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Maritime Shipping Decarbonization: Roadmap to Meet Zero-Emission Target in Shipping as a Link in the Global Supply Chains

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Abstract: The main subject of research involves the characteristics and assessment of the already ongoing process of maritime shipping radical decarbonization. There were identified and analyzed international legal and administrative regulatory measures as well as a package of technical, technological, operational and economic solutions, including the possibility of choosing alternative low-emission fuels that are necessary to achieve the already set targets by 2050. This research aimed to indicate and assess the most promising types of measure which are to be applied to achieve the required reduction of CO_2 emissions in global shipping as well as developing a potential roadmap leading to their implementation. In the conducted research work, mainly qualitative analyses were applied, i.e., factor analysis (FA), comparative analysis (CA), and a series of consultations with representatives of the maritime industry were carried out, following the procedure typical for the Delphi technique. The main result of the research work is the development of a scenario for potential supply and distribution of fuels to the maritime shipping market by 2050. The basic conclusion is that shortages in manufacturing, commercialization, and supply of low and zero-emission fuels to the shipping market may be the main obstacle hampering the reaching of the targets of shipping industry decarbonization. Such a scenario could significantly slow down the stepping up process of greening the global supply chains.

Keywords: shipping industry decarbonization; regulatory measures; alternative marine fuels; pathways to zero-emission

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1. Introduction

Maritime transport is a key link in the global logistics supply chains. It plays a vital role in the world economy, strongly affecting the efficiency, visibility, and agility of global supply chains as well as influencing the smooth commodities' flows of global trade in logistics terms. Nowadays, more than 82% of the world's trade volume is carried by sea. Taking into account the average distance of 1 ton of cargo (5230 Mm), this means that sea transport constitutes 92% of transport performance related to global trade handling [1]. In 2021, ca.11,1 billion tons of goods were carried by sea, indicating an increase in volume transported by sea by 40.5% compared to 2010. The volume of cargo transported was almost 3.9 times larger than in 1990. Since 1970, sea-borne trade would grow on average by more than 2% per year, and the rate of this growth outpaced the growth rate of global GDP and the OECD countries' industrial production [2]. In terms of value, global sea-borne transport of cargo accounts for ca. 66% of the total value of maritime trade assessed in 2020 at 14.7 trillion USD and is steadily growing [3].

Maritime transport is a backbone of the global economy and a significant driver of world trade development as well as a key component able to boost efficiency of global supply chains, generating, however, numerous negative externalities. They are seen in terms of external costs and are mainly expressed in form of negative environmental effects such as GHG emissions. Shipping GHG emissions are an integral part of total CO_2 emissions from global mobility sector of ca. 7.9 billion tons in 2020. It means that the share of mobility sector accounted for ca. 19.5% of global carbon emissions and 2.0% in NO_x emissions [4]. It is due to the fact that global transport is still 95% dependent on oil and this is hard to change. As far as the shipping industry is concerned, it produced just 2.3% of the world's GHG emissions, i.e., 0.947 billion tons of CO_2 and contributed less than 12% of global transport's GHG emissions [5]. What is more, marine pollution in the form of oil spills has been drastically reduced in the past 10 years despite the massive growth in the volume of seaborne trade. Considering the above, it can be concluded that sea shipping is one of those modes of transport or forms of mobility in wider sense that compared with land transport, is a comparatively minor contributor to its pollution.

Such a relatively optimistic view of maritime transport as a global carbon dioxide polluter, contributing slightly more than 10% of global mobility GHG emissions, does not mean that this strategic mode of transport does not require deeper decarbonization. Referring to recent research, it is assumed that due to the still growing activity in the global scale and increase in volume of the world commodity trade, even if current and committed policies aimed at transforming the mobility sector towards significant reduction of GHG emissions toward net-zero transition were to succeed, transport's carbon emissions would still grow almost 20% by 2050 [6]. It is projected that the maritime shipping sector alone, which is difficult-to-decarbonize and that was not part of the Paris agreement, is to represent up to 10% of all global emissions by 2050 if left unchecked. Ships operate usually for several years or even for decades and seeing that currently liquid marine fuels derived from crude oil are mainly used in shipping, they run largely on the most polluting type of fossil diesel, participating in the global warming.

The oil refining processes produce only a few types of marine fuels such as marine gas oil (MGO), marine diesel oil (MDO), and most commonly used heavy fuel oils (HFO) [7]. Marine diesel engines were adapted to burn residual fuels with viscosity at 50 °C up to 700 cSt. Due to the following regulations [8–10], other biofuels for shipping have been introduced, such as: biodiesel, methanol, ethanol, biobutanol, bio-ethers, palm, vegetable or cooking oil, and others. However, their share is limited to certain cases and places (mainly inland transport) [11–14]. Electrification seems not to be a viable option. Only a few electric vessels (ferries) have been built which use electric energy from batteries, but the electric energy derived mainly from onshore power plants and the capacity of energy accumulation is still limited to short voyages below 50 Nm (90 km).

Considering that the currently existing standard of sustainability of global maritime transport is unsatisfactory from the point of view of key regulatory authorities, e.g., International Maritime Organization (IMO) and European Union (EU), as well as commitments already accepted by many countries resulting from concluded agreements and legal arrangements (protocols) of international UN climate conferences (Kioto 1997, COP21 Paris 2015, COP26 Glasgow 2021), aimed at a radical reduction of the global GHG emissions in the upcoming three decades, many regulatory measures has been already taken to transform the world shipping industry as a vital sector of the global mobility and key link of logistics supply chains towards zero-carbon emissions. The way to achieve this goal is however not simple and easy without the clear long-term strategy as well as a progressive and viable action plan, commonly accepted by IMO, maritime countries, and the global shipping community.

