrastructure for ammonia-fuelled and hydrogen-fuelled vessels passing the Suez Canal [121]. Another project, Azane Fuel Solutions' Ammonia Fuel Bunkering Network, is underway in Norway and concerns the first floating ammonia terminal, which is to be launched in 2024 [122].

Table 7 provides a brief summary of the key data described in the text above.

Table 7. Summary of numbers of vessels, fuel availability, bunkering methods currently in use, and planned infrastructure regarding bunkering alternative fuels.

Type of Fuel	No. of Ships		Fuel Availability	Bunkering Method Currently Used			Port Infrastructure Availability		Location	
	Active	In Order	Sea Terminals	STS	PTS	TTS	Existing	Planned	Existing	Planned
LNG	320	518	High	Y	Y	Y	Y	Y	W	W
LPG	28	93	High	Y	Y	Y	Y	Y	W	W
Methanol	22	58	Limited	Y	N	Y	Y	Y	NE	E/SA
Hydrogen	6	19	Limited	N	N	Y	Y	Y	NE	NE
Ammonia	0	0	Limited	N	Y	N	Y	Y	NE	MED, NE

Y—yes; N—no; W—worldwide; E—North Europe; SA—South Asia; MED—Mediterranean.

5. Level of Advancement of Polish Ports in Bunkering Alternative Fuels for Ships

5.1. Research Methodology

The aim of this study was to assess the level of advancement of Polish ports in bunkering alternative fuels for ships and to explore the ports' plans to adapt to the changing environment in this context.

Insight into this topic is important due to the significant role of these ports in the Baltic Sea region. It is enough to mention that the port of Gdansk, for example, is the largest container port on the Baltic Sea and the second largest port on the Baltic Sea in terms of total cargo handling. Table 8 shows information providing a cursory overview of these ports.

Table 8. Selected parameters for the ports as of 2022.

	Port of Gdańsk	Port of Szczecin-Świnoujście	Port of Gdynia
Surface area (land)	1092 ha	679 ha	973 ha
Total length of quays	23.7 km	11.1 km	11.2 km
Total turnover	68.2 M tonnes	36.8 M tonnes	28.2 M tonnes
Container turnover	2.07 million TEU	75,381 TEU	986,000 TEU
Max. draught	17 m (outer port), 10.2 m (inner port)	13.5 m	13 m

A qualitative research method was chosen as the most appropriate for this study. Given the topic and purpose of the study, a semi-structured approach was chosen for the interviews. Accordingly, semi-structured interviews were conducted using an interview protocol consisting of 12 major open-ended questions (see Appendix A), while leaving open the possibility of prompting for and further discussing issues that arose during the interviews [123].

A request was sent to the authorities of three major Polish ports—the port of Gdynia, the port of Gdańsk, and the port of Szczecin-Świnoujście—asking for an interview to take place and providing an interview questionnaire to help prepare for the interview. Initially, all interviewees preferred to give only written responses. Unfortunately, the answers were evasive or very general, so renewed requests for a personal meeting or an online interview were sent, to which two ports agreed. Each interview lasted about 1.5 h and was conducted in early November 2022. The data were captured through note-taking, as none of the participants consented to be recorded.

The respondents were appointed by the ports' CEOs and were those individuals with the best understanding of the issues at stake, while the written responses were official and prepared by the relevant persons or departments, also appointed by the CEOs. When interviewed, the respondents were very cautious and repeatedly claimed that they could not provide certain information due to confidentiality reasons. Sometimes, they provided such information but also claimed that it could not be used in the article. However, the information was very valuable, as it gave the authors a broader perspective and deeper insight into the topic.

The analysis of the interview data was organized using codes that were initially named according to sections in the interview protocol. These were supplemented with in vivo codes; i.e., words or phrases actually used by participants that were relevant to the research question.

The survey could not be deepened to an extent that satisfied the authors due to the insufficient knowledge and preparation of the respondents, as the survey covered a wide range of topics and the use of alternative fuels is still at an early stage of implementation.

5.2. Results and Discussion

5.2.1. Current State and Plans (Code One)

The first thematic code deals with the existing infrastructure enabling bunkering of alternative fuel vessels, as well as investments that are being planned or under consideration.

Poland's only LNG import terminal is located in the port of Świnoujście, to which imported LNG is delivered by gas tankers from Qatar and the US. Within the country, the raw material is distributed via pipelines and road tankers or transported in ISO containers. By 2027, a modern FSRU terminal is to be built in the port of Gdańsk, which will strengthen the importance of this part of the coast in the economic map of the Baltic Sea region and open the possibility of direct bunkering of LNG-fuelled ships. According to the respondent, the investment is at the stage of designing the wharf together with the undersea section of the gas pipeline, which will run along the bottom of the Gulf of Gdańsk.

There are two LPG terminals of different sizes: one in the northern port in Gdańsk, which is an import–export bulk terminal, and the other, smaller one in the port of Gdynia. Both are served from the landside by road and rail tankers and can handle bunkering operations for LPG-fuelled ships.

With regard to the possibility of hydrogen bunkering, currently, only the port of Gdynia is considering such an option and making efforts to establish a hydrogen hub. The goal of such hubs is to decarbonise port terminals by using hydrogen to power equipment, producing and storing green hydrogen near the port, and using hydrogen to power ships calling at the port. In this regard, the port signed a letter of intent regarding cooperation in the field of hydrogen management with the Estonian port of Tallinn.

As far as ammonia and methanol bunkering are concerned, the respondents revealed that this topic is not currently being addressed. However, it is possible to make some assumptions about this, given the specific ferry and container shipowners that regularly use the port's services and their preferences in terms of alternative fuel choices. For example, one of the largest container operators, A.P. Moller-Maersk, the ocean-going vessels of which regularly call at the port of Gdańsk for the Baltic Hub terminal, has announced that it has ordered 19 vessels with dual-fuel engines capable of operating on green methanol [124]. Perhaps, then, bunkering infrastructure for this fuel will be built in the port of Gdańsk. Table 9 summarizes the above considerations.

Table 9. Alternative fuel bunkering infrastructure: existing, planned, and under consideration.

	Port of Gdańsk	**Port of Szczecin-Świnoujście**	**Port of Gdynia**
LNG	Planned in 2027: regasification LNG terminal (FSRU); capacity up to 6.1 billion m³ per year	LNG import terminal; two cryogenic LNG storage tanks with a capacity of 160,000 m³ each	-
LPG	LPG terminal (import and export) on the territory of the northern port in Gdańsk; 16 diked tanks with a total storage capacity of 13,200 tonnes	-	LPG terminal; 12 storage tanks with a total capacity of approx. 1500 tonnes
Methanol	Possible	Not yet discussed	Not yet discussed
Ammonia	Not yet discussed	Not yet discussed	Not yet discussed
Hydrogen	Not yet discussed	Not yet discussed	Under consideration

5.2.2. Bunkering Methods (Code Two)

The second thematic code deals with bunkering methods that are currently in use or planned.

Currently, only truck-to-ship bunkering of LNG-fuelled ships is available in Polish ports. In the port of Gdańsk, bunkering takes place at one designated quay, for which safety plans have been developed and approved. In other ports, there are designated wharves, which, due to their parameters and technical conditions, offer the possibility of conducting LNG bunkering operations via road tanker from the landside.

