sustainability

Article

Decarbonization of Maritime Transport: Is There Light at the End of the Tunnel?

Harilaos N. Psaraftis [1,*] and Christos A. Kontovas [2]

[1] Department of Technology, Management and Economics, Technical University of Denmark, 2800 Kongens Lyngby, Denmark
[2] Offshore and Marine Research Institute (LOOM), Maritime and Mechanical Engineering—School of Engineering and Liverpool Logistics, Liverpool John Moores University, Liverpool L3 3AF, UK; c.kontovas@ljmu.ac.uk
* Correspondence: hnpsar@dtu.dk

Abstract: The purpose of this paper is to assess the status and prospects of the decarbonization of maritime transport. Already more than two years have passed since the landmark decision of the International Maritime Organization (IMO) in April 2018, which entailed ambitious targets to reduce greenhouse gas (GHG) emissions from ships. The paper attempts to address the following three questions: (a) where do we stand with respect to GHG emissions from ships, (b) how is the Initial IMO Strategy progressing, and (c) what should be done to move ahead? To that effect, our methodology includes commenting on some of the key issues addressed by the recently released 4th IMO GHG study, assessing progress at the IMO since 2018, and finally identifying other issues that we consider relevant and important as regards maritime GHG emissions, such as for instance the role of the European Green Deal and how this may interact with the IMO process. Even though the approach of the paper is to a significant extent qualitative, some key quantitative and modelling aspects are considered as well. On the basis of our analysis, our main conjecture is that there is not yet light at the end of the tunnel with respect to decarbonizing maritime transport.

Keywords: IMO; CO_2 emissions; greenhouse gas emissions; decarbonization; maritime transport

check for updates

Citation: Psaraftis, H.N.; Kontovas, C.A. Decarbonization of Maritime Transport: Is There Light at the End of the Tunnel? *Sustainability* **2021**, *13*, 237. https://doi.org/10.3390/su13010237

Received: 20 November 2020
Accepted: 24 December 2020
Published: 29 December 2020

1. Introduction

The purpose of this paper is to take stock of recent developments as regards the decarbonization of maritime transport and assess prospects for the future. Already more than two years have passed since April 2018, when the International Maritime Organization (IMO)—the specialized agency of the United Nations (UN) regulating maritime transport—reached a landmark agreement to reduce greenhouse gas (GHG) emissions from ships, so it seems pertinent to analyze where the maritime sector stands and where it is going as regards that agreement.

The agreement in question came in the 72nd session of IMO's Marine Environment Protection Committee (MEPC 72) and is known as the Initial IMO Strategy [1]. It stipulates, among other things, ambitious targets to reduce these emissions, and expresses a strong political will to phase them out as soon as possible. The most ambitious of these targets is to reduce GHG emissions by 2050 at least 50% vis-à-vis 2008 levels, and there is also an intermediate target to reduce CO_2 emissions per transport work by 2030 at least 40%, again vis-à-vis 2008 levels. Some scientists and other stakeholders believe that the above targets are in line with those set in the Paris Agreement on climate change (COP21), whereas others disagree, believing that the targets are not ambitious enough or that they cannot be reached.

Being in line with the approach followed by the UNFCCC (the United Nations Framework Convention on Climate Change) since the Kyoto Protocol in 1992, the Paris Agreement continued to exclude international shipping and aviation from its mandate. The rationale is that these come under the jurisdictions of the IMO and ICAO (the International Civil

Aviation Organization), respectively. Additionally, and according to Oberthür [2] another reason is that no consensus could be reached on how to allocate emissions to countries; many options were considered including no allocation at all, allocation to the country where the fuel is sold, allocation to the country of the transporting company or the operator, to the country of departure or destination, and possibly others.

It is also noted that, at least until the fall of 2020, the only mandatory regulatory action limiting GHG emissions from ships has been the adoption of the so-called Energy Efficiency Design Index (EEDI) by the IMO, which is an index that measures CO_2 emissions per tonne-mile. This was decided upon at MEPC 62 in July 2011 [3] after a vote in which a number of developing countries raised strong objections to the agreement. MEPC 62 also adopted the so-called Ship Energy Efficiency Management Plan (SEEMP).

Some two and a half years after the adoption of the Initial IMO Strategy, and as this paper was being finalized, a proposal on a possible short-term measure was approved by MEPC 75 (November 2020), subject to a comprehensive assessment of its impact on states, which would have to be conducted before MEPC 76, when the measure is expected to be adopted (June 2021). The main aim of this measure is the satisfaction of the 2030 target.

The literature on ship emissions is immense, and it is not in the scope of this paper to perform a comprehensive review of it. As early as 2000, the IMO published its first study on GHG emissions from ships, which estimated that international shipping in 1996 contributed about 1.8 per cent of the world total anthropogenic CO_2 emissions. International marine emissions were estimated using a fuel-consumption methodology and a statistical emission model. The first method was based on both actual and theoretical emission factors combined with actual fuel consumption, i.e., based on international marine bunker fuel sale figures. The second approach was a statistical emission model representing the merchant world fleet. The first step was a breakdown of the world fleet according to ship type, ship size, and engine type; a total of 43,325 vessels (excluding fishing vessels) accounting for about 95% of the tonnage were analyzed. The main advantage of using a dual approach is that one is able to provide estimate ranges of GHG emissions instead of a single estimate.

Measuring maritime emissions is of paramount importance. However, very few studies had actually tried to quantify emissions from ships before the IMO 2000 study. Early works focused mainly on non-GHG gases, see for example Bremnes [4]. Corbett and Fischbeck [5] presented a global emissions inventory of NOx and SOx emissions from ships. Their model used data from marine exhaust emission tests reporting fuel-based emission rates (i.e., used mainly to derive the emission factors), international marine-fuel usage information, and the characteristics of the engines of commercial vessels.

After IMO [6] the number of studies estimating global carbon emissions significantly grew. Detailed methodologies for constructing fuel-based inventories of world ship emissions have been published by Corbett and Köhler [7], Endresen et al. [8,9], Eyring et al. [10], Jalkanen et al. [11], Olmer et al. [12], and Johansson et al. [13], among others.

The interested readers are referred to Miola and Ciuffo [14] who present an excellent meta-analysis of the studies published until around 2011 and to Nunes et al. [15] for a review of 26 activity-based studies published since 2010 including details on parameters used. Miola and Ciuffo [14] provide also a critical analysis of the emission modelling approaches and data sources available (including AIS data), identifying their limitations and constraints. There is also some good discussion on the various bottom-up and top-down approaches. In addition, the third IMO GHG Study [16] presented an excellent analysis of the data quality issues and the uncertainties related to both top-down and bottom-up approaches.

The IMO has commissioned a total of four GHG studies, the first in 2000 [6], the second in 2009 [17], the third in 2014 [16], and the fourth just recently in 2020 [18]. A paper of ours on CO_2 statistics for the world's commercial fleet [19] was completed just before the second IMO GHG study was released.

This paper attempts to answer the following questions:

- Where do we stand with respect to maritime GHG emissions?
- How is the Initial IMO Strategy progressing?
- What should be done to move ahead?

As the rest of the paper will argue, there is cause for concern on the overall path to stated targets. At the same time, some proposals are made to improve the situation.

The rest of the paper is organized as follows. Section 2 addresses where we stand as regards maritime GHG emissions and comments on the newly released fourth IMO GHG study. Section 3 comments on the Initial IMO Strategy. Finally, concluding Section 4 formulates some thoughts on what may lie ahead.