Developing such a strategy is not easy, considering that ocean-going vessels operate in the global scale on many different global freight market segments and that they are owned and operated by various shipowners more or less interested in such a path of radical transformation (time pressure, costs, potential benefits, and losses). It means that the whole process of global shipping decarbonization is very difficult to regulate, govern, administer, and monitor [4,5,15]. However, the authors of this paper are convinced that the shipping industry possesses significant decarbonization potential to meet the regulatory goals and has to reduce currently generated emissions through a simultaneous combination of technical, technological, operational and organizational activities and projects. The main promising and effective measure seems to be retrofitting to use zero-carbon fuels, such as green ammonia or hydrogen, as well as wider use during the ship voyage "slow steaming" practices. On average, a 20% reduction in ship speeds can save about 32–40% of CO_2 emission (and fuel consumption).

These issues are the main subject of the authors' research, aimed at assessing the current state of shipping decarbonization and indicating the best solutions within the already existing package of suggested measures by international maritime institutions, research centers, shipowners, and shipbuilding industry. The authors' considerations also take into account the effects that the decarbonization process may have on global supply chains to make them greener and better suited to the standards of a circular economy.

The conducted research aimed to identify and indicate as well as assess the most promising types of measures which are to be applied to achieve the required reduction of CO_2 emissions in global shipping. The authors' intention was to develop a potential roadmap in form of the most likely scenario for the delivery and distribution of different marine fuel types to the shipping market by 2050. Therefore, the main research goal was to develop such a scenario. In order to develop it, numerous research findings from existing studies and reports were evaluated. Then, on this basis, the authors made an attempt to present their own scenario regarded as a roadmap of maritime shipping decarbonization. The roadmap defines the real possibilities of application to the shipping market of low and zero-emission fuels, typical for the current stage of the upcoming shipping's fourth propulsion revolution.

However, we need to be aware of a still existing huge spectrum of uncertainty concerning the choice of the best possible and acceptable pathway by the shipping industry, potentially enabling the shipping sector's faster access to the new generation of renewable and low-carbon fuels. They seem to be not accessible for the shipping industry in a short run, which may mean delays in decarbonizing this sector. Therefore, the authors suggest that much more cooperation among all parties interested in solving this challenging issue is crucial.

2. Research Methodology

Mainly qualitative research methods were applied to carry out the set research goals and to achieve the expected and acceptable research results which have been presented in the form of a constructed scenario.

In order to achieve the abovementioned goals and research tasks, the following research methods and techniques were used: factor analysis (FA), comparative analysis (CA), desk research based on a critical analysis of the literature. Factor analysis and comparative analysis were applied at the first stage of the research process for enabling the authors to investigate the research problem and find the best way to elaborate the research results that cannot easily be measured directly.

At the next stage, using the comparative analysis, as well as desk research and brainstorming as the heuristic method, the authors assessed the most promising types of measures aimed at significant reduction of GHG emissions in the shipping industry. Then, after analysing the direct, indirect, and diesel-electric propulsion systems applied in shipping and evaluating the equivalent energy capacity of fuel in vessel tanks (CA, FA), the authors proposed their own scenario of shipping decarbonization.

The proposed scenario which may indicate the best roadmap towards decarbonizing the shipping industry was developed using the heuristic method such as brainstorming. In addition, in order to learn more about the activities of leading global container operators undertaken to implement the strategy of reducing GHG and decarbonizing sea shipping in the perspective of 2030 and 2050, long-lasting multi-stage consultations with representatives of the shipping sector were conducted. The consultations were carried out according to the procedure typical for the Delphi heuristic technique. The consultations carried out in the multi-phase formula made it possible to obtain the opinion of experts which was not easy to obtain from sources other than themselves.

In order to obtain a valuable opinion from expert-practitioners from the shipping industry, the authors assembled a three-person team of experts consisting of two representatives of the leading container shipping companies having their branch offices in Poland and one representative of the Polish Society for the Classification of Ships (PRS). All three expert-mechanical engineers were the heads of the technical department of their companies.

Such a small group of experts resulted from the fact that out of six potential representatives of leading container shipping companies based in Poland, only two received the consent of the company's management board to participate actively in this form of consultation. The authors, however, wanted only to obtain an opinion on the implementation of the strategy of decarbonizing sea shipping with the use of various types of alternative fuels directly from shipping companies.

The first stage of the long-lasting multi-phase consultations consisted in conducting an interview with each expert in which two questions were asked. The first question was: what are the most important and demanding tasks and plans to be implemented related to the need to decarbonize the sea shipping in relation to your company and the entire shipping industry? The second question concerned the types of measures that the shipping company and the whole industry wants to use to achieve the goals of lower and finally zero-emission targets established by IMO and EU.

The obtained results differed significantly, indicating an individualized approach of shipowners to achieving the goals of decarbonization of the shipping sector. Opinions expressed by experts revealed significant differences concerning both the choice of types of measures they prefer to meet the decarbonization goals by 2030 and 2050, as well as the potential application of selected types of various green alternative fuels. The inability to develop a long-term strategy for the decarbonization of the sea fleet at the current stage of the industry's ability to produce and market supply of demanded alternative fuels for the shipping sector was also underlined. The high investment risk related to the renewal of tonnage and the choice of propulsion sources for newly built ships was indicated too.

After the opinions expressed during the first round were made available to all experts, the second stage of the research process was carried out in the form of a survey. It was aimed at verification and clarification of previously expressed opinions and comments made by the experts. The intention of the authors was to try to approximate the positions of experts and to develop a common opinion on the matter in question. However, it turned out to be impossible as the obtained responses from the experts still differed significantly. Representatives of shipping companies indicated various paths of achieving the set goal of decarbonization, clearly preferring either operational and technical measures or only those that involved the use of new green alternative fuels. The representative of PRS expressed an unequivocal opinion that both operational and technical solutions aimed at reducing greenhouse gas emissions should be applied, as well as the implementation and wider use of new alternative fuels. All experts substantiated their opinions in a satisfactory manner.