The first LNG bunkering operations at Polish ports took place in March 2019, one in the port of Gdynia and one in the port of Gdańsk, accompanied by numerous media reports. At that time, LNG was pumped from tanker trucks into bulk carriers that did not regularly call at ports. So far, the number of ships supplied with LNG fuel is not impressive, amounting to only 12, the same ones that initiated the ports' experience with LNG bunkering.

Table 10 summarizes the bunkering methods available in Polish ports, limited to LNG fuel as this is the only one currently in use.

Table 10. LNG bunkering methods available in the surveyed Polish ports.

	Port of Gdańsk	Port of Szczecin-Świnoujście	Port of Gdynia
Ship-to-ship	Under consideration	Under consideration	Under consideration
Truck-to-ship	In operation	In operation	In operation
Port-to-ship	Not yet discussed	Under consideration (ferry terminal)	Under consideration (ferry terminal)

The currently used truck-to-ship bunkering method is, relatively, the cheapest and the most flexible. According to the information received, ports have considered the possibility of future use of ship-to-ship and tank-to-ship bunkering methods, but whether this becomes a reality will depend on the volume of demand for alternative fuel supplies and the availability of funds.

One respondent shared the observation that: "unfortunately, it is the case when words, and intentions are not followed by action", while another said, "there is a lot of inertia when it comes to decision-making at different levels". The project to build an LNG bunker ship can serve as an example. Even before LNG bunkering in ports began, one of the ports surveyed had signed a letter of intent with fuel suppliers regarding the construction of a barge adapted to bunkering other ships with LNG (ship-to-ship method). The project was to be implemented under a program of the National Centre for Research and Development (NCBR), which has so far failed to produce any results.

At this point, it should be noted that these ports (ferry terminals) are already regularly used by ferry operators with ships that could be ready to switch to an LNG fuel. There are three dual-fuel and LNG-ready ferries that will join the Świnoujście (Poland)–Ystad (Sweden) ferry line in 2025–2027. LNG-ready ferries already call at the ferry terminal in the port of Gdynia but, currently, due to the high price of LNG fuel, do not yet use it, but this does not mean that this will not change in the near future. This means that the ports hosting these ships will have to provide them with fast and safe bunkering facilities.

5.2.3. Demand Analysis (Code Three)

The third thematic code concerns the survey of shipowners' demand for alternative fuels.

Polish seaports are aware of changing trends in ship refuelling. Thus, they are studying (to a greater or lesser extent) the demand among the maritime fleet for particular types of fuel as alternatives to fossil fuels. The most extensive research was carried out by the port of Gdynia, which surveyed potential customers—shipowners—several times, considering this as part of its cooperation with other ports in the Baltic Green Corridor initiative (see code seven). One of the objectives of the survey was to determine the type of alternative fuel that shipowners would like to refuel with at the port of Gdynia. On the other hand, the port of Szczecin, as part of the expansion of the LNG re-export facility, carried out a feasibility study that considered market demand for alternative fuels. However, the port has not carried out a direct analysis of the demand for such fuels among its customers; i.e., shipowners. Poland's largest port, Gdańsk, has also declared that it is analysing the possibility of implementing infrastructure for alternative fuels, such as hydrogen, methanol, ammonia, and LNG, in the port. Permanent contact between port representatives and the shipowner community is supposed to help in making the right choice of fuel for which bunkering infrastructure would be prepared.

The port of Gdynia's survey was addressed to both liner and tramp carriers and covered all possible fuels. The greatest demand for alternative fuels, especially LNG, was declared by ferry and freight ro-ro shipping operators. Relatively high future demand was also reported for the container sector. An analysis of the fuel market carried out by the port of Szczecin showed that the ferry operators were those most interested in alternative fuels.

The port of Gdańsk, on the other hand, for reasons of confidentiality, has not revealed which shipowners in which segment of the shipping market would be willing to use bunkering of alternative fuels in the future. In fact, it is not even known whether such a study was conducted at all.

It should be emphasised that the ports analysing fuel supply options are seeing changes in the shipbuilding market, with the majority of vessels ordered being dual-fuel (diesel + alternative fuels). The main types of alternative fuels of interest to shipowners are LNG and methanol. These trends are reflected in the numbers of orders for new ships that will have such LNG- or methanol-fuelled propulsion capacities (see Section 4.2).

5.2.4. Funds (Code Four)

The fourth thematic code concerns the financing of the technical facilities for bunkering.

As there are no final decisions about the construction of future marine alternative fuel bunkering terminals, various sources of funding are being considered. These will depend on the type of bunkering berths and the strategy adopted for their construction.

A problem often raised by the interviewees was the difficulty of obtaining funding ("*We have plans, but we don't know if we will get the money to realize them*"). The bunker concept mentioned above is not being implemented due to a lack of funds. There are also insufficient funds for reliable market research and analysis. In addition, these problems are exacerbated by the uncertain political and economic situation in the region [125].

It is believed that the investment needed to improve the availability of alternative fuels in ports could be a joint financial venture between the port and the externally raised capital. All ports envisage various sources of funding for ship bunkering infrastructure, both their own and external funds. Of great importance is the possibility of obtaining funding from the EU projects and EU funds (e.g., the Connecting Europe Facility (CEF)), as all ports are located in the Baltic–Adriatic Corridor, which is part of the TEN-T network. In addition, joint financing projects involving the port authorities and external investors who would manage the completed infrastructure are being considered. As the interviewees pointed out, sources of funding are difficult to clearly identify at present, as there are no specific investment projects being planned.

Among the external entities that could be involved in the construction of bunker infrastructure in the future, the ports mainly mentioned state-owned companies from the energy sector, without revealing their names for commercial reasons.

5.2.5. Uncertainty (Code Five)

The fifth thematic code (in vivo code) deals with the concept of uncertainty in the broadest sense, as during the interviews there were many statements attributable to this concept. The interviewees often used such sentences and phrases as, *"who knows it", "no telling what the future will bring", "this whole topic is a big question mark", "we have many doubts"*.

Indeed, port investments in the development of bunkering infrastructure are accompanied by a number of uncertainties, of which the interviewees highlight those listed below in particular:

- Uncertainty about what fuel will become the fuel of the future in shipping;
- Uncertainty about the availability of fuel if competition for it with other sectors of the economy begins;
- Uncertainty about the international and national regulations and the timing of the implementation of the requirements contained therein;
- Uncertainty about the economic and political situation in the country, which could make it difficult to raise funds for the construction of the necessary bunkering infrastructure;
- Uncertainty about the safety associated with the use of alternative fuels (in particular, hydrogen and ammonia).

These statements related to uncertainty are addressed in many places in the text of the article, so there is no need to develop all of them here. Primarily, port authorities do not know what fuel will become popular with shipowners, especially those using their services. Thus, there is a fear that ports will be left with unused assets in the form of the infrastructure for bunkering a particular alternative fuel should it turn out that another fuel becomes the choice of shipowners. Shipowners would then move to another port where it would be possible to bunker the fuel of their choice, which would mean a loss of the market for the ports.