2. Where Do We Stand as Regards Maritime GHG Emissions?

Perhaps the most definitive statement on where we stand on maritime GHG emissions is contained in the fourth IMO GHG study [18], released in July 2020 and approved by the IMO at MEPC 75 (November 2020). It is not in the scope of this paper to provide a complete review of the study. This could be a major undertaking. However, we take this opportunity to comment on some of what we consider key issues addressed by the study. This is done in the sections that follow.

2.1. GHG Trends

The fourth IMO GHG study's results are surely worthy of note. First of all, the study found that total maritime GHG emissions, both international and domestic (of which more in Section 2.2), including CO_2, CH_4, and N_2O, and expressed in CO_2 equivalent emissions (CO_2e), have increased from 977 million tonnes in 2012 to 1076 million tonnes in 2018 (a 9.6% increase). Roughly 98% of these are CO_2 emissions.

According to the Initial IMO Strategy [1], GHG emissions by 2050 need to be at least 50% lower than what they were in 2008, which is considered as a base year. According to the third IMO GHG study [16], in 2008, GHG emissions were 940 million tonnes, of which 921 million tonnes were attributed to CO_2.

The fourth IMO GHG study presented the results of three different approaches: bottom-up vessel based, bottom-up voyage based, and top down; see Figure 1. The bottom-up voyage-based method defines international emissions as those that occurred on a voyage between two ports in different countries (see also below), whereas the bottom-up vessel-based method defines emissions according to ship types, as per the third IMO GHG Study [16]. Both are calculated using an activity-based approach, according to which fuel consumption is estimated for all ships in the world fleet (see also Section 2.5 below). The top-down method calculates emissions based on fuel sales data. There is about a 10–15% difference between bottom-up and top-down, which is narrower than the equivalent gap in the third IMO GHG study, which was around 30–38%. This indicates a convergence between bottom-up and top-down results.

In the third IMO GHG study, the method that was used for distinguishing between international and domestic shipping was based on the ship type and size; for instance, emissions from yachts, tugs, fishing vessels, and ferries less than 2000 GT fell into domestic shipping [16]. This approach is referred to as the vessel-based (Option 1) method. The new approach—referred to as voyage-based (Option 2)—uses AIS data to identify port calls, which allows for a distinction between international and domestic trips, as further explained in Section 2.2.

In terms of breakdown among ship types, Figure 2 is indicative, showing HFO-equivalent fuel consumption for the major types of vessels in 2018. One can notice that the class of dry bulk carriers is a very close second to containerships in terms of fuel consumption. This can be explained perhaps by the observation that the dry bulk fleet is more numerous than the containership fleet (11,268 ships vs. 5171 ships in 2018), which perhaps neutralizes the fact that containership average speeds (and hence average per ship fuel consumptions) are typically higher versus equivalent figures for bulk carriers.

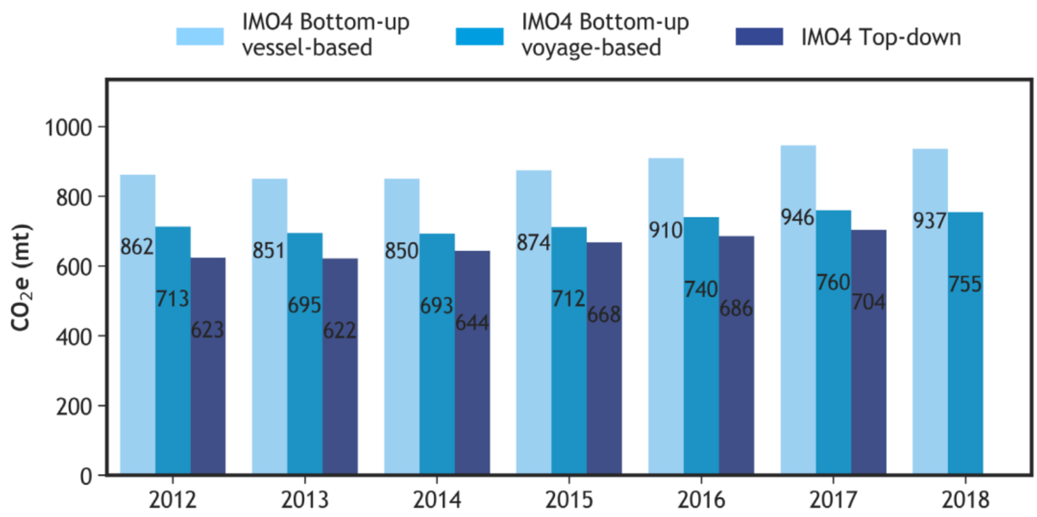

Figure 1. Annual greenhouse gas emissions (in CO_2e—excluding Black Carbon) for international shipping—Source: [18].

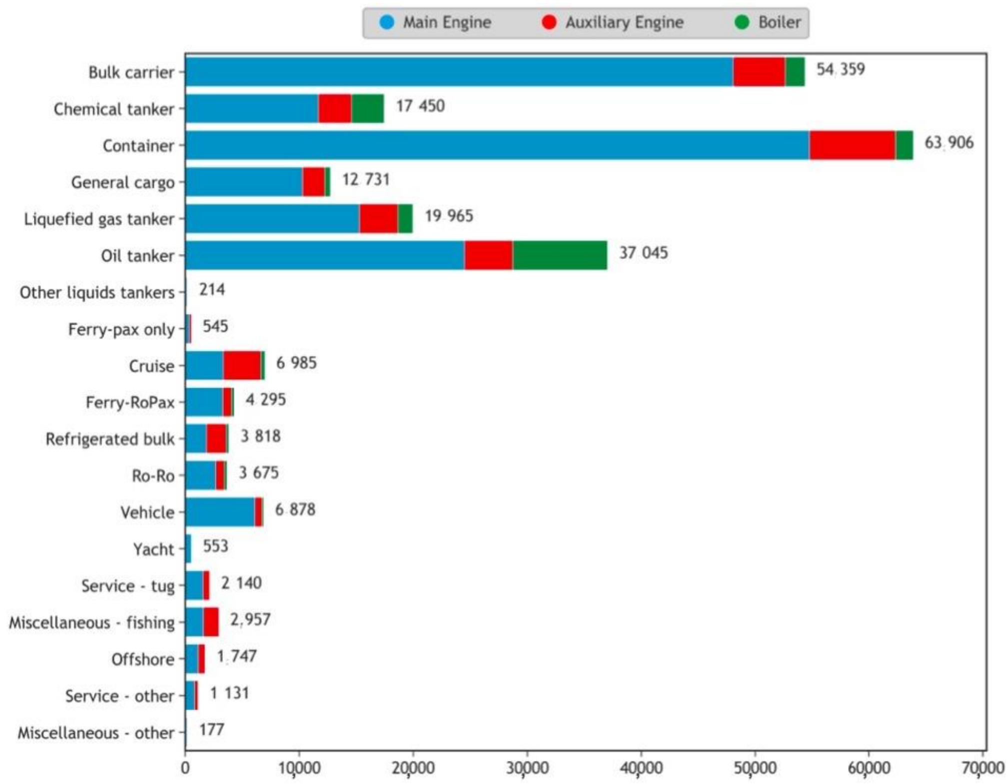

Figure 2. International, voyage-based allocation, HFO-equivalent fuel consumption (thousand tonnes), 2018—Adapted from [18].

2.2. International vs. Domestic Shipping

The fourth edition of the GHG study used a novel method for the differentiation of emissions between international and domestic shipping. The authors argue that this is in better agreement with the Intergovernmental Panel on Climate Change (IPCC) Guidelines. This method was enabled by advances in the use of AIS data to identify port calls, which allows allocation of discrete voyages to be classified as either international or domestic shipping. The study found that every single vessel has some portion of international emissions. For major ship types dominant such as oil tankers, bulk carriers, and containers, the study found that the smallest size categories have 20–40% of their emissions allocated to international shipping. For larger vessels, the allocation to international shipping varies depending on ship type, e.g., containers ~80%, oil tankers and bulk carriers ~90%, and liquefied gas tankers ~100% (see also Figure 3).