The opinions of experts obtained, unsatisfactory for the authors after the second round of research, prompted the team to undertake the third and final stage of research. Another survey was prepared with only one question addressed to the same group of experts. This question refined the previous questions addressed to experts and boiled down to the determination of the most preferred types of alternative fuels that the company they represent intends to use in the transition period until 2030 and in the perspective until 2050. In their replies, all three experts have clearly indicated that by 2030–2035, LNG and methanol which ultimately should be produced using energy from renewable sources will remain the most effective and promising sources of propulsion.

After analyzing the order portfolios of new ships in world shipyards in terms of the newly built vessels' propulsion sources, the authors accepted the position expressed by the experts. Their last opinion as well as several comments contained in the responses to the survey as well in the statements made during the interview conducted with each of the experts, were used after a discussion among the authors' team to develop the scenario of possible changes in the marine fuel market by 2050 at intervals of every 10 years.

With this in mind, the authors attempted to obtain the opinion of the shipping industry on the basis of three rounds of meetings and discussions as well as several consultations with the representatives of the leading container shipping companies having their branch offices in Poland, as well as the Polish classification society PRS.

It should also be highlighted that as a kind of case study (CS), examples were given of the global container operators Maersk and MSC in terms of implementing their corporate decarbonization strategy.

3. International Regulations Aimed at Transforming the Maritime Shipping towards Zero-Emission Target

The crucial role in setting the targets of reduction of GHG emissions in the global shipping industry plays the International Maritime Organization (IMO). Since 1 January 2000, IMO has introduced a requirement to limit nitrogen oxides emission (as equivalent of N_2O) from marine diesel engines. Currently, in special areas, there is a limit to a tier 3, in others to a tier 2 (for the ships which were constructed on and after 1 January 2011). Since 1 January 2020, the emission of sulfur oxides from marine fuels is limited to an equivalent up to 0.5% of sulfur content in heavy oils and 0.1% for diesel oils. Thanks to this, the emission of sulfur oxides into the atmosphere has significantly decreased (about 6 times) [16].

Carbon dioxide emissions have been limited by the IMO Regulation on Energy Efficiency for Ships on and after 1 January 2013 [15]. In order to limit the negative impact of GHG emissions in world shipping on Earth climate, the IMO has set the objective of reducing carbon dioxide emissions, taking into account the transport effect, by at least 30% by 2030 and 70% by 2050 compared to 2008. Taking into account the equivalent carbon dioxide emission (as GHG effect), this is to be 50% by 2050 [17].

Taking into account IMO's ambition and its set long-term target to halve the GHG emission from shipping by 2050 in comparison to 2008 and to decarbonize shipping as soon as possible in this century, this UN organization has introduced six mandatory requirements addressing the GHG emissions. These are [17]:

- The Energy Efficiency Design Index (EEDI) for newbuilds;
- The Ship Energy Efficiency Management Plan (SEEMP) for all ships above 400 GT in operation;
- The Fuel Oil Consumption Data Collection System (DCS);
- The Energy Efficiency Design Index for Existing Ships (EEXI) which will enter into force as of 1 January 2023;
- The Carbon Intensity Indicator (CII);
- A strengthening of the SEEMP with mandatory content achieving the CII targets.

It is recommended that the CI Indicator should be calculated on the basis of annual operational CII and then compared with the given values on a scale from A (the best) to E (the worst). If the vessel reaches the D or C category in the next two years, then, in the following year, it should obtain at least category C. If it does not get it, the port maritime administration may detain it and demand its scrapping [17]. It should be noted that the already established IMO regulatory measures and requirements constitute a major challenge for both ship operators and the shipbuilding industry. The implementation of mandatory requirements set by the IMO target is not a simple matter. Therefore, viable solutions are being sought in many already mentioned areas to meet the IMO demands.

In addition to the IMO's regulations, the European Union has also set its own goals for decarbonizing maritime shipping [18]. Maritime transport plays significant role in the EU economy, being an important source of employment and income, it is a catalyst for economic development. Almost 90% of the EU's external freight trade is seaborne. Short sea shipping represents one third of intra-EU exchanges in terms of ton-km, ensuring at the same time good quality of life and prosperity in the EU's maritime regions as well as, thanks to the topquality level of maritime transport services, a higher level of competitiveness. Furthermore, taking into account that each year more than 400 million passengers embark and disembark at European ports, it creates an additional impetus to take steps to intensify regulatory measures aimed at radical reduction of CO_2 emissions from the shipping, going further than in the case of IMO. For this reason, the European Commission's objective is to protect EU with very strict safety rules preventing sub-standard shipping, reducing the risk of serious maritime accidents, and minimizing the environmental impact of maritime transport.

The main course of action of the European Commission (EC), set out in its strategic document European Green Deal, comes to raise the 2030 GHG emission reduction target to at least 55% compared with 1990 [19]. The European Climate Law [11] sets into law the long-term objective of a climate-neutral EU by 2050 and a collective, net GHG emission reduction target (emissions after deduction of removals) of at least 55% in 2030 compared with 1990 [20]. Climate neutrality means that by 2050, the EU aims to achieve net-zero GHG emissions.

The implementation of such an ambitious target to achieve climate neutrality for the EU economy as a whole requires a 90% reduction in GHG emissions from the transport sector by 2050 with respect to 1990 (EU, EGD). In its next document—The Sustainable and Smart Mobility Strategy (SSMS) from 2020, the EC sets out a roadmap to attain smart and sustainable mobility and identified policy levers that can deliver this 90% reduction in the transport sector's emissions by 2050 [18]. Following this, the EC published in July 2021 a set of detailed legislative proposals, called the 'Fit for 55' package, to achieve the targets agreed in the European Climate Law. The package contains new legislative proposals, as well as proposals to update existing EU legislation. With respect to the transport industry including waterborne transport, they correspond to the proposals set out in SSMS [18–21].