In turn, many shipowners are also hesitant to switch to zero-emission fuel because they do not know what fuel will be widely available on the market, what its price will be, and whether ports will have the capability to supply it.

It is a classic “chicken and egg” dilemma, with both ports and shipowners waiting for the latter to make choices and investments that will direct the market.

Both ports and shipowners are equally uncertain about the shape of the future regulations to reduce shipping emissions and the market-based measures that would support this process. Discussions at the IMO on these market-based measures, alternative fuels, safety rules for their use, etc., are protracted, as the often conflicting interests of various member states collide there, making it difficult to reach the consensus that the entire shipping industry is waiting for.

These uncertainties mean that ports are afraid to make investment decisions and instead focus on monitoring the activities of other ports in the region.

5.2.6. Safety (Code Six)

The sixth thematic code (in vivo code) deals with the safe use of alternative fuels.

The interviewees indicated that the safe use of alternative shipping fuels is one of the most important challenges for global shipping. The lack of experience in operating with alternative fuels, particularly hydrogen and ammonia, raises legitimate concerns due to their hazardous properties (described in Section 3).

These concerns are fully justified, as the port of Gdynia, for example, is an urban port surrounded by residential neighbourhoods. Any incident involving these fuels would pose a threat to the local community: “I can’t even imagine the consequences if, for example, there was a hydrogen leak”, said one interviewee.

As for LNG, despite the experience gained in bunkering it, it still requires much more care and caution than conventional marine fuels because the release of LNG during the process is difficult to control and could lead to an uncontrolled fire or explosion. This means that ships that want to use it must carry out a risk assessment procedure that demonstrates that the fire safety of the LNG is at least equivalent to that of conventional fuel. Due to the high flammability of LNG, it is necessary to study safety issues related to LNG operations, the safety exclusion zone for LNG bunkering sites, and the risk of fire on board LNG-fuelled vessels.

The interlocutors stressed that the way in which these risks are managed when bunkering alternative fuels in Polish ports is governed by regulations, class rules, guidelines, and standards. The guidelines in place in Polish ports cover all aspects of the safe storage and bunkering of LNG in ports. The bases for their development are international and local regulations and maritime administration regulations. All the parties involved in the process are required to strictly adhere to them. The bunkering conditions are established in each case by the supplier with the representative of the maritime administration responsible for port safety. The final confirmation of the possibility of bunkering at the indicated berths and the established conditions are verified at the stage of risk assessment for individual locations. All the described activities show that, in Polish ports, safety is not a barrier to bunkering and the use of LNG as a marine fuel.

5.2.7. Cooperation (Code Seven)

The last thematic code addresses the problem of cooperating in order to facilitate the availability of alternative fuels. It refers to cooperation in a broader context: cooperation between seaports and shipowners, between ports, and between ports and governments or other stakeholders (e.g., fuel suppliers).

Indeed, some countries, shipping-related industries, ports, and shipowners have already undertaken voluntary cooperation to support the establishment of zero-emission maritime routes and corridors (so called "green shipping corridors") in order to demonstrate and trial low-carbon and zero-carbon technologies and fuels. Such cooperation aims at a better understanding of their development, costs, and impacts, as well as at exploring opportunities and challenges [126]. Collaboration in green shipping corridors can also help decision makers decide in which direction regulatory actions, financial incentives and support, specific safety solutions, etc., should be oriented. Through initiatives in green corridors, a kind of spillover effect may be created, proving that certain solutions are possible and helping to accelerate decarbonisation, which will reduce emissions from shipping in other corridors [126].

Only the port of Gdynia can enjoy cooperation at the international level, but it was initiated by other ports. The port participates in the Green Corridor Initiative as a partner in the Green Corridor in Northern Europe and the Baltic Sea project led by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. As part of this project, it works closely with the ports of Rotterdam, Hamburg, Tallinn, and Roenne. At this point, it is worth noting that this corridor is one of 21 green corridors that have already been initiated [127], but this has come about through agreements and MoUs among participants in particular shipping routes rather than through exhaustive studies and formal declarations [128]. These green corridors are the aftermath of the Clydebank Declaration on Green Shipping Corridors presented at COP26 in Glasgow, to which 24 countries are now signatories (as of 5.02.23). Poland, unfortunately, has not signed this declaration.

Ports are signalling problems related to cooperating with shipowners in obtaining information about their plans to switch to alternative fuels. As it turns out, shipowners are often reluctant to share such information, even though trust-based cooperation with ports should be in their interest. This was illustrated explicitly by a statement from one of the respondents: *"Many shipowners ignore inquiries, as if it were not in their interest. We don't know if they have plans or not, or if they do and don't want to disclose them"*.

Difficult to understand, though it remains a fact, is the lack of such cooperation at the national level, which was emphasized by interviewees, who said: *"We all face the same problem, but we don't talk about it"* and *"We do not share information, it is 'every man for himself' situation"*. Such a lack of cooperation and joint effort to offer the possibility of bunkering alternative fuels in Polish ports on a wider scale may cause the ports to lag behind the competition.

6. Conclusions

It is currently impossible to identify a one-size-fits-all fuel solution that could drive future zero-emission shipping. It seems that, since the nature of global shipping is heterogeneous, the fuel adopted and development paths chosen should also be heterogeneous.

Analysis of the information obtained indicates that LNG has now become the most widely used alternative fuel of interest to shipping. With the rapid development of bunkering infrastructure, LNG is now the main alternative to marine diesel and heavy fuel oil (MDO and HFO). The demand for LNG-fuelled ships worldwide illustrates the great interest of shipowners and operators in using LNG as a marine fuel. It is therefore encouraging that Polish ports are prepared for LNG bunkering, albeit on a small scale for now.

The use of methanol as a future prospective marine fuel has recently attracted a great deal of attention from shipowners due to its clean combustion and the possibility of obtaining supplies from various sources. Plans for the development of bunkering berths should therefore consider the possibility of supplying ships with this type of fuel, especially since the number of ships ordered to run on this fuel is increasing. Fuels such as ammonia and hydrogen are promising but at present have not yet reached the required technological maturity to become widely available for shipping.

Ports have to play a key role on the road to zero-carbon shipping by enabling shipowners to bunker alternative fuels depending on their needs. With the increase in the number of vessels using alternative fuels, the number of ports where it is possible to bunker such fuels is also growing. Thus, it is the LNG bunkering infrastructure that is the most developed. In general, European ports lead the way in the development of bunkering infrastructure, followed by major ports in Asia and North America. In contrast, for other fuels, the bunkering infrastructure is either only in the testing phase, in pilot projects, at the stage of investment plans, or not being considered at all at this stage.

Infrastructure is mainly developing in ports handling container shipping on Asia–Europe and Asia–North America routes as a direct result of an increase in orders for the construction of new container ships using specific alternative fuels.

Ensuring the availability of alternative fuels, such as LNG, methanol, and hydrogen, in Polish seaports is a challenge they must face in the coming years. Changes in the order books of shipyards indicate that the importance of alternative fuels is growing. Therefore, investment in bunkering facilities for vessels powered by alternative fuels should become one of the priorities for these ports.