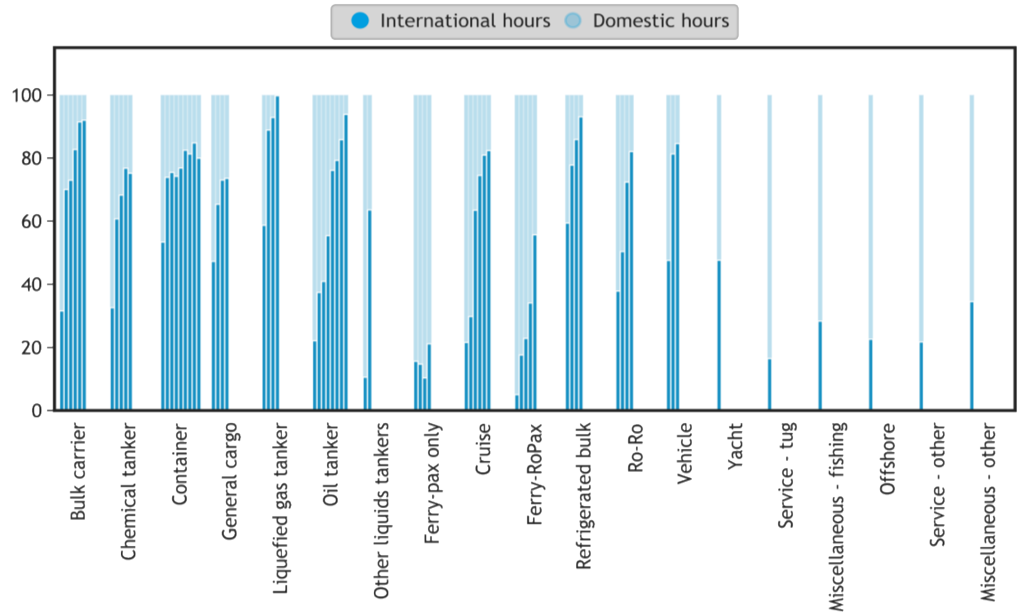

Figure 3. Proportion of time spent on international and domestic voyages on average by ship type and size in 2018 (%), where ship sizes are ordered small to large. Source: [18].

This new approach led to a significant finding: In 2018, international shipping was responsible for 755 million tonnes of CO_2e emissions out of a total of 1076 million tonnes—that is 70%. To put it in another way, 30% of total shipping emissions fell within domestic emissions, that is, are now part of the national GHG inventories, roughly twice the magnitude estimated in previous studies. The reason for this change is solely due to the change in the methodology to estimate international emissions. In fact, following the approach used in the third IMO GHG study, international shipping GHG emissions were found to represent 87% of total shipping emissions.

We note here that this might have serious political ramifications, as domestic emissions fall within national responsibilities. The guidelines of the IPCC for the preparation of GHG inventories and the reporting guidelines on annual inventories outline that emissions from maritime transport should be calculated as part of the national inventories but should be excluded from national totals and reported separately. Therefore, even though the details of the new method are not yet absolutely clear, this allocation is indeed closer to the IPPC's definition of international emissions—that is, "emissions from journeys that depart in one country and arrive in a different country". However, we note that many times the distinction between domestic and international voyages is not binary. A ship may at any point in time carry a mix of domestic and international cargoes. In fact, most of the cargoes on a ship that visits a sequence of several (say) Chinese ports before going to Europe may be international. In that sense, one would need to be careful on whether to label *all* of that ship's emissions during the domestic leg of the ship's trip as domestic. A better way might be neither vessel-based nor voyage-based, but cargo-based, but this is probably the subject of further research. For an excellent analysis of issues surrounding emissions allocation in shipping, see Zhu [20].

In addition, one might argue that the correct approach is to estimate all the emissions produced within the domestic boundaries of each country. There are actually several studies that have assessed emissions within national or port boundaries; see Nunes et al. [15]. This is actually possible using AIS data, which inherently include both spatial and temporal information. Therefore, it is theoretically feasible to estimate emissions within specific geographic areas. In this way, even the "domestic" part of international voyages could be estimated. The main difficulty is the extremely large volume of data required. As stated in Yang et al. [21], if for a single vessel AIS data is transmitted every 10 s, then in a single year, a total of over 3 million records could be generated. A rather small interval is actually required in order to avoid misallocation of emissions. In any case, this is a huge task and not compatible neither with the IPPC's definition nor with the info gathered by the current reporting schemes, for instance the IMO Data Collection System (DCS) and the EU Monitoring, Reporting, and Verification (MRV) scheme.

As a result of the new method, international shipping GHG emissions (in CO_2e) in 2008, according to the voyage-based allocation, were estimated at 794 million tonnes—that is, 15% lower than the same estimate for 2008 in the third IMO GHG Study [16]. Both approaches used the same methodology, the difference being mainly in the way they attributed voyages pertaining to international shipping. Given the importance of the baseline year 2008 in the Initial IMO Strategy, a question is, would the IMO keep the original estimate of the 2008 GHG emissions (as per the third IMO GHG study), or would the new, lower estimate (as per the fourth IMO GHG study) be used?

In our opinion, the new method to delineate international from domestic maritime GHG emissions runs the risk of creating confusion or loopholes regarding who is responsible for what, as international GHG emissions come under the jurisdiction of the IMO, whereas domestic emissions are the jurisdiction of member states (and, at a higher level, of the UNFCCC). In reducing GHG emissions from ships, we believe that fragmentation and overlaps of responsibilities should be avoided, and a uniform approach should be taken.

2.3. Speed over Ground vs. Speed through Water

AIS data obviously keep track of a ship's speed over ground. This is not necessarily the same as the ship's speed through water, due to the possible presence of currents and tides. However, in resistance and hence power and fuel consumption calculations, it is speed through water that is the relevant variable. A ship going 15 knots over ground head-on against a current of 3 knots consumes much more fuel and emits much more GHGs than the same ship going 15 knots over ground with an astern current of 3 knots. In this case, and assuming a cubic speed law, "much more" means more than a factor of 3 on a per day basis and more than a factor of 2 on a per trip basis. This is the difference between going 18 knots vs. 12 knots through water with no current. Additionally, the average of the above two fuel consumptions is not the fuel consumption at the average speed of 15 knots and no current. Three-knot currents are not uncommon across the globe. This means that if speed over ground is used instead of speed through water in these calculations (see also Section 2.5), fuel consumption may be misrepresented up or down, the magnitude of the error not known. Yet, there is no correction in the various bottom-up models used in IMO GHG studies to account for differences between these two speeds, speed over ground being the one used because of AIS.

2.4. AIS data vs. Weather Information

Suppose a ship is observed sailing at an (over ground, AIS-reported) speed of 10 knots in a particular situation. 10 knots is a low speed. The pertinent question is, are the 10 knots due to a deliberate slowdown of the ship to that speed (slow steaming), or to the fact that the ship cannot go faster as it tries to counter bad weather? The fuel consumptions in these two cases are drastically different, the latter scenario likely involving significantly higher fuel consumption and hence CO_2 emissions. Yet, there is no distinction between these two cases in an AIS-based model. There is a standard and uniform, independent of ship and speed, in fact independent of actual weather conditions, "weather correction factor" (or, sea margin) of 15% that is assumed in the fuel consumption calculation formula and is used in all cases (see also Section 2.5). However, this factor is aggregate and used across the board, and there is no attempt to link AIS information for a specific trip, which is very detailed and ship/trip-specific, with corresponding information on the prevailing weather conditions that pertain to that specific trip at the time the trip was taken. The lack of such a link may involve another approximation error, whose magnitude is again unknown. In particular, if the ship slows down due to bad weather, the fuel consumption model (see Section 2.5) underestimates fuel consumption.