With regard to maritime transport, the EC recognized that it requires specific solutions necessary for its decarbonization by 2050. This is due to the fact that now there are no market-ready zero-emission technologies and a huge amount of money needs to be invested in refueling equipment along with the indispensable infrastructure of the production and distribution of new carbon neutral fuels. In addition, the EC also took into account factors such as relatively long cycle of ships' development as well as their life cycles. As a result of this, the EC made an attempt to provide the maritime transport with a priority pathway specific for this sector, potentially enabling its faster access to the new generation of renewable and low-carbon fuels, which seem to be not accessible for the shipping industry in a short run. Therefore, the EC initiative, named FuelEU Maritime, tries to address this difficult issue. Its main goal is to accelerate the production and implementation of new low-carbon fuels as soon as possible [18]. To achieve this goal, the EC is going to increase and extend the cooperation among all parties interested in faster transformation of the shipping industry towards new 4th energy propulsion revolution. Its initiative goes towards establishing a collaborative platform of stakeholders in form of a Renewable and Low-Carbon Fuels Value Chain Alliance (RLCFVCA). It could complete the already undertaken initiatives of the EC such as the European Clean Hydrogen Alliance and the European Battery Alliance. The new proposed alliance-RLCFVCA should integrate the interested representatives of shipping, industry, public authorities as well as civil society in promoting and implementing renewable and low-carbon emission fuels in maritime transport.

Moreover, in order to improve the energy efficiency and reduce emissions of vessels also other promising forms of meeting zero-emission maritime transport have been proposed. The EC also promotes ambitious standards for vessels' design as well as their operation. To achieve these goals, the EU needs to work together with all international organizations and, especially, with IMO as well as many other industry associations, such as ECSA, ICS, BIMCO, etc., and research institutes. In addition, the EU should promote development of disruptive technologies to bring zero-emission vessels to the market. It means that the EU committed in the regulation of the maritime shipping needs to focus at the same time on creating the enabling environment in wider sense to achieve the already set goals. Creating such an environmentally friendly order in maritime shipping which, in its essence, has a global dimension, should be based on including adequate carbon pricing policies as well as research and innovation (R&I) in particular through partnerships. All these activities undertaken in both the regulatory and real sphere of the global maritime transport are to be closely coordinated with all parties involved in restructuring the existing global supply chains into green supply chains based on circular economy principles.

4. The Main Types of Measures to Achieve the Zero-Emission Target by Maritime Shipping Industry

The need to significantly improve the energy efficiency of ships and reduce greenhouse gas emissions in global maritime transport requires radical measures necessary for achieving the goals set by international regulatory entities. The maritime shipping industry faces nowadays huge challenges and needs relatively fast to shift to innovative forms of vessel construction as well as exploiting and, above all, putting into effect new alternative sources of their propulsion. The time is running out, considering that international shipping uses on average 4 million barrels of oil a day (ca. 478 thousand m^3 a day), i.e., 4% of the global oil production, and fossil-based fuels make up more than 98% of total current fuel requirement of the shipping sector [21,22]. Therefore, it needs to innovate and develop apart from technical and organizational solutions, first of all, new technologies to deliver the zero-emission propulsion systems required to meet climate goals.

This is a very complex problem, considering that currently merely 0.1% of energy consumed in shipping comes from low-carbon fuels according to the International Energy Agency (IEA) [6,16]. This means that taking into account the already existing scenarios proposed by regulators for the implementation in shipping of low and zero-carbon fuels, their share in total energy consumption in this sector will be probably less than 3% by 2030 and would not exceed the ceiling of 33% by 2050 [3,5,6]. It is far below the level needed to meet the net-zero target.

Moreover, referring to the IEA's findings, there is a noticeable deficiency of so expected nowadays innovative investments in zero-emission fuels as well as disruptive projects which would be mature enough. In reference to the official data provided by the IEA, the total amount of corporate R&D innovative investment has decreased significantly over the years 2017–2019. These investments fell from $2.7 billion in 2017 to 1.6 billion in 2019 [5,22]. This means that public funds (IMO, EU) should be included in the process of decarbonization of the maritime transport sector on a much larger scale than it was before 2020. For this reason, a proposed $5 billion IMO Maritime Research Fund (IMRF) is urgently required to apply in the shortest possible time a package of zero-carbon emission technological solutions in the shipping industry, which should be supported with IMRF [3,6,8]. In fact, the IMRF could significantly increase the current ceiling of R&D spendings for innovative technologies aimed at reducing the carbon emissions in shipping even up to three times. As a result, the government funds would be partially relieved, which is very important in the period of an upcoming global recession. Such a solution would also create an opportunity for the development and deepening of public–private partnership in the field of supporting R&D projects in shipping funded through the IMRF scheme [4,22,23]. The proposed fund to be raised from 2023 via mandatory R&D contributions from shipping companies is widely supported by the world shipping community.

Referring to the above considerations and taking into account the results of the recent studies concerning these issues, it should be stated that a variety of measures will be needed to reach the already set decarbonization's target of maritime transport. One of the likely scenarios has assumed that there is a potential to reduce shipping GHG emissions by 2035 due to reduction of carriage of fossil fuels by sea as well as further progress in trade regionalization. However, recent research indicates that this will only result in a moderate decrease. It means that in order to achieve required decarbonization of shipping by 2035, many additional solutions have to be implemented, including operational and technical improvements in shipping industry.

Among the most promising and efficient types of measures, potentially indicators for achieving this objective, three types of measures can be included:

- Technological;
- Operational;
- Measures related to alternative fuels and energy [4,23,24].

Within the group of technological measures, there are mainly measures such as light materials, slender design, less friction, waste heat recovery. Operational type of the indicated measures includes lower speeds, ship size, ship–port interface. In turn, in the group of alternative fuels/energy sources, there are included sustainable biofuels, hydrogen, ammonia, electric ships, wind assistance, and probably many others.

Technological measures are seen as extremely important from the point of view of the possibility of reducing GHG emissions in shipping because improving energy efficiency by application of technological measures is the key goal of the global regulation on the energy efficiency of ships. This regulation is part of Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL Convention). This regulation, which has been already listed in the second paragraph (sections), requires vessels built after 1 January 2013 to comply with a minimum energy efficiency level: the Energy Efficiency Design Index (EEDI). The EEDI is a measure of the CO_2 emission (g/ton-km) that takes into account not only ship design but also engine performance data. Every five years, the EEDI level is increased by 10%, i.e., starting in the first phase (2015–2020) with an initial CO_2 reduction level of 10%, in the next five year period, a 20% level needs to be obtained, and 30% in the years 2025–2030, respectively [23,24]. However, it needs to be stressed that the EEDI regulation applies only to newbuilt vessels. This in turn means that it may take many years before it covers all oceangoing ships.