The level of advancement of Polish seaports in the construction of bunkering infrastructure for alternative fuels is relatively low. While some ports are quite advanced in their planning to cater to the needs of vessels using alternative fuels, Polish ports are still in the early stages of conversations with their stakeholders to identify which new fuels should be included in their plans. In this regard, ports' experiences are limited to only a few bunkering cases with LNG fuel, and a preliminary market survey is currently being conducted. Therefore, it seems necessary to take action to accelerate investments in adapting the infrastructure of Polish ports to the changing trends.

One of the key decisions is to determine which type of fuel the bunkering infrastructure should be expanded for. This is even more challenging because shipowners also find it difficult to evaluate alternatives to traditional fuels and decide which fuel option is the best for ships' actual operating conditions. This uncertainty can be reduced through closer cooperation between ports and shipowners, between individual ports, and between ports and other shipping stakeholders. Unfortunately, there is a lack of cooperation between Polish ports in this area, as well as with the relevant government departments, whose lack of involvement either as regulators or coordinators is noticeable.

Since the issues addressed in the article are changing dynamically and each day brings new reports on the subject, this article is the first contribution to the study of the progress of Polish ports in developing infrastructure for alternative fuel bunkering.

Author Contributions: Conceptualization, M.K., M.P., and I.U.-P.; methodology, M.K. and M.P.; software, M.K. and M.P.; validation, M.K., M.P., and I.U.-P.; formal analysis, M.K., M.P., and I.U.-P.; investigation, M.K., M.P., and I.U.-P.; resources, M.K., M.P., and I.U.-P.; data curation, M.K., M.P., and I.U.-P.; writing—original draft preparation, M.K. and M.P.; writing—review and editing, M.K., M.P., and I.U.-P.; visualization, M.K. and M.P.; supervision, M.K. All authors have read and agreed to the published version of the manuscript.

Funding: The publication fee was financed by Gdynia Maritime University's grants: "Monitoring and analysis of the impact of selected substances and materials in terms of environmental protection (project grant number WZNJ/2023/PZ/10) and "Chain management models in a turbulent environment - assessment of the current state and directions of their evolution" (project grant number WZNJ/2023/PZ/06).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Interview questions:

Group 1

(1) Has the port carried out an analysis of shipowners' demand for alternative fuels, taking into account the specific type of fuel such as e.g., methanol, hydrogen, ammonia, LNG, LPG or other?
(2) Which shipowners have expressed interest in the availability of alternative fuels at the port? (If shipowners cannot be named, please indicate the scope of their activities: ferry and ro-ro shipping, short sea container shipping, ocean shipping, tramp shipping).
(3) What type of fuel would potential shipowners be interested in and what would guide their choice?
(4) Have there been discussions or consultations with shipowners and representatives of other ports concerning the so-called Green Corridors or route activities?

Group 2

(1) Are discussions taking place with possible suppliers of alternative fuels? Will the chosen fuel be produced in Poland or will it be imported from abroad?
(2) Are potential suppliers of these fuels at all interested in cooperating with the port?

Group 3

(1) What solutions for the supply and storage of a particular type of alternative fuel are being considered by the port?
(2) What was the rationale behind the choice of a particular fuel bunkering method (ship-to-ship, track loading, bunker vessel loading, local storage, tank-to-ship, other)?
(3) How does the Port plan to manage the risks associated with alternative fuel bunkering (safety issues related to transport, possible storage, and the bunkering process itself)?
(4) When are the technical facilities for the bunkering of alternative fuels planned to be realised?

Group 4

(1) What are the sources of funding for bunkering infrastructure (in the context of alternative fuels) and related R&D: Port Authority's own funds, funds of an external investor (infrastructure operator, PPP, EU funds)?
(2) Which institutions and onshore companies are involved in the development of infrastructure for alternative fuels (State Treasury companies, private companies)?

References

1. United Nations. *UNCTAD Review of Maritime Transport 2022*; UN: Geneva, Switzerland, 2022.
2. IEA. *International Shipping*; IEA: Paris, France, 2022. Available online: https://www.iea.org/reports/international-shipping (accessed on 10 October 2022).
3. Tan, E.C.D.; Hawkins, T.R.; Lee, U.; Tao, L.; Meyer, P.A.; Wang, M.; Thompson, M. Techno-Economic Analysis and Life Cycle Assessment of Greenhouse Gas and Criteria Air Pollutant Emissions for Biobased Marine Fuels. Available online: https://www.maritime.dot.gov/innovation/meta/techno-economic-analysis-and-life-cycle-assessment-greenhouse-gas-and-criteria-air (accessed on 1 November 2022).
4. Faber, J.; Hanayama, S.; Zhang, S.; Pereda, P.; Comer, B.; Hauerhof, E.; van der Loeff, W.S.; Smith, T.; Zhang, Y.; Kosaka, H.; et al. *Reduction of GHG Emissions from Ships—Fourth IMO GHG Study 2020—Final Report*, International Maritime Organization (IMO): London, UK, 2020.
5. Smith, T.W.P.; Jalkanen, J.P.; Anderson, B.A.; Corbett, J.J.; Faber, J.; Hanayama, S.; O'Keeffe, E.; Parker, S.; Johansson, L.; Aldous, L.; et al. *Third IMO GHG Study 2014*; International Maritime Organization (IMO): London, UK, 2015.
6. European Commission. *2020 Annual Report from the European Commission on CO_2 Emissions from Maritime Transport*; COM(2021) 6022 Final; European Commission: Brussels, Belgium, 2021.
7. UNFCCC. The Paris Agreement. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed on 29 May 2020).