2.5. Fuel Consumption Calculation

As in the third IMO GHG study [16], the model used in the fourth IMO GHG study [18] (p. 78), in order to quantify a ship's required propulsive power when it is navigating at a particular speed (over ground), is based on (a modified version of) the so-called "admiralty formula", as follows:

$$\dot{W}_i = \frac{\delta_w \cdot \dot{W}_{ref} \cdot \left(\frac{t_i}{t_{ref}}\right)^m \cdot \left(\frac{v_i}{v_{ref}}\right)^n}{\eta_w \cdot \eta_f} \quad (1)$$

Here, $\dot{W}_{ref}$ is the reference power as given in the fleet database, t_i and v_i are the instantaneous drafts and speeds, respectively, as these are provided by AIS. The reference draft (t_{ref}) and speed (v_{ref}) are also from the fleet database. The draft ratio exponent m is assumed to be 0.66, while the speed ratio exponent n is assumed to be 3, being the same as in the third IMO GHG Study [16]. In the denominator, η_w represents the weather modifier to the ship's propulsive efficiency (the value corresponding to a 15% sea margin is 0.867), and η_f is the fouling modifier. A correction factor, δ_w, to $\dot{W}_{ref}$ is applied to certain ship types and sizes to adjust the speed–power relationship, as provided by the fleet database.

In addition to the approximations in formula (1) as per Section 2.3 (speed over ground) and Section 2.4 (weather), an additional approximation involves the use of the ratio of ship drafts (t_i/t_{ref}) instead of the (more correct) ratio of ship displacements in the admiralty formula [22]. This is tantamount to assuming that ship displacement is a linear function of draft, which is surely an approximation. This approximation may be more reasonable if a ship resembles a box and less reasonable for slender designs. The reason that drafts are being used is that they are available in the AIS data, whereas displacement information is not available.

The ship's draft is actually an important parameter for an additional reason: In addition to Equation (1), it is used as a proxy to estimate the amount of cargo onboard the ship, information required for calculations on EEOI (Energy Efficiency Operational Indicator). Estimating cargo onboard the ship as a function of draft surely entails an additional approximation. Moreover, according to the study itself, there are two additional sources of uncertainty: (a) there is no AIS-reported draft information in 2012–2016 for around 10% of the vessels, and (b) some of the draft values are erroneous, the latter being related to human error, also as draft measurements are entered manually on most vessels.

We also note that in order to calculate the cargo carried, the model needs to estimate the lightweight of the ship (the works of Kristensen [23] and Lützen and Kristensen [24] are used), and the amounts of ballast and fuel carried. These calculations entail additional approximations.

Last but not least, and as argued in Psaraftis [25], the accuracy of information on v_{ref} in fleet databases is often poor, with no independent verification of its accuracy. Moreover, even the exponent n = 3 is not necessarily accurate (containerships being likely to have a higher figure; see [26]), not to mention that additional approximations are introduced by the hull fouling modifier, the actual values of which are not known but are assumed in the study.

In short, we think that the approximations discussed in Section 2.3–Section 2.5, and the associated errors thereof, can potentially be substantial.

2.6. Normal Cruising vs. Slow Transit Phases

Figure 4 from the study is also worthy of note. It presents the breakdown of GHG emissions across different phases of operation for each ship type, as estimated using the voyage-based allocation.

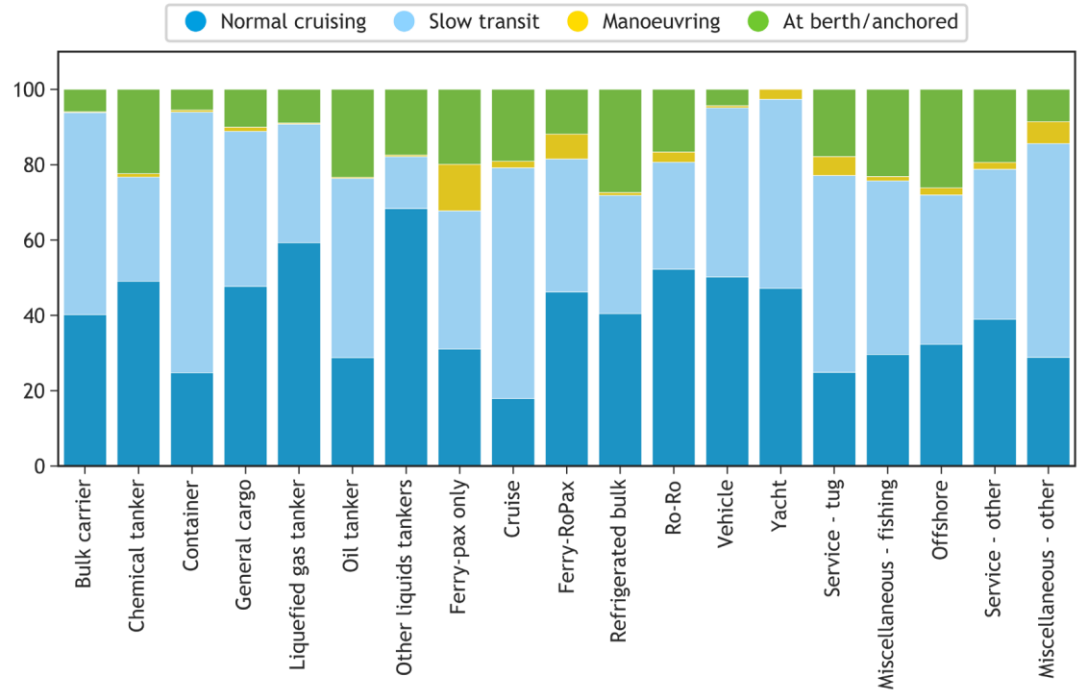

Figure 4. Proportion of international GHG emissions (in CO_2e) by operational phase in 2018—Source: [18].

It can be seen that containerships, oil tankers, and cruise ships have the smallest share of their emissions associated with the so-called "normal cruising" phase, due to the dominance of time spent in the so-called "slow transit" phase. The latter is typically defined when ship is at sea, but the main engine load is less than 65% of the maximum. For containerships, it can be seen that in 2018, this phase accounted for as much as about 70% of a ship's annual GHG emissions, whereas the cruising phase (defined as having engine load 65% or higher) accounted for only about 25%. This result confirms downward trends in ship speeds in various markets in recent years, which are due to factors such as fleet overcapacity and low freight rates, even though the 4th IMO GHG study did not attempt to investigate the reasons for such lower speeds. Independent of this, project ShipClean (https://www.chalmers.se/en/projects/Pages/ShipCLEAN---Energy-efficient-marine-transport-through_1.aspx) reported that significant slow steaming was observed in transpacific container trades in 2018, with westbound speeds as low as 12.5 knots, which correspond to main engine loads as low as 10% [27,28]. The same project also documented significant speed directional imbalances in these trades, something that is also prevalent elsewhere.

Be that as it may, the use of the term "slow transit" or "slow cruising" for a ship's operational phase in the four IMO GHG study may be confusing if misused for the phase of slowing down when a ship approaches a port, which is surely not what is meant. The same is the case for the term "normal cruising", which, as defined, has been the exception rather than the rule in many cases. In many of the shipping markets today, slow steaming is normal practice.