Considering that the average age of the ships is 24–26 years, it means that only a significant part of the vessels can be converted by EEDI by 2040. In this time, however, the EEDI will be no more a challenging target, because the newbuild ships and especially container ones will significantly exceed the currently set mandatory EEDI's levels of CO_2 emission reduction [24,25]. Moreover, it was found that the obtained results usually not reflect the wider use of an innovative solution within electrical and mechanical technology used on board, but were achieved in a very simple way through changing the hull design or optimization of conventional equipment [26]. As a consequence, the impacts of EEDI on the reduction of CO_2 emissions are considered to be relatively low [27].

It should be stated that almost all the above indicated measures and technological solutions are currently available on the market. However, not all options can be efficiently applied. Furthermore, it should also be emphasized that potentially existing CO_2 emission reduction capacity in the operating fleet varies depending on the type of ship, its engine condition, as well as sometimes operational profile and weather constraints.

The OECD report [23] presents the potential fuel savings that can be obtained with the use of particular types of technological measures [23,28–30]:

- Light materials—0–10%;
- Slender design—10–15%;
- Propulsion improvement devices—1–25%;
- Bulbous bow—2–7%;
- Air lubrication and hull surface—2–9%;
- Deep heat recovery—0–4%.

It should be stressed that emission reduction potentials were assessed individually. The given ranges indicate possible fuel savings, which can significantly differ depending on varying factors such as vessel size, shipping segment, operational profile, route, etc. Hence, the comparison of the indicated results is to some extent limited. If the interaction between these measures is taken into account, the given numbers can be cumulated. Ranges roughly indicate possible fuel savings depending on varying conditions such as vessel size, segment, operational profile, route, etc., hence limiting the possibilities for comparison. Numbers can be cumulated after considering potential interactions between the measures.

Due to their lower block coefficient, vessels with the slender hull designs as compared to standard designs, are characterized by lower fuel consumption by 10 to 15% at lower speeds to 25% per nautical mile at 15–16 knots [29]. However, this implies altering the ship length to optimize length and the hull fullness ratio. It can sometimes significantly limit the operators' willingness to carry out such usually expensive renovations [23,29–31].

Regarding operational measures it should be stated that they relate to the way in which ships or, in wider sense, maritime transport systems are being operated. Within this category comprising four different measures, slower speeds and larger ship sizes have already impacted on reducing emissions in shipping in the mid of the last decade. Larger ship size can be considered as a technical measure too. However, it should be taken into account that the increasing size of the ship affects the use of its capacity in terms of vessel's capacity utilization. In addition, installing in ports onshore power facilities is contributing significantly to minimizing the emissions of vessels at berth in seaport. An onshore power supply for vessels whilst in port, i.e., cold ironing, as the green technical solution, helps eliminate the emissions of auxiliary engines at berth. It results into a great extent in global environmental gains. Therefore, seaport power facilities are seen as an important part of a wider set of port-oriented measures that could significantly support decarbonization in world shipping and speed up the global supply chains' greening. As a result, they are regarded as operational measures and not technical ones.

When assessing the potential of a possible reduction of CO_2 emissions thanks to the application of operational measures, it can be concluded that it is particularly high in relation to the speed of the ship. It is presented as follows [23,26,27,31]:

- Speed—0–60%;
- Ship size—0–30%;
- Ship–port interface—1%;
- Onshore power—0–3%.

It should be noted that emission reduction potentials apply to the entire sea fleet. The same as in the previous table, numbers cannot be cumulated without considering potential interactions existing among the presented measures.

Considering the use of low-emission fuels and energy sources as a potential and, at the same time, the most promising type of measures (efficient tool) for reducing GHG emissions from shipping, it should be stated that this type of fuels and energy, has usually lower or zero ship emissions when used for ship propulsion. However, it should be taken into account that most already known alternative fuels are not derived from fossil-fuel resources. Therefore, upstream emissions may arise in the production of some of them. The well-to-wake principle needs to be applied in this field. Considering only the most promising types of fuel and energy options, it is possible to estimate, with reference to OECD report, their potential impact on emission reductions in the shipping sector [4,23,32].

Measures of CO_2 emission reductions [23,30,31]:

- Advanced biofuels—25–100%;
- LNG—0–20%;
- Hydrogen—0–100%;
- Ammonia—0–100%;
- Fuel cells—2–20%;
- Electricity—0–100%;
- Wind—1–32%;
- Solar—0–12%;
- Nuclear—0–100%.

Similar to the previous data, it should be stated that: emission reduction potentials were assessed individually and the given ranges indicate possible fuel savings which can significantly differ depending on varying factors such as vessel size, segment, operational profile, route, etc. Hence, the comparison of the indicated results is to some extent limited. If the interaction between these measures is taken into account, the given numbers can be cumulated [23,32].

It needs also to be emphasized that considering upstream emissions of synthetic fuels and electricity, an almost 100% emission reduction can occur only if they are produced by renewable energy sources. It should be noted as well that at the current stage of manufacturing and distributing these alternative fuels and energy options, not all of these options have reached market maturity yet [6,23].

The above provided general overview of the possible measures that could lead to a reduction in CO_2 emissions from international shipping points out that the fact that a single type of measure can lead to a significant reduction in CO_2 emissions. However, it is unlikely that such a measure on its own could be the most effective way in terms of cost effectiveness to meet the targets of shipping decarbonization in a term by 2035 [22,23,33]. Moreover, the implementation of one measure might be incompatible with other measures already existing in the shipping industry.