8. IMO. *Resolution MEPC.203(62) Amendments to the Annex of the Protocol of 1997 to Amend the International Convention for the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto—(Adopted on 15 July 2011) (Inclusion of Regulations on Energy Efficiency for Ships in MARPOL Annex VI)*; International Maritime Organization (IMO): London, UK, 2011.
9. IMO. *Resolution MEPC.350(78) Guidelines on the Method of Calculation of the Attained Energy Efficiency Existing Ships Index (EEXI) (Adopted on 10 June 2022)*; International Maritime Organization (IMO): London, UK, 2022.
10. IMO. *Resolution MEPC.304(72) Initial IMO Strategy on Reduction of GHG Emissions from Ships, Adopted on 13 April 2018*; International Maritime Organization (IMO): London, UK, 2018.
11. IMO. R*esolution MEPC. 328(76), Amendments to the Annex of the Protocol of 1997 to Amend the International Convention for the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 (Revised MARPOL Annex VI)*; International Maritime Organization (IMO): London, UK, 2021.
12. EU. Regulation 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'). *Off. J. Eur. Union* **2021**, *L 243/1*, 1–17.
13. The US Clean Shipping Act 202. Available online: https://lowenthal.house.gov/sites/lowenthal.house.gov/files/ASL-Clean-Shipping-Act-2022.pdf) (accessed on 14 October 2022).
14. IMO. *Introducing Lifecycle Guidelines to Estimate Well-to-Wake Greenhouse Gas (GHG) Emissions of Sustainable Alternative Fuels to Incentivize Their Uptake at Global Level*; ISWG-GHG 9/2 (EU); International Maritime Organization (IMO): London, UK, 2021.
15. Percić, M.; Vladimir, N.; Fan, A. Life-cycle cost assessment of alternative marine fuels to reduce the carbon footprint in short-shipping: A case study of Croatia. *Appl. Energy* **2020**, 279, 115848. https://doi.org/10.1016/j.apenergy.2020.115848.
16. Percić, M.; Vladimir, N.; Fan, A. Techno-economic assessment of alternative marine fuels for inland shipping in Croatia. *Renew. Sustain. Energy Rev.* **2021**, *148*, 111363. https://doi:10.1016/j.rser.2021.111363.
17. Calderón, M.; Illinf, D.; Veiga, J. Facilities for bunkering of liquefied natural gas in ports. *Trans. Res. Proc.* **2016**, 14, 2431–2440. https://doi.org/10.1016/j.trpro.2016.05.288.
18. Foretich, A.; Zaimes, G.G.; Hawkins, T.R.; Newes, E. Challenges and opportunities for alternative fuels in the maritime sector. *Marit. Transp. Res.* **2021**, *2*, 100033. https://doi.org/10.1016/j.martra.2021.100033.
19. Svanberg, M.; Ellis, J.; Lundgren, J.; Landälv. Renewable methanol as a fuel for the shipping industry. *Renew. Sustain. Energy Rev.* **2018**, *94*, 1217–1228. https://doi.org/10.1016/j.rser.2018.06.058.
20. Aneziris, O.; Koromila, J.; Nivolianitou, Z. A systematic literature review on LNG safety at ports. *Saf. Sci.* **2020**, *124*, 104595. https://doi:10.1016/j.ssci.2019.104595.
21. Ashrafi, M.; Lister, J.; Gillen, D. Toward harmonization of sustainability criteria for alternative marine fuels. *Marit. Transp. Res.* **2022**, *3*, 100052. doi.org/10.1016/j.martra.2022.100052.
22. KPGM International. *The Pathway to Green Shipping*; KPGM: Berlin, Germany, 2021.
23. DNV-GL Maritime. Assessment of Selected Alternative Fuel and Technologies; DNV: Bærum, Norway, 2018.
24. Andersson, K.; Salazar, C.M. *Methanol as a Marine Fuel Report*; Methanol Institute: Alexandria, VA, USA, 2015.
25. Ellis, J.; Tanneberger, K. *Study on the Use of Ethyl and Methyl Alcohol as Alternative Fuels in Shipping*; European Maritime Safety Agency: Gothenburg, Sweden, 2015.
26. Prussi, M.; Scarlat, N.; Acciaro, M.; Kosmos, V. Potential and limiting factors in the use of alternative fuels in the European maritime sector. *J. Clean. Prod*. **2021**, *291*, 125849. https://doi.org/10.1016/j.jclepro.2021.125849.
27. BPO. *Alternative Fuels' Infrastructure for Ships in the Baltic Ports—Current Status and Outlook—Report*; BPO: Tallinn, Estonia, 2020.
28. ABS. *Methanol as Marine Fuel—Sustainability Whitepaper*; ABS: London, UK, 2021.
29. IAE. *Net Zero by 2050: Roadmap for the Global Energy Sector*; IAE Publications: Paris, France, 2021.
30. Al-Enazi, A.; Okonkwo, E.; Bicer, Y.; Al-Ausari, T. A review of cleaner alternative fuels for maritime transport. *Energy Rep*. **2021**, *7*, 1962–1985. https://doi.org/10.1016/j.egyr.2021.03.036.
31. Stanĉin, H.; Mikulcić, H.; Wang, X.; Duić, N. A review on alternative fuels in future energy system. *Renew. Sustain. Energy Rev*. **2020,** *128*, 109927. https://doi.org/10.1016/j.rser.2020.109927.
32. Bicer, Y.; Dincer, I. Clean Fuel options with hydrogen for see transportation: A life cycle approach. *Int. J. Hydrog. Energy* **2018**, *42*, 1179–1193. https://doi.org/10.1016/j.ijhydene.2017.10.157.
33. Moradi, R.; Groth, K.M. Hydrogen storage and delivery: Review of the state of art technologies and risk and reliability analysis. *Int. J. Hydrog. Energy* **2019**, *44*, 12254–12269. https://doi.org/10.1016/j.ijhydene.2019.03.041.
34. Wang, H.; Dautidis, P.; Zhang, Q. Ammonia-based green corridors for sustainable maritime transportation. *Dig. Chem. Eng.* **2023**, *6*, 100082. https://doi.org/10.1016/j.dche.2022.100082.
35. Solakivi, T.; Paimander, A.; Ojala, L. Cost competitiveness of alternative maritime fuels in the new regulatory framework. *Transp. Res. D Transp. Environ.* **2022**, *113*, 103500. https://doi.org/10.1016/j.trd.2022.103500.
36. Hansson, J.; Brynolf, S.; Fridell, E.; Letveer, M. The potential role of ammonia as marine fuel-based on energy system modelling and multi-criteria decision analysis. *Sustainability* **2020**, *12*, 3265. https://doi.org/10.3390/su12083265.
37. Al-Booasi, F.Y.; El-Halwagi, M.M.; Moore, M.; Nielsen, R.B. Renewable ammonia as an alternative fuel for the shipping industry. *Curr. Opin. Chem. Eng.* **2021**, *31*, 100670. https://doi.org/10.1016/j.coche.2021.100670.