2.7. On MACCs and Future GHG Emissions Projections

Marginal Abatement Cost Curves (MACCs) are critical when it comes to assessing which technologies are prone to lead to GHG emissions reductions and at what cost. The Marginal Abatement Cost (MAC) of a technology is defined as the marginal cost of implementing such technology divided by the amount of CO_2 it can avert. The new study spent considerable time discussing the subject and updating the MACCs that were outlined in previous GHG studies. To that effect, the study assessed the abatement potential and costs of 44 technologies in four groups: energy-saving technologies, use of renewable energy, use of alternative fuels, and speed reduction. The study projected that in 2050, 64% of the total amount of CO_2 reduction is expected to be ascribed to the use of alternative fuels.

A problem here is that there is significant lack of transparency on how these MACCs have been constructed, in terms of costs and other data. Moreover, some measures that were included in other studies, such as for instance the adoption of more slender hull designs that would reduce ship resistance, or Just-In-Time port arrivals [29], were not included in the MACCs of the fourth GHG study. Omission of some GHG reduction alternatives would render projections of future GHGs inaccurate and GHG solutions sub-optimal. In addition, MACCs are very much relevant whenever market-based measures (MBMs) are contemplated, because a MAC of a specific technology can become negative due to the use of an MBM, thus rendering that technology economically viable. However, there is no mention of MBMs in the study. It is hard to imagine low or zero carbon fuels being implemented without some sort of MBM that would incentivize their development, and difficult to believe that the use of these fuels would just happen by itself.

Finally, as regards speed reduction that is one of the potential measures included in the MACCs outlined in the four GHG study, it is clear that speed reduction can lead to significant GHG emissions reductions. However, and as Psaraftis [28] points out, speed reduction can be the outcome of (a) a voluntary action (slow steaming) as a result of market conditions, (b) a speed limit, and (c) a response to a bunker levy. Outcomes (a), (b), and (c) are very different, at least in terms of cost and therefore MAC. It is not clear which of the above options are examined in the fourth GHG study.

2.8. Methane and Black Carbon Emissions

An interesting result of the study has been the significant increase in CH_4 emissions, from 59,000 tonnes in 2012 to 148,000 tonnes in 2018 (vessel-based calculations). This is a 174% increase, attributed mainly to a 30% increase in the use of LNG (liquefied natural gas) as fuel and the ensuing methane slip during the period. It is however noteworthy to mention that for 2012, the study estimates CH_4 emissions to be 78% lower than those estimated for the same year in the third IMO GHG Study. This is according to the authors due to different modelling assumptions, i.e., the previous IMO study assumed that LNG vessels were using an Otto cycle engine, which has a high CH_4 emissions factor, whereas the latest study sorts LNG-powered engines into four categories, the predominant engine type being an LNG-diesel (dual fuel) engine with a low CH_4 emissions factor [18] (p. 191). However, methane slip in dual fuel engines is, according to industry circles, still an issue.

The study also reports on black carbon (BC) emissions—the first GHG study to do so. BC, which is not a greenhouse gas, is a component of fine particulate matter and has a very strong warming effect. It reports an increase in BC emissions of approximately 12% from 2012 to 2018—this is actually higher than the reported CO_2 emissions increase. This is an area that certainly deserves some further research; see also the submission by Finland and Germany [30] that presents some analysis that indicates that new blends of low sulfur marine fuel can contain a large percentage of aromatic compounds, which have a direct impact on black carbon emissions. In any case, we feel that this study will provide some important evidence in relation to the near-future IMO talks on BC regulations, which would include the adoption of a ban of HFO in the Artic. Non-GHGs such as BC are of extreme importance, as there might be other climate side-effects that have so far been largely ignored by the IMO; see [31] for more on the integration of climate change and air pollution regulations.

2.9. Summary

As expected, the fourth IMO GHG study was approved in IMO's MEPC 75 (November 2020), and, in that sense, it can be considered as "the Bible" of knowledge on maritime GHG emissions, at least for the foreseeable future. Surely such knowledge is a necessary prerequisite for any attempt to reduce these emissions. If we do not know where we stand, it will be impossible to choose the path that would reach whatever target is set.

An observation is that complexity and sophistication seem to be rising as we move from earlier editions to most recent editions of IMO GHG studies. The first IMO GHG study in 2000 was 169 pages. The second one in 2009 was 280 pages. The third one in 2014 was 327 pages. The fourth one in 2020 was 578 pages, and it would be even longer if many of the figures were kept at normal size. Interesting and worthy of note as the fourth GHG study's results might be, and even though the authors of this study should be commended for their efforts, it has become practically impossible to validate the ever-increasing number of assumptions that ever more complex analyses make in order to arrive at these results, or understand exactly how the increasingly complex models used in this study operate. To much of the scientific community, most of these models are "black boxes", meaning that many of the algorithms and the data they use are not readily available for scrutiny and are full of assumptions on critical parameters, many of them not explicitly stated. Full transparency is an essential element of any scientific endeavor, and lack of full transparency undermines the credibility of any scientific result. Moreover, those of the few mathematical relations that are available for scrutiny, for instance formula (1) in Section 2.5, are seen to involve many approximations and assumptions and thus many possible errors.

The combination of lack of modelling transparency and the potential errors as identified in previous sections can lead to this implication: for all the elaborate effort that went into the fourth GHG study, and for all the very useful information and other data this study has compiled, we do express some honest reservations on the methodology of this study as a basis to estimate maritime GHG emissions. This is true as regards estimates of past GHG emissions, and is even more true regarding projections of future GHG emissions.

Is there an alternative, at least to keep track of current GHG emissions? We think there is, and it is a "Columbus egg" solution. Mandate a device inside the stack of all ships (maybe above a certain size) that can directly measure GHG emissions, and have that device send its measurements directly to the IMO. Direct emissions monitoring provides robust and transparent data for the operators, and for automatic reporting to the regulator (the IMO) and the enforcement authorities. According to Devanney [32], "CO_2 stack emissions can be monitored to an accuracy of better than +/−2% in a reliable, tamper-proof, difficult to spoof manner for about $60,000 per ship. And as a bonus, we can throw in a direct, encrypted transfer of the data via satellite to a central processing entity." Note that this was in a 2011 paper, and there has been much progress since.

Such devices could be certified by the IMO or by other regulatory bodies such as the USA's EPA, Germany's TÜV, and the British MCERTS. Similar devices (which however do not measure flow volume) are compulsory on ships equipped with scrubbers to measure sulfur emissions as part of the onboard procedures for demonstrating compliance with the "2015 Guidelines for Exhaust Gas Cleaning Systems"; see [33]. These devices could directly transmit GHG statistics to the IMO. Installing such devices would obviate the need for future GHG studies and could provide instant information to the IMO on where we stand as regards GHG emissions. These devices can also verify compliance with the sulfur regulations—no need for onboard inspections to be carried out by the Port State Control or drones to sniff emissions.

As for any simple solution, there will be objections to it. One objection may be from ship owners, who may be afraid (and maybe for a good reason) that this may eventually be used to directly tax GHG emissions [32]. Another objection may come from those who undertake studies that estimate GHG emissions, or from certified verifiers of GHG emissions. These objectors may, for different reasons, find all kinds of defects in the direct measurement idea, for instance that such devices do not exist, they are unreliable, can be tampered with, are expensive, etc. There are many interests at the IMO, and the fate of any solution depends, to a significant extent, on the degree of support that the solution may find, or not find, among IMO stakeholders (for a recent analysis of influence as well as transparency at the IMO see [34]).