Therefore, it has to be concluded that rather a combination of these measures is needed, giving the chance to reach the already set targets by regulatory entities. Such combinations of measures and their types may in fact pave the possible pathways to decarbonize international shipping in the short, medium, and long term [23–27]. Different pathways can be constructed by combining types of abovementioned measures, i.e., the operational and technical measures, as well as the use of alternative fuel at different times and degrees. We consider, however, that the most promising way to achieve the goals of decarbonizing maritime transport is through the use of alternative fuels and energy partially combined with other already mentioned types of measures. This solution gives the opportunity to maintain high logistics standards of global supply chains and is the basis for their further greening too, which can be regarded as an added value of such a strategy of shipping industry decarbonization.

5. Arrangement of Main Propulsion Systems for Ocean-Going Vessels

To ensure the lowest possible fuel consumption per route, ship propulsion system solutions are designed to reach the highest possible total propulsion efficiency. It is important to assume the operating speed of the ship. The total fuel consumption and emission of CO_2 are significantly influenced by the diversity of loads and demand for electricity in all operating states of a ship. If one of the operating states dominates (e.g., in ocean shipping), this facilitates the design of the propulsion system. Due to classification society regulations and a base of ocean-going vessels, there are a few different arrangements of the marine energetic system. It consists with one to four main engines, a minimum of two auxiliary generator sets and boilers for the production of heating steam. In electric main drives, there are not traditional main diesel engines, but main generator sets that can replace auxiliary gensets if the condition of ensuring the total demand for electricity is met. Specific fuel oil consumption (SFOC) depends on the diesel engine load and is lowest in the range of 60–85% of the nominal engine power. For partial loads in the range of 15–50% of the nominal power (slow steaming), it is higher by 5 to 25%, respectively. The total fuel consumption depends primarily on the power demand for the propulsion of the ship (this is 70–85% of the demand for the sum of all required energies). On a given route, they will be influenced by many factors, i.e., sea condition, wind strength and direction, strength and direction of sea currents, ship loading condition, fouling of ship hull, etc. However, the speed of the ship has a meaningful influence on this. It determines the power demand for the propulsion. It is approximated by a parabola of third degree, in which the speed of the ship occurs in the third power. Changing the speed of the vessel affects the travel time. Reducing the speed of the ship significantly reduces the need for power for propulsion and increases the SFOC infinitely. With constant engine and propulsion system efficiency, driving down the speed of the ship twice will reduce the power demand eight times, eight times the fuel consumption will be reduced, but the travel time will be extended by two times. Theoretically, the reduction in total fuel consumption would be fourfold, in fact, it is about 1.8–3.3 times. This is the main argument for ships to sail more slowly (slow steaming), because the carbon dioxide emission for the transport effect will be reduced.

The most commonly used system is a direct propulsion system with one slow-speed diesel engine, presented in Figure 1.

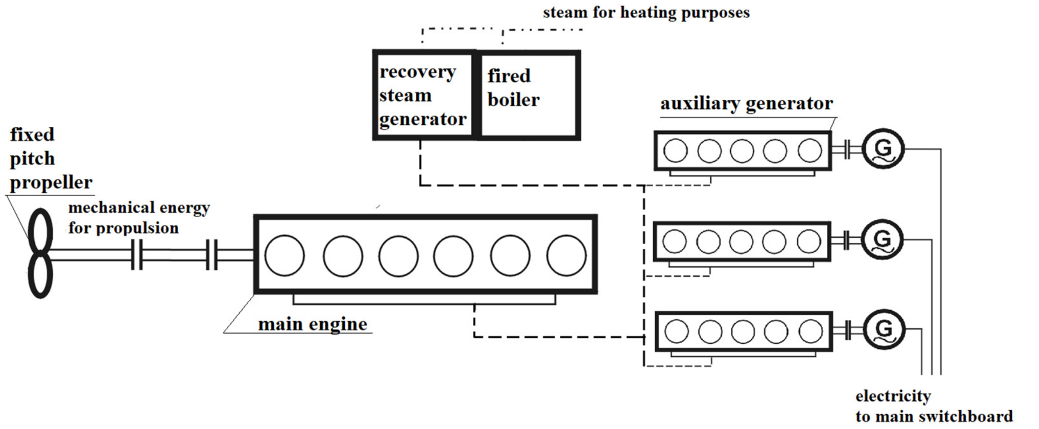

Figure 1. Direct propulsion system with 3 auxiliary generators and steam generators (own drawing).

When using an indirect drive (with a reduction gear), preference is given to propulsion systems with two medium-speed diesel engines (an increase in power, flexibility, and reliability are achieved). The possible ship energetic system is shown in Figure 2.

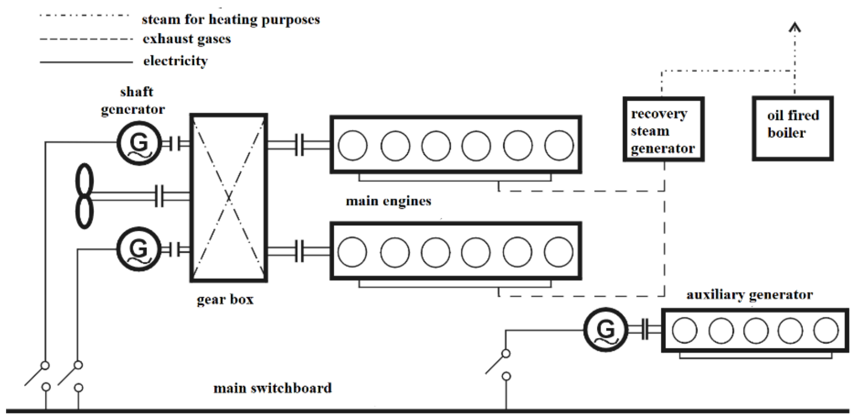

Figure 2. Indirect propulsion system with two shaft generators, one auxiliary genset and steam generator (own drawing).