38. Ershov, M.A.; Savelenko, V.D.; Makhmudova, A.E.; Rekhletskaya, E.S.; Makhova, U.A.; Kapustin, V.M.; Mukhina, D.Y.; Abdellatief, T.M.M. Technological Potential Analysis and Vacant Technology Forecasting in Properties and Composition of Low-Sulfur Marine Fuel Oil (VLSFO and ULSFO) Bunkered in Key World Ports. *J. Mar. Sci. Eng*. **2022**, 10, 1828. https://doi.org/10.3390/jmse10121828.
39. Abdellatief, T.M.M.; Ershov, M.A.; Kapustin, V.M.; Abdelkareem, M.A.; Kamil, M.; Olabi, A.G. Recent trends for introducing promising fuel components to enhance the anti-knock quality of gasoline: A systematic review. *Fuel* **2021**, *291*, 120112. https://doi.org/10.1016/j.fuel.2020.120112.
40. Abdellatief, T.M.M.; Ershov, M.A.; Kapustin, V.M.; Chernysheva, E.A.; Savelenko, V.D.; Salameh, T.; Abdelkareem, M.A.; Olabi, A.G. Novel promising octane hyperboosting using isoolefinic gasoline additives and its application on fuzzy modelling. *Int. J. Hydrog. Energy* **2022**, *47*, 4932–4941. https://doi.org/10.1016/j.ijhydene.2021.11.114.
41. Ershov, M.A.; Potanin, D.A.; Tarazanov, S.V.; Abdellatief, T.M.M.; Kapustin, V.M. Blending characteristics of isooctane, MTBE, and TAME as gasoline components. Energy Fuels **2020**, *34*, 2816–2823. https://doi.org/10.1021/acs.energyfuels.9b03914.
42. Baresic, D.; Palmer, K. *Climate Action in Shipping. Progress towards Shipping's 2030 Breakthrough*; Report of UMAS and UN Climate Change High Level Champions; Global Maritime Forum: Copenhagen, Denmark, 2022. Available online: https://www.globalmaritimeforum.org/getting-to-zero-coalition/ resources-page (accessed on 25 September 2022).
43. Smith, T.; Baresic, D.; Fahnestock, J.; Galbraith, C.; Perico, C.V.; Rojon, I.; Shaw, A. A Strategy for the Transition to Zero-Emission Shipping, An Analysis of Transition Pathways, Scenarios, and Levers for Change; UMAS: London, UK ,2021.
44. EU. *Proposal for a Regulation of the European Parliament and of The Council on the Use of Renewable and Low-Carbon Fuels in Maritime Transport and Amending Directive 2009/16/EC)*; COM(2021) 562 Final; European Commission: Brussels, Belgium, 2021.
45. ISO. *Guidelines for Systems and Installations for Supply of LNG as Fuel to Ships*; ISO: Geneva Switzerland, 2015.
46. Wang, Y.; Wright, L.A. A Comparative Review of alternative fuels for the Maritime Sector: Economic, Technology, and Policy Challenges for Clean energy Implementation. *World* **2021**, *2*, 456–481. https://doi.org/10.3390/world2040029.
47. Jeong, B.; Lee, B.S.; Zhou, P.; Ha, S.M. Evaluation pf safety exclusion zone for bunkering station of LNG-fuelled ships. *J. Mar. Eng. Technol*. **2017**, *16*, 121–144. https://doi.org/10.1080/20464177.2017.1295786.
48. Thinkstep. *Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel*; Thinkstep: Leinfelden-Echterdingen, Germany, 2019.
49. Le Fevre, C. *A Review of Demand Prospects for LNG as a Marine Transport Fuel*; Oxford Institute for Energy Studies: Oxford, UK, 2018. https://doi.org/10.26889/9781784671143.
50. Al-Breiki, M.; Bicer, Y. Comparative life cycle assessment of sustainable energy carriers including production, storage, overseas transport and utilization. *J. Clean. Prod*. **2021**, *279*, 123481. https://doi.org/10.1016/j.jclepro.2020.123481.
51. Linstad, E.; Eskeland, G.S.; Rialland, A.; Valland, A. Decarbonizing Maritime Transport: The importance of Engine Technology and Regulations for LNG to Serve as a Transition Fuel. *Sustainability* **2020**, *12*, 8793. https://doi.org/10.3390/su12218793.
52. DNV GL. *Comparison of Alternative Marine Fuels*; DVN GL: Høvik, Norway, 2019.
53. IMO. *Amendments to the IGF Code and Development of Guidelines for Low-Flashpoint Fuels*; CCC 8/3; International Maritime Organization (IMO): London, UK, 2022.
54. UN. *United Nations Environmental Program (UNEP)*; UN: New York, NY, USA, 2006.
55. Deniz, C.; Zincir, B. Environmental and economical assessment of alternative marine fuel. *J. Clean. Prod*. **2016**, *13*, 438–448. https://doi.org/10.1016/j.jclepro.2015.11.089.
56. McKinlay, C.J.; Turnock, S.R.; Hudson, D.A. *A Comparison of Hydrogen and Ammonia for Future Long Distance Shipping Fuels*; The Royal Institution of Naval Architects LNG/LPG and Alternative Fuels: London, UK, 2020.
57. Goldmann, A.; Sauter, W.; Oettinger, M.; Kluge, T.; Schröder, U.; Seume, J.R.; Friedrichs, J.; Dinkelacker, F. A Study on Electrofuels in Aviation. *Energies* **2018**, *11*, 392. https://doi.org/10.3390/en11020392.
58. Acar, C.; Dincer, I. Review and evaluation of hydrogen production options for better environment. *J. Clean. Prod.* **2019**, *218*, 835–849. https://doi.org/10.1016/j.jclepro.2019.02.046.
59. IMO. *Amendments to the IGF Code and Development of Guidelines for Low-Flashpoint Fuels*; CCC 7/3/9; International Maritime Organization (IMO): London, UK, 2021.
60. IMO. *Development of Guidelines for the Safety of Ships Using Ammonia as Fuel*; CCC 8/13/1; International Maritime Organization (IMO): London, UK, 2022.
61. Yapicioglu, A.; Dincer, I. A review on clean ammonia as a potential fuel for power generators. *Renew. Sustain. Energy Rev.* **2019**, *103*, 96–108. https://doi.org/10.1016/j.rser.2018.12.023.
62. Kim, K.; Roh, G.; Kim, W.; Chun, K. A preliminary study on an alternative ship propulsion system fueled by ammonia, Environmental and Economic assessments. *J. Mar. Sci. Eng*. **2020**, *8*, 183. https://doi.org/10.3390/jmse8030183.
63. Interreg North-West Europe H2SHIPS. *Comparative Report on Alternative Fuels for Ships Propulsion*; Interreg: Lille, France, 2020.
64. Jiang, L.; Kronbak, J.; Christensen, L. The costs and benefits of sulphur reduction measures: Sulphur scrubbers versus marine gas oil. *Transp. Res. Part D Transp. Environ.* **2014**, *28*, 19–27. https://doi.org/10.1016/j.trd.2013.12.005.
65. Corvus Energy. Case Study: Norled AS, MF Ampere, Ferry. Available online: http://files7.webydo.com/42/421998/UploadedFiles/a4465574-14ff-4689-a033-08ac32adada1.pdf (accessed on 10 November 2022).