We think that some courage would be necessary to proceed to such a direct measurement solution. At the moment, it is not even on the table at the IMO, even though the EU

MRV scheme includes this solution in its roster of solutions to report fuel consumption, among several others. A move in the right direction is the implementation of IMO's DCS on fuel consumption for all ships of 5000 GRT and above from 2019 on; however, additional steps need to be taken if one is to make direct measurement of emissions a mandated measure.

But even assuming that this issue is resolved and GHG emissions can be estimated in a more reliable way, the very pressing question is how to reduce them. The next section attempts to address this question.

3. Assessing Progress on the Initial IMO Strategy

As stated earlier, in 2018, the IMO adopted the so-called Initial IMO Strategy [1], which set out a vision to drastically reduce GHG emissions from international shipping. Ambitious targets were set (a)"to reduce CO_2 emissions per tonne-mile as an average across international shipping by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared with 2008"; and (b) "to reduce the total annual GHG emissions by at least 50% by 2050, whilst pursuing efforts towards totally phasing them out". The Initial IMO Strategy also calls "to peak GHG emissions from international shipping as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008" [1].

More than two years after the Initial IMO Strategy was adopted, the question is, where do we stand as regards progress on realizing the above targets? To attempt to answer this question, the following can be said:

The Initial IMO Strategy did not initially prioritize among the wide array of candidate measures, except it was decided to focus on short-term measures, that is, measures to be agreed upon and implemented by 2023. A detailed schedule of action to 2023 was drafted; however, difficulties of negotiating a consensus on this plan across stakeholders were apparent, as most notably attested by the substitution of the word "prioritization" (of the candidate measures) by the word "consideration", which surely projects a much weaker political will.

Related difficulties of political nature are not uncommon at the IMO. In fact, two stated principles that were centrally included in the Initial IMO Strategy are (a) non-discrimination/ no more favorable treatment and (b) common but differentiated responsibilities and respective capabilities (CBDR-RC). These seem to be in direct conflict with one another. CBDR-RC has been the main political argument of a group of developing countries to resist GHG emissions reduction, not just for shipping but across the board, on the grounds that this would impede their economic development. In that sense, the stance of these countries is that their obligation to reduce GHGs should be less stringent than that of developed countries. Even though CBDR-RC has not been explicitly invoked very frequently after the adoption of the Initial IMO strategy, no way to circumvent CBDR-RC has been found. As Psaraftis and Kontovas [34] pointed out, it is conceivable that shipping companies or other industrial interests in these countries may be responsible for these countries' stance on CBDR-RC and hence GHGs. In that sense, CBDR-RC, even though it invokes a societal cause enshrined in the Kyoto protocol, may be used as an argument to "camouflage" whatever other real reasons might exist for those countries' stance on GHGs.

Then there was an inordinate, at least in our opinion, amount of discussion on the imposition of mandatory speed limits as a short-term tool to reduce GHG emissions, apparently as a bridge until longer-term measures could be adopted. The standard bearers for such a proposal were non-governmental organizations (NGOs) such as the clean shipping coalition (CSC). These NGOs had originally proposed speed limits as far back as 2010; however, their proposals were rejected by the IMO. However, after MEPC 72 (April 2018), these proposals resurfaced, and in addition to CSC, more players joined the speed limit bandwagon. France submitted a document to the IMO supporting the idea. Greece submitted another document advocating mandatory speed adjustments or maximum allowed main engine fuel consumptions. At both MEPC 74 (May 2019) and the sixth intersessional meeting that preceded it, environmental groups protested in front of the IMO headquarters, asking for ships to slow down to save the planet. MEPC 74 did not endorse the measure and the speed limit lobby further lost steam at the seventh intersessional meeting after MEPC 74 (November 2019), as the short-term roster of measures that were recommended then did not favor speed limits as an option. For a comparison between speed limits and a bunker levy, see [28]. In that reference, it is argued that speed limits can hardly incentivize an improvement in ship energy efficiency, are likely to cause considerable distortions, and would be difficult to enforce.

In a parallel development, and in the context of the European Green Deal [35], the President of the European Commission indicated in December of 2019 that shipping would be included in the EU Emissions Trading System (ETS), and the European Parliament voted in September of 2020 to include shipping into the EU ETS. This was a major development, and one that appears to meet with the strong opposition of major shipping associations. The European Commission is working on an impact assessment study to ascertain exactly how such a scheme will be implemented, with results expected in the summer of 2021. An ETS definitely belongs to the category of MBMs, which as mentioned above IMO lists as potential medium-term measures.

At this point in time, the two processes, IMO and EU, appear to be completely disconnected. There is no substantial mention of EU ETS in any of the current items on the IMO GHG agenda. However, the inclusion of shipping into the EU ETS may render measures or any other measure not fully relevant if implemented in parallel with the EU ETS. In contrast to the IMO process, which has been delayed due to the COVID-19 outbreak in the spring of 2020, the EU process is very much up and running, with a flurry of legislative activities in the European Parliament, which seems eager to push the EU ETS agenda. The pertinent question is, assuming that the plans to include shipping into the EU ETS go ahead, as it looks likely, how would these plans intersect with the implementation of any short-term measure that would be adopted at the IMO?

The answer to this question is not clear yet. An inclusion of shipping into the EU ETS could also potentially undermine IMO's agenda on MBMs, as the difficulties of combining a global IMO MBM with a regional EU ETS could be substantial.

An interesting development that could boost R&D for energy saving technologies and alternative fuels is the proposal that several major shipping associations to the IMO (ICS, BIMCO, WSC, Intertanko, Intercargo, Interferry, CLIA, and IPTA) submitted to IMO/MEPC 75. They proposed a 2 USD/tonne mandatory surcharge on bunker fuel, which could generate about 5 billion USD over a 10-year period, to fund a non-governmental R&D organization in order to accelerate efforts toward decarbonization [36]. This proposal is not considered as an MBM; however, its proposers stated that its architecture could be used in case the IMO wants to proceed with a levy, implying that this is their preferred MBM. However, the response to this proposal by IMO member states at MEPC 75 (November 2020) was lukewarm at best, with some member states even suggesting that this proposal would introduce MBMs to the IMO via the back door. Thus, no decision on the matter was made at MEPC 75. As this paper was being finalized, the fate of this proposal remained unclear.

At the same time, and after a discussion that lasted some 2.5 years, MEPC 75 decided on a short-term measure. This measure is more focused towards meeting the 2030 carbon intensity target than the 2050 target.

More specifically, MEPC 75 approved a combined short-term mandatory measure that was agreed during the seventh intersessional meeting (October 2020). This would require ships of 5000 GRT and above to combine two measures to reduce their carbon intensity and achieve the IMO's 2030 goals. These would add further to the existing requirements that are described above. Currently, per the EEDI regulation, ships built after 2012 are required to be designed and built more efficiently than the baseline. A similar approach is to be used for existing vessels based on a new indicator, the Energy Efficiency Existing Ship Index (EEXI), applicable after 2022. The attained EEXI should be calculated and verified for each existing ship, and this would indicate the "estimated performance of the ship in terms of energy efficiency". Ships will be required to meet a required EEXI—that is a percentage of the EEDI baseline value—depending on the ship type and category. For example, the reduction factor (in percentage) for the EEXI relative to the EEDI baseline for a very large containership (above 200,000 DWT) is set to be at 50%, whereas for a tanker or bulk carrier of similar size it is only 15%. This annual ship-category and type specific, reduction factor is to be increased progressively to meet the objectives of the Initial IMO Strategy. Note that, unlike a true operational efficiency standard, the EEXI would limit the amount of CO_2 emitted per unit of transport supply rather than per unit of actual transport work, that is, does not take into account the cargo transported. It is expected that these limits will not be difficult to achieve, even for older vessels using Engine Power Limitation (EPL), which is one of the main ways to achieve the desired EEXI. Given the widespread use of slow-steaming in recent years, it is unclear what the effect of this measure would be in reducing GHG emissions.