In the case of large passenger ships or vessels with very variable energy demand, preference is given to energetic systems with multiple generator sets. Thrusters (as ship propulsion) are driven by electric motors. This gives a very high energy flexibility of the ship. The overall efficiency of power generation is relatively high, because it is possible to adjust the number of parallel working generator sets to current demand. This solution is shown in Figure 3.

One of the important assumptions of the vessel design is the autonomy of the ship. In ocean shipping, 30 or even 45 days of sailing without calling at the port will be accepted. This requires an adequate supply of fuel and, consequently, an adequate capacity of fuel tanks. Depending on the type of fuel (e.g., its density and Lower Heating Value), they will have to occupy a significant space on the ship.

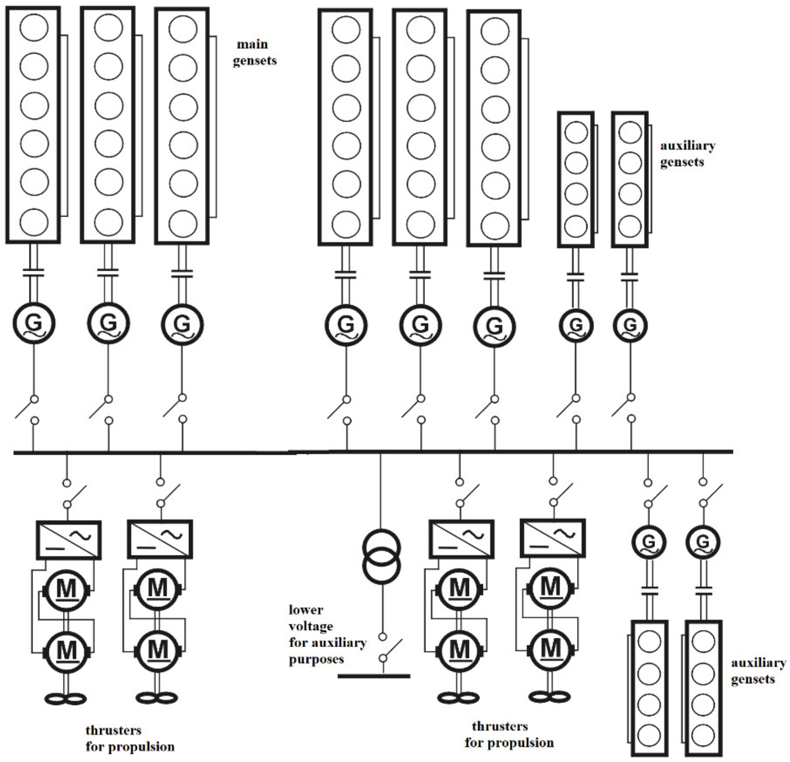

Figure 3. Diesel-electric system with 6 main and 4 auxiliary gensets (own drawing).

6. Transitional and Future Fuels for Maritime Shipping

The bunker demand for marine fuels is ca. 370 million tons/year corresponding to an equivalent of 42.7 MJ/kg of Lower Heating Value (ISO standard of LHV for fossils fuels derived from crude oil). With the same demand for energy contained in marine fuels as in 2020, it would be necessary to have an equivalent of 324 million ton for LNG, 338 million ton for LPG, 777 million ton for methanol, 600 million ton for ethanol, and 835 million ton for ammonia. For comparison, global ammonia production in 2020 was only about 144 million ton (38 million ton in China), and it is produced mainly from natural gas. Now, carbon dioxide emission from ammonia production accounted for about 1% of global total emissions! Using the same technology for production of 835 million of ammonia as marine fuel, the emission reaches the level of 5.8% (over two times more than that of the total emission from shipping in 2020).

The cumulative storage energy in fuel vessel tanks should be on the same level according to the required ship's autonomy. Comparison of equivalent energy capacity in vessel's tanks for different types of possible marine fuels has been presented in Table 1.

Due to changes in IMO regulations and EP directives on the reduction of carbon dioxide emissions from maritime transport, it seems necessary to move away from marine fuels derived from crude oil, in favor of fuels with less or zero carbon content.

Unfortunately, neither the IMO nor any other international organization has indicated a route for the transition to alternative and target fuels. It seems that the current trend of switching to LNG as a marine fuel will have to be stopped after 2035 (maybe synthetic natural gas will be used longer), due to the need to directly reducing carbon dioxide emissions by about 90%. The forecasts (scenarios) of the share of individual fuels in the marine fuel market in the following years until 2050 have no real grounds to justify the type of target fuel. It seems to be hydrogen, but despite the significant development of hydrogen technologies, it is difficult to predict the future of the marine fuel market. Ship-owners take the risk of switching to a particular type of fuel without being sure that they have chosen the right path.

Table 1. Comparison of equivalent energy capacity of fuel in vessel's tanks (for HFO = 1) (own elaboration).

Type of Fuel/Parameter	Density [kg/m^3]	Lower Heating Value [MJ/kg]	Equivalent Energy Capacity [(D_{HFO}*LHV_{HFO})/(D_x*LHV_x)]
Heavy fuel oil (HFO)	940	39	1
Marine diesel oil (MDO)	870	41.5	1.015
Marine gas oil (MGO)	840	43	1.015
Bio-diesel	880	37.2	1.120
Renewable diesel	780	44.1	1.066
Fatty acid methyl esters (FAME)	765	43	1.206
Methanol	794	22	2.099
Ethanol	789	28	1.660
Ammonia	682	18.6	2.890/3.468 *
Propane	493	46.6	1.596/2.075 *
Methane (LNG, SNG)	460	50	1.594/2.551 *
Hydrogen (liquid)	71	120	4.303/8606 *

* Additional volume for thermal insulation and a shape of the tank: ammonia * 1.2; propane * 1.3; methane * 1.6; hydrogen * 2.0.