66. IMO. *A Study on the Transportation Cost of a Liquefied Hydrogen Carrier Using Boil-Off-Gas as a Fuel*; CCC 8/INF. 17; International Maritime Organization (IMO): London, UK, 2022.
67. Frei, M.S.; Mondelli, C.; García-Muelas, R.; Kley, K.S.; Puértolas, B.; López, N.; Safonova, O.V.; Stewart, J.A.; Ferré, D.C.; PérezRamírez, J. Atomic-scale engineering of indium oxide promotion by palladium for methanol production via CO2 hydrogenation. *Nat. Commun*. **2019**, *10*, 3377. https://doi.org/10.1038/s41467-019-11349-9.
68. Patel, S.K.S.; Gupta, R.K.; Kalia, V.C.; Lee, J. Integrating anaerobic digestion of potato peels to methanol production by methanotrophs immobilized on banana leaves. *Bioresour. Technol*. **2021**, *323*, 124550. https://doi.org/10.1016/j.biortech.2020.124550.
69. Zincir, B.; Deniz, C.; Tuner, M. Investigation of environmental, operational and economic performance of methanol partially premixed combustion at slow speed operation of a marine engine. *J. Clean. Prod*. **2019**, *235*, 1006–1019. https://doi.org/10.1016/j.jclepro.2019.07.044.
70. Wei, L.; Yao, C.; Wang, Q.; Pan, W.; Han, G. Combustion and emission characteristics of a turbocharger diesel engine using high premixed ratio pf methanol and diesel fuel. *Fuel* **2015**, *140*, 156–163. https://doi.org/10.1016/j.energy.2015.12.020.
71. Kang, W.C.; Myongho, K.; Jae-Jung, H. Development of a Marine LPG-Fueled High-Speed Engine for Electric Propulsion Systems. *J. Mar. Sci. Eng*. **2022**, *10*, 1498. https://doi.org/10.3390/jmse10101498.
72. Andrews, J.; Shabani, B. Where does hydrogen fit in a sustainable energy economy? *Procedia Eng*. **2012**, *49*, 15–25. https://doi.org/10.1016/j.proeng.2012.10.107.
73. IMO. *Development of Guidelines for the Safety of Ships Using Ammonia as Fuel*; CCC 8/13/2; International Maritime Organization (IMO): London, UK, 2022.
74. Chen, C.; Yao, A.; Yao, C.; Wang, B.; Lu, H.; Feng, J.; Feng, L. Study of the characteristics of PM and the correlation of soot and smoke opacity on the diesel methanol dual fuel engine. *Appl. Therm. Eng*. **2019**, *148*, 391–403. https://doi.org/10.1016/j.applthermaleng.2018.11.062.
75. *ISO 14040:2006*; Environment Management-Life Cycle Assessment-Principles and Framework. ISO: Geneva, Switzerland, 2006.
76. Linstad, E.; Lagemann, B.; Rialland, A.; Ganlem, G.; Valland, A. Reduction of maritime GHG emissions and potential role of E-fuels. *Transp. Res. Part D* **2021**, *101*, 103075. https://doi.org/10.1016/j.trd.2021.103075.
77. Bengtsson, S.; Andersson, K.; Fridell, E. A comparative life cycle assessment of marine fuels: Liquefied natural gas and three other fossil fuels. In *Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ*. **2011**, *225*, 97–110. https://doi.org/10.1177/1475090211402136.
78. Lind, M.; Pettersson, S.; Karlsson, J.; Steijaert, B.; Hermansson, P.; Haraldson, S.; Axell, M.; Zerem, A. Sustainable Ports as Energy Hubs, The Maritime Executive. 2020. Available online: https://www.maritime-executive.com/editorials/sustainable-ports-as-energy-hubs (accessed on 2 December 2021).
79. Puig, M.; Wooldridge, C.; Darbra, M. *ESPO Environmental Report 2022*; ESPO Secretariat: Dublin, Ireland, 2022.
80. Gibbs, D.; Rigot-Muller, P.; Mangan, J.; Lalwani, C. The role of sea ports in end-to-end maritime transport chain emissions. *Energy Policy* **2014**, *64*, 337–348. https://doi.org/10.1016/j.enpol.2013.09.02.
81. Urbanyi-Popiołek, I.; Klopott, M. Container Terminals and Port City Interface—A Study of Gdynia and Gdańsk Ports. *Transp. Res. Procedia* **2016**, *16*, 517–526. https://doi.org/10.1016/j.trpro.2016.11.04.
82. Klopott, M. Restructuring of Environmental Management of Baltic Ports—Case of Poland, *Marit. Policy Manag.* **2013**, *40*, 439–450. https://doi.org/10.1080/03088839.2013.798440.
83. Winnes, H.; Styhre, L.; Fridell, E. Reducing GHG emissions from ships in port areas. *Res. Transp. Bus. Manag.* **2015**, *17*, 73–82. https://doi.org/10.1016/j.rtbm.2015.10.008.
84. Notteboom, T.; van der Lugt, L.; van Saase, N.; Sel, S.; Neyens, K. The Role of Seaports in Green Supply Chain Management: Initiatives, Attitudes, and Perspectives in Rotterdam, Antwerp, North Sea Port, and Zeebrugge. *Sustainability* **2020**, *12*, 1688. https://doi.org/10.3390/su12041688.
85. Klopott, M. Port as a link in the green supply chain—The example of the Port of Gdynia. In *Maritime Transport IV*; Rodriguez-Martos Dauer, R., Ed.; Universitat Politècnica de Catalunya: Barcelona, Spain, 2009.
86. An, J.; Lee, K.; Park, H. Effects of a Vessel Speed Reduction Program on Air Quality in Port Areas: Focusing on the Big Three Ports in South Korea. *J. Mar. Sci. Eng*. **2021**, *9*, 407. https://doi.org/10.3390/jmse9040407.
87. Mjelde, A.; Endresen, Ø.; Bjørshol, E.; Gierløff, C.W.; Husby, E.; Solheim, J.; Mjøs, N.; Eide, M.S. Differentiating on port fees to accelerate the green maritime transition. *Mar. Pollut. Bull*. **2019**, *149*, 110561. https://doi.org/10.1016/j.marpolbul.2019.110561.
88. Alamoush, A.S.; Ölçer, A.I.; Ballini, F Ports' role in shipping decarbonisation: A common port incentive scheme for shipping greenhouse gas emissions reduction. *Clean. Logist. Supply Chain.* **2022**, *3*, 100021. https://doi.org/10.1016/j.clscn.2021.100021.
89. Styhre, L.; Winnes, H.; Black, J.; Lee, J.; Le-Griffin, H. Greenhouse gas emissions from ships in ports—Case studies in four continents. *Transp. Res. Part D Transp. Environ*. **2017**, *54*, 212–224. https://doi.org/10.1016/j.trd.2017.04.033.
90. Acciaro, M.; Ghiara, H.; Cusano, M.I. Energy management in seaports: A new role for port authorities *Energy Policy* **2014**, *71*, 4–12. https://doi.org/10.1016/j.enpol.2014.04.013.
91. Densberger, N.L.; Bachkar, L. Towards accelerating the adoption of zero emissions cargo handling technologies in California ports: Lessons learned from the case of the Ports of Los Angeles and Long Beach. *J. Clean. Prod.* **2022**, *347*, 131255. https://doi.org/10.1016/j.jclepro.2022.131255.