The second component of the measure is related to operational carbon intensity reduction requirements, based on a new operational carbon intensity indicator (CII), and is to be applied after 2025. After the end of each calendar year, the annual operational CII will be calculated using data collected as part of the IMO DCS. This annual index (attained CII) will then be verified against the required annual operational CII to determine the operational rating (given on a five-point scale from "A" to "E"). Vessels that are underperforming (rated E or rated D for three consecutive years) will have to develop a plan of corrective actions; however, there is no serious enforcement mechanism, and such ships would continue to sail. At the same time, the MARPOL revisions encourage administrations, port authorities, and other stakeholder to provide incentives for high performing vessels (those rated as A or B), although it is not clear what these incentives would be. The operational indicators are yet to be agreed, but they can be based either on transport work using the energy efficiency operational indicator (EEOI) or the annual efficiency ratio (AER).

Per IMO rules, the decision of MEPC 75 on the short-term measure would be followed by its eventual adoption at MEPC 76 (June 2021). Further, MEPC 75 decided that a comprehensive impact assessment of the measure would have to be conducted and submitted before MEPC 76 (June 2021) and is to be considered as an integral part of the package. This assessment would investigate the potential impacts of the measure on states, including disproportionately negative impacts. Some IMO member states, including developing economies, small island developing states (SIDS) and least developed states (LDCs) are concerned that measures to curb GHG emissions that lead to speed reduction or lead to increased transport costs or generally to negative or disproportionately negative impacts on the respective economies. A number of impact assessment studies have been conducted for the variety of short-term measures proposed to the IMO, but none has been conducted for the combined measure.

4. Conclusions

On the basis of the above, what can we say as regards the prospects of shipping decarbonization?

First of all, it is too early to assess and comment on the combined short-term measure, and its comprehensive impact assessment is pending. Environmental groups and some countries in Europe and the Pacific have expressed dissatisfaction as regards the measure's level of ambition; however, it is not clear if something better can find consensus at the IMO. In addition, if negative or disproportionately negative impacts are found, these might slow down the speed of implementation of the measure, or even derail it completely. This remains to be seen.

As regards meeting the 2030 target, a number of carbon intensity metrics including EEOI (g CO_2/t/nm) and AER (g CO_2/dwt/nm) were reported in the fourth IMO GHG study. EEOI takes into account the actual cargo transported, and it is probably a better reflection of the true carbon intensity, provided of course that cargo onboard can be accurately estimated. Although the calculation of the EEOI is considered as the primary monitoring tool—as per the 2016 Guidelines for the development of a Ship Energy Efficiency Management Plant (SEEMP)—EEOI-related data are not reported to the IMO and could be difficult to verify. Various other reservations are also reported on the reliability of EEOI as an operational index (see [25,37,38] among others). By contrast, the deadweight of a vessel is known and is reported along with the data collected as per IMO's DCS. The calculation of the AER for a vessel is therefore very straightforward.

According to the fourth IMO GHG study, the industry has already achieved a 29% reduction (from 15.16 g CO_2/t/nm in 2008 to 10.7 g CO_2/t/nm in 2018). A further analysis of the voyage-based EEOI reveals that containerships and bulk carriers have already achieved a reduction of around 35%, and bulk carriers a remarkable reduction of 60%. On the other hand, LNG tankers show an increase of 7%. If AER is used as a proxy for carbon intensity, international shipping has achieved already a 21% reduction, versus the 40% reduction target of 2030. Note that these carbon intensity metrics make more sense if viewed at a global (or even sectoral) fleet level rather than at an individual ship level, due to the number of uncertain factors that may impact the environmental performance of any individual ship.

However, even if one assumes that meeting the 2030 target may look within reach, meeting the 2050 target is a very different story. It is clear that for this to happen, one would need a quantum leap in energy saving technologies and alternative fuels. In spite of continuing progress, our opinion is that such a quantum leap will not happen by itself. One would need to provide the proper incentives to do so. The pertinent question is, what should such an incentive be. We believe that an answer (and perhaps the only answer) is MBMs. These could incentivize the development of alternative fuels and other energy saving technologies that are currently non-viable, plus they could produce short-term benefits as well, by inducing slower speeds and thus reduced emissions. Putting it more simply, so long as fossil fuels are cheap, people will use them, and MBMs would be a mechanism to internalize the external costs of GHG emissions and apply the polluter pays principle.

However, MBMs are currently almost invisible on the IMO agenda. Some Pacific SIDS have asked MEPC 75 to reopen the MBM discussion as soon as possible; however, there was no consensus for this proposal, and it is still unclear how and when this discussion will continue at the IMO. Surely MBMs are very visible on the EU agenda; however, it is not yet clear what the inclusion of shipping into the EU ETS would entail. More on MBMs can be found in [39,40].

In our opinion, the pace of implementing the Initial IMO Strategy has been, at least thus far, rather slow. At the time of writing of this paper, the most significant development after April 2018 has been the decision of MEPC 75 to proceed with a combined short-term measure. This measure seems to be primarily tailored to satisfy the 2030 40% target. However, how far the measure might take us along that path is not yet clear. A fortiori, how far this measure will succeed in terms of meeting the 2050 50% target is, at this point in time, completely unknown. No other medium-term or long-term measure is yet on the table at the IMO.

In conclusion, and as the subtitle of the paper has posed the question if in the quest to decarbonize shipping there is light at the end of the tunnel, our very honest position, and based on all we know at this point in time is, "not yet".

Author Contributions: Conceptualization: H.N.P. and C.A.K.; formal analysis: H.N.P. and C.A.K.; writing: H.N.P. and C.A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Publicly available datasets were analyzed in this study. The Fourth IMO GHG Study (IMO document MEPC 75/7/15) can be downloaded (registration required) via the IMODOCS website (https://docs.imo.org/Default.aspx).

Acknowledgments: This paper is the result of unfunded research collaboration between the two authors. They would like to thank Kostas Gkonis, George Gratsos, Poul Woodall, Panos Zachariadis and three anonymous reviewers for their comments on two previous versions of the paper.