Bearing this in mind, the authors, based on numerous research findings from existing studies and reports and using brainstorming as the heuristic method and taking into account the opinions of expert-representatives of shipping companies, obtained as part of the long-lasting multi-stage consultations carried out in the formula typical of Delphi's heuristic technique, have made an attempt to develop a potential roadmap in form of a probable scenario for the delivery and distribution of different marine fuel types to the shipping market by 2050 [12,13,17,34]. The constructed scenario, seen as the roadmap, defines the real possibilities of application to the shipping market of low and zero-emission fuels, typical for the current stage of the slowly ongoing shipping's 4th propulsion revolution. The most realistic chosen scenario of possible changes on the marine fuel market by 2050 at intervals of every 10 years is presented in Figure 4.

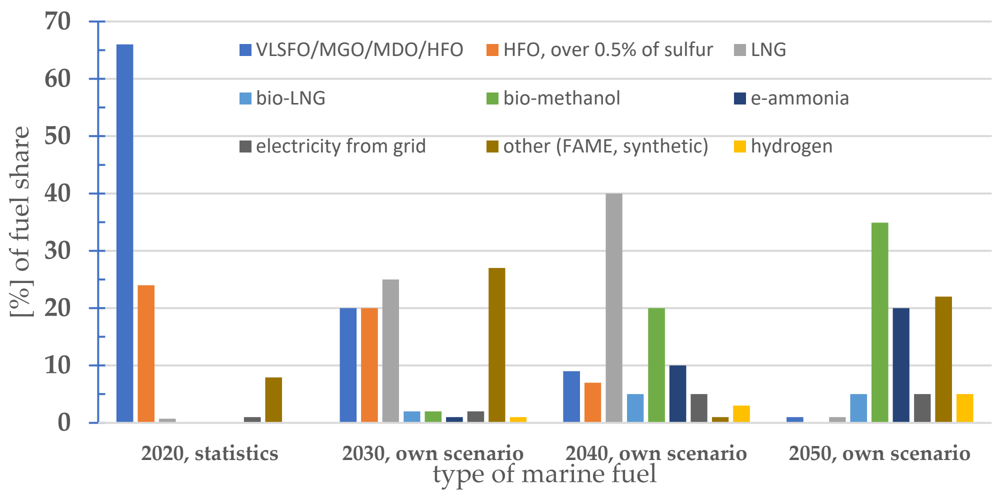

Figure 4. Statistics from 2020 and possible scenarios for the distribution of different marine fuel types to the shipping market by 2050.

Attempts are being made to meet the requirements of CO_2 emissions by leading shipowners on the maritime container market. In March 2022 [35,36], Maersk engaged in strategic partnerships around the world with six companies to acquire green methanol (bio-methanol and e-methanol) on a large scale to 2025. Total production of green methanol is expected to reach 700,000 tons by 2025 and 1.2 million tons beyond 2025. In comparison, the total energy demand for shipping in calculations only on methanol should reach 777 million tons. It is impossible to switch on methanol even for one significant shipowner. The other shipowner MSC, presented its plans [37] in response to the European Green Deal to reduce CO_2 emissions through the use of alternative fuels. In the perspective of 2050, it intends to reach net-zero CO_2 emissions from shipping by combining three main decarbonization routes with maximum CO_2 emission reduction potential:

- Fleet management and voyage plan optimization up to −5%;
- Machinery efficiency and wind assistance up to −30/55%;
- Gas (transition fuel, probably LNG) up to −10%, biodiesel up to −100%, electric battery or hydrogen fuel cells up to −100%, and ammonia or hydrogen up to −100%.

It should be noted that these are plans that may differ dramatically from the final achievement. In principle, directions of actions that can be aimed at improving the current state have been indicated but not the final results.

7. Discussion

The conducted analysis and the research results obtained allow for the formulation of several conclusions regarding the ongoing process of maritime transport decarbonizing. The research results indicate that maritime shipping could potentially meet the IMO and EU regulatory targets and reduce significantly currently generated emissions through a simultaneous and sophisticated combination of proposed, undertaken, and successively implemented technical, technological, operational and organisational types of measures and projects. The most promising way to achieve the already set targets of decarbonizing maritime transport is through the use of alternative fuels and energy, partially combined with other types of measures. However, the radical shift towards low and zero-carbon fuels, such as green ammonia, hydrogen, bio-methanol and others, which paves a way towards the shipping's 4th propulsion revolution, is significantly restrained. It is a result of the currently existing constraints in manufacturing, commercialization, distribution, and supply to the shipping markets of this type of alternative fuels. Such constraints and barriers existing nowadays in this field were analyzed in the paper and the aim of the authors was to indicate the most efficient and realistic way to overcome them.

The shipping sector will have to experience a new deep technological transformation needed to meet maturity in terms of high environmental standards in less than three decades. However, neither the IMO nor any other international organization has indicated the shipping operators a right transition pathway towards the alternative and target fuels. Therefore, most of them are looking for their own solutions and ideas aimed at meeting the decarbonization targets. In this situation, in addition to regulatory policies and effective public–private alliances established by the interested parties, it requires a major scaling up of finance for technology development. Moreover, significant and long-term, high-risk investments will be required to trigger the step-change to advance technology readiness levels and efficiently pilot these technologies.

8. Conclusions

One of the biggest challenges is currently maintaining a long-term equilibrium between the regulatory sphere establishing the ambitious decarbonizing policy and strategic action plans and the real sphere, i.e., the shipping sector in terms of agreeing on an decarbonizing pathway of the shipping sector by 2050 acceptable by all parties involved. Only this solution gives the realistic possibility of acceptable absorption of the established decarbonization targets by shipowners in all maritime transport sectors. Such a pass-way (roadmap) towards shipping decarbonisation indicates the developed scenario for the manufacturing and distributing of different marine fuels types to the shipping market by 2050.

Such a solution requires a far-reaching integration of all parties interested in the process of the maritime transport decarbonization. It applies to the entire production and distribution chain of low-carbon fuels as well as global supply chain in which one of the key links is maritime transport [38]. This approach gives the real opportunity of introducing and maintaining uniform sustainability standards in all links of the global logistics supply chains. It should create a stronger basis for their further greening and better suited to the standards of circular, digital economy, what can be regarded as an added value of such comprehensively treated strategy of shipping industry decarbonization.

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