92. European Commission. *Communication on a New Approach for a Sustainable Blue Economy in the EU*; COM(2021) 240 Final; European Commission: Brussels, Belgium, 2021.
93. IMO. *Reduction of GHG Emissions from Ships. Ports' Perspective on Key Considerations Regarding the Decarbonization of Shipping, Submitted by IAPH*; MEPC 79/7/19; International Maritime Organization (IMO): London, UK, 2022.
94. IMO. *Resolution MEPC.323(74) on Invitation to Member States to Encourage Voluntary Cooperation between the Port and Shipping Sectors to Contribute to Reducing GHG Emissions from Ships*; International Maritime Organization (IMO): London, UK, 2019.
95. European Commission. *Proposal for a Regulation of the European Parliament and of The Council on the Deployment of Alternative Fuels Infrastructure, and Repealing Directive 2014/94/EU of the European Parliament and of the Council*; COM(2021) 559 Final; European Commission: Brussels, Belgium, 2021.
96. IRENA. *A Pathway to Decarbonize the Shipping Sector by 2050*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2021.
97. Gucma, M.; Bąk, A.; Chłopińska, E. Concept of LNG transfer and bunkering model of vessels at South Baltic sea area. *Annu. Navig*. **2018**, *25*, 79–91. https://doi.org/10.1515/aon-2018-0006.
98. Sharples, J. LNG Supply Chains and the Development of LNG as a Shipping Fuel in Northern Europe. The Oxford Institute for Energy Studies. Available online: https://www.oxfordenergy.org. pdf (accessed on 27 October 2022).
99. DNV. Alternative Fuels Insight Platform. Available online: https://afi.dnv.com/statistics/DDF10E2B-B6E9-41D6-BE2F-C12BB5660103 (accessed on 17 November 2022).
100. SEA-LNG. Global Fleet. Available online: https://sea-lng.org/why-lng/global-fleet (accessed on 12 November 2022).
101. ShippaxMarket 22. *The 2021 Ferry, Cruise, Ro-Ro and High-Speed Year in Review with Analyses and Statistics*; Shippax: Halmstad, Sweden, 2022.
102. SEA-LNG. A Fuel in Transition. A View from the Bridge, SEA-LNG.ORG Report 2022. Available online: https://sea-lng.org/2022/01/sea-lng-2021-22-a-view-from-the-bridge/.pdf (accessed on 22 October 2022).
103. DNV. Orders for LNG-Fueled Ships at Record Pace. Available online: https://maritime-executive.com/article/dnv-orders-for-lng-fueled-ships-at-record-pace (accessed on 12 October 2022).
104. Conversion of LNG Terminals for Liquid Hydrogen or Ammonia. Fraunhofer Institute for Systems and Innovation Research ISI. Available online: https://www.google.com/Report_Conversion_of_LNG_Terminals_for_Liquid_Hydrogen_or_Ammonia.pdf (accessed on 2 January 2023).
105. World LPG Association (WLPGA). LPG Bunkering Guide for LPG Marine Fuel Supply. Available online: https://www.google.com/FLPG-Bunkering-2019.pdf (accessed on 2 January 2023).
106. Nektarios, A.M.; Konstantinos, D.M. Geopolitical Risk and the LNG-LPG Trade. *Peace Econ. Peace Sci. Public Policy* **2022**, *28*, 243–265. https://doi.org/10.1515/peps-2022-0007.
107. Methanol Vessels on the Water and On the Way. Available online: https://www.methanol.org/wp-content/uploads/2022/07/Final-On-the-Water-and-on-the-Way.pdf (accessed on 11 October 2022).
108. Methanol Institute. Ports with Available Methanol Storage Capacity. Available online: https://www.methanol.org/marine/ (accessed on 15 November 2022).
109. Report on Methanol Supply, Bunkering Guidelines, and Infrastructure. Available online: https://www.fastwater.eu pdf (accessed on 18 October 2022).
110. Methanol Dual-Fuel Chemical Tanker Takaroa Sun Conducts World's First Barge-to-Ship Methanol Bunkering. Available online: https://www.nyk.com/english/news/2021/20210513_01.html (accessed on 15 October 2022).
111. Stena Germanica First Non-Tanker Vessel in the World to be Ship-to-Ship Bunkered with Methanol. Available online: https://www.shippax.com/en/news/stena-germanica-first-non-tanker-vessel-in-the-world-to-be-ship-to-ship-bunkered-with-methanol-.aspx (accessed on 6 January 2023).
112. Stena and Oljola Join Hands for a Dedicated Methanol Bunker Vessel. Available online: https://www.fleetmon.com/maritime-news/2022/40145/stena-and-oljola-join-hands-dedicated-methanol-bun/ (accessed on 19 November 2022).
113. Ustolin, F.; Campari, A.; Taccani, R. An Extensive Review of Liquid Hydrogen in Transportation with Focus on the Maritime Sector. *J. Mar. Sci. Eng*. **2022**, *10*, 22–23, 1222. https://doi.org//10.3390/jmse10091222.
114. Hydrogen Bunkering Starts at Dutch Port, Offshore Wind Vessel First to Fuel Up. Available online: https://www.offshorewind.biz/2022/08/11/hydrogen-bunkering-starts-at-dutch-port-offshore-wind-vessel-first-to-fuel-up/ (accessed on 19 November 2022).
115. Port of Amsterdam, Partners Push ahead with Plans for Large-Scale Hydrogen Import Facilities. Available online: https://www.offshore-energy.biz/port-of-amsterdam-partners-push-ahead-with-plans-for-large-scale-hydrogen-import-facilities/ (accessed on 30 October 2022).
116. Hydrogen as a Marine Fuel. Sustainability White Paper. ABS. 2021. Available online: https://safety4sea.com/new-paper-examines-projected-role-of-hydrogen-as-marine-fuel/ (accessed on 2 October 2022).
117. DNV. Smells Like Sustainability: Harnessing Ammonia as Ship Fuel. Available online: https://www.dnv.com/expert-story/maritime-impact/Harnessing-ammonia-as-ship-fuel.html (accessed on 20 November 2022).

118. *Ammonfuel—An Industrial View of Ammonia as a Marine Fuel*; Alfa Laval, Hafnia, Haldor Topsoe, Vestas, Siemens Gamesa, Report; Hafnia: Hellerup, Denmark, 2020.
119. Prause, F.; Prause, G.; Philipp, R. Inventory Routing for Ammonia Supply in German Ports. *Energies* **2022**, *15*, 6485. https://doi.org/doi.org/10.3390/en15176485.
120. Ash, N.; Scarbrough, T. *Sailing on Solar: Could Green Ammonia Decarbonize International Shipping?*; Environmental Defence Fund: London, UK, 2019.
121. Green Fuel Alliance Plans Green Ammonia Facility for Bunkering at Suez Canal. Available online: https://www.offshore-energy.biz/green-fuel-alliance-plans-green-ammonia-facility-for-bunkering-at-suez-canal/ (accessed on 2 October 2022).
122. AZANE. Fuel Solutions. Available online: https://www.econnectenergy.com/articles/azane-fuel-solutions (accessed on 12 November 2022).
123. Adams, W.C. Conducting Semi-Structured Interviews, In *Handbook of Practical Program Evaluation*, 4th ed.; Wholey, J., Hatry, H., Newcomer, K., Eds.; Jossey-Bass: San Francisco, CA, USA, 2015. https://doi.org/10.1002/9781119171386.ch19.
124. Moller, A.P. Maersk Continues Green Transformation with Six Additional Large Container Vessels. Available online: https://www. maersk.com/news/articles/2022/10/05/maersk-continues-green-transformation (accessed on 7 October 2022).
125. Angelopoulos, J.; Sahoo, S.; Visvikis, I.D. Commodity and Transportation Economic Market Interactions Revisited: New Evidence from a Dynamic Factor Model. *Transp. Res. E Logist. Transp. Rev.* **2020**, *133*, 101836. https://doi.org/10.1016/j.tre.2019.101836.
126. Building Transparency for Investment in Alternative Fuel Infrastructure. Available online: https://www.dredging.org/news/101/building-transparency-for-investment-in-alternative-fuel-infrastructure (accessed on 8 July 2022).
127. Getting to Zero Coalition, the Next Wave Green Corridors—A Special Report. 2021. Available online: https://www.globalmaritimeforum.org/content/2021/11/The-Next-Wave-Green-Corridors.pdf (accessed on 21 February 2022).
128. COP26: Clydebank Declaration for Green Shipping Corridors; Policy Paper. Available online: https://www.gov.uk/government/publications/cop-26-clydebank-declaration-for-green-shipping-corridors/cop-26-clydebank-declaration-for-green-shipping-corridors (accessed on 3 April 2022).