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

References

1. IMO. *Initial IMO Strategy on Reduction of GHG Emissions from Ships. IMO Resolution MEPC.304(72)*; International Maritime Organization (IMO): London, UK, 2018; Available online: https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.304(72).pdf (accessed on 20 November 2020).
2. Oberthür, S. Institutional interaction to address greenhouse gas emissions from international transport: ICAO, IMO and the Kyoto Protocol. *Clim. Policy* **2003**, *3*, 191–205. [CrossRef]
3. IMO. *Inclusion of Regulations on Energy Efficiency for Ships in MARPOL Annex V-Resolution MEPC.203(62)*; International Maritime Organization (IMO): London, UK, 2011.
4. Bremnes, P. *Calculation of Exhaust Gas Emission from Sea Transport. Methodology and Results*; EMEP Workshop on Emissions from Ships: Oslo, Norway, 1990; pp. 7–8.
5. Corbett, J.J.; Fischbeck, P.S.; Pandis, S.N. Global nitrogen and sulfur inventories for oceangoing ships. *J. Geophys. Res. Atmos.* **1999**, *104*, 3457–3470. [CrossRef]
6. IMO. *First IMO GHG Study 2000*; International Maritime Organization (IMO): London, UK, 2000.
7. Corbett, J.J.; Koehler, H.W. Updated emissions from ocean shipping. *J. Geophys. Res. Atmos.* **2003**, *108*, D20. [CrossRef]
8. Endresen, Ø.; Sørgård, E.; Sundet, J.K.; Dalsøren, S.B.; Isaksen, I.S.; Berglen, T.F.; Gravir, G. Emission from international sea transportation and environmental impact. *J. Geophys. Res. Atmos.* **2003**, *108*, D17. [CrossRef]
9. Endresen, Ø.; Sørgård, E.; Behrens, H.L.; Brett, P.O.; Isaksen, I.S. A historical reconstruction of ships' fuel consumption and emissions. *J. Geophys. Res. Atmos.* **2007**, *112*, D12. [CrossRef]
10. Eyring, V.; Köhler, H.; Van Aardenne, J.; Lauer, A. Emissions from international shipping: 1. The last 50 years. *J. Geophys. Res. Atmos.* **2005**, *110*, D17. [CrossRef]
11. Jalkanen, J.-P.; Brink, A.; Kalli, J.; Pettersson, H.; Kukkonen, J.; Stipa, T. A modelling system for the exhaust emissions of marine traffic and its application in the Baltic Sea area. *Atmos. Chem. Phys.* **2009**, *9*, 9209–9223. [CrossRef]
12. Olmer, N.; Comer, B.; Roy, B.; Mao, X.; Rutherford, D. *Greenhouse Gas Emissions from Global Shipping, 2013–2015 Detailed Methodolog*; ICCT (International Council on Clean Transportation): Washington, DC, USA, 2017; Volume 52.
13. Johansson, L.; Jalkanen, J.-P.; Kukkonen, J. Global assessment of shipping emissions in 2015 on a high spatial and temporal resolution. *Atmos. Environ.* **2017**, *167*, 403–415. [CrossRef]
14. Miola, A.; Ciuffo, B. Estimating air emissions from ships: Meta-analysis of modelling approaches and available data sources. *Atmos. Environ.* **2011**, *45*, 2242–2251. [CrossRef]
15. Nunes, R.; Alvim-Ferraz, M.; Martins, F.; Sousa, S. The activity-based methodology to assess ship emissions-A review. *Environ. Pollut.* **2017**, *231*, 87–103. [CrossRef]
16. IMO. *Third IMO GHG Study*; International Maritime Organization (IMO): London, UK, 2014; Available online: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf (accessed on 20 November 2020).
17. IMO. *Second IMO GHG Study 2009*; International Maritime Organization (IMO): London, UK, 2009; Available online: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/SecondIMOGHGStudy2009.pdf (accessed on 20 November 2020).
18. IMO. *Fourth IMO GHG Study 2020*; International Maritime Organization (IMO): London, UK, 2020.
19. Psaraftis, H.N.; Kontovas, C.A. CO_2 emission statistics for the world commercial fleet. *WMU J. Marit. Aff.* **2009**, *8*, 1–25. [CrossRef]
20. Zhu, W. Impact of Emission Allocation in Maritime Transportation. Doctoral Thesis, Norwegian University of Science and Technology, Trondheim, Norway, 2015.
21. Yang, D.; Wu, L.; Wang, S.; Jia, H.; Li, K.X. How big data enriches maritime research–a critical review of automatic identification system (AIS) data applications. *Transp. Rev.* **2019**, *39*, 755–773. [CrossRef]
22. Barrass, B. *Ship Design and Performance for Masters and Mates*; Elsevier: London, UK, 2004.
23. Kristensen, H.O. *Determination of Regression Formulas for Main Dimensions of Tankers and Bulk Carriers Based on IHS Fairplay Data*; University of Southern Denmark: Odense, Denmark, 2012.
24. Kristensen, H.O. *Statistical Analysis and Determination of Regression Formulas for Main Dimensions of Container Ships Based on IHS Fairplay Data*; University of Southern Denmark: Odense, Denmark, 2013.
25. Psaraftis, H.N. Decarbonization of maritime transport: To be or not to be? *Marit. Econ. Logist.* **2019**, *21*, 353–371. [CrossRef]
26. Psaraftis, H.N.; Kontovas, C.A. Speed models for energy-efficient maritime transportation: A taxonomy and survey. *Transp. Res. Part C Emerg. Technol.* **2013**, *26*, 331–351. [CrossRef]

27. Vilas, R. Container Shipping Performance: A Case Study on a Transpacific Service. Master's Thesis, Technical University of Denmark, Kongens Lyngby, Denmark, 2018.
28. Psaraftis, H.N. Speed optimization versus speed reduction: Are speed limits better than a bunker levy? *Marit. Econ. Logist.* **2019**, *21*, 524–542. [CrossRef]
29. Bouman, E.A.; Lindstad, E.; Rialland, A.I.; Strømman, A.H. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping—A review. *Transp. Res. Part D Transp. Environ.* **2017**, *52*, 408–421. [CrossRef]
30. IMO. *Initial Results of a Black Carbon Measurement Campaign with Emphasis on the Impact of the Fuel Oil Quality on Black Carbon Emissions. IMO doc. PPR/7/8, Submitted by Finland and Germany*; International Maritime Organization (IMO): London, UK, 2019.
31. Kontovas, C.A. Integration of air quality and climate change policies in shipping: The case of sulphur emissions regulation. *Mar. Policy* **2020**, *113*, 103815. [CrossRef]
32. Devanney, J. Direct Taxation Is the Best Way to Curb CO2 Emissions. Available online: https://lloydslist.maritimeintelligence.informa.com/LL009769/Direct-taxation-is-the-best-way-to-Curb-CO2-emissions (accessed on 20 November 2020).
33. IMO. *2015 Guidelines for Exhaust Gas Cleaning Systems. IMO doc. Resolution MEPC.259(68)*; International Maritime Organization (IMO): London, UK, 2015; Available online: http://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Marine-Environment-Protection-Committee-(MEPC)/Documents/MEPC.259(68).pdf (accessed on 20 November 2020).
34. Psaraftis, H.N.; Kontovas, C.A. Influence and Transparency at the IMO: The Name of the Game. *Mar. Policy Manag.* **2020**, *22*, 151–172. [CrossRef]
35. EU. *The European Green Deal. EU doc. COM(2019) 640*; European Commission. 2019. Available online: https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf (accessed on 20 November 2020).
36. IMO. *Proposal to Establish an International Maritime Research and Development Board (IMRB). Submitted by BIMCO, CLIA, ICS, INTERCARGO, INTERFERRY, INTERTANKO, IPTA, and WSC*; International Maritime Organization (IMO): London, UK, 2019; Available online: https://www.ics-shipping.org/docs/default-source/Submissions/IMO/final-imrb-submission-to-mepc-75.pdf (accessed on 20 November 2020).
37. Polakis, M.; Zachariadis, P.; de Kat, J.O. The Energy Efficiency Design Index (EEDI). In *Sustainable Shipping*; Psaraftis, H.N., Ed.; Springer: Cham, Switzerland, 2019; pp. 93–135.
38. Panagakos, G.; Pessôa, T.d.S.; Dessypris, N.; Barfod, M.B.; Psaraftis, H.N. Monitoring the carbon footprint of dry bulk shipping in the EU: An early assessment of the MRV regulation. *Sustainability* **2019**, *11*, 5133. [CrossRef]
39. Psaraftis, H.N. Market-based measures for greenhouse gas emissions from ships: A review. *WMU J. Marit. Aff.* **2012**, *11*, 211–232. [CrossRef]
40. Lagouvardou, S.; Psaraftis, H.N.; Zis, T. A Literature Survey on Market-Based Measures for the Decarbonization of Shipping. *Sustainability* **2020**, *12*, 3953. [CrossRef]