Reducing GHG emissions in shipping – Measures and Options

Elizabeth Lindstad [1], Torstein Ingebrigtsen Bø[1,2], Gunnar S. Eskeland[3]

[1]Sintef Ocean AS (MARINTEK), Trondheim, Norway
[2]Norwegian University of Science and Technology (NTNU), Trondheim, Norway
[3]Norwegian School of Economics (NHH) and SNF and CenSES, Bergen, Norway

Email: Lindstad@sintef.no

ABSTRACT

CO_2 emissions from maritime transport represent around 3% of total anthropogenic CO_2 emissions. These emissions are assumed to increase by 50% to 250% up to 2050 in business-as-usual scenarios with a tripling of world trade, while climate target of 1.5° - 2 °C requires 50 – 85 % reductions across all economic sectors. The maritime sector thus faces demanding challenges to reduce its emissions. Previous studies (Buhaug et al 2009; Lindstad, 2013; Bouman et al 2017) have indicated that by combination of design and operational measures based on today's technologies, emissions can be reduced by 75% up to 2050. This study examines the main reduction measures identified in previous studies and investigates to what degree the measures are implemented and used by the industry. Moreover, we assess how current policies encourage or discourage the implementation of the main reduction measures, and point towards important areas of policy realignment.

KEYWORD: Maritime transport; Shipping and the environment; Greenhouse gases; Abatement options; Emission reductions IMO.

1. INTRODUCTION

From the first days of human civilization, sea transport has dominated trades between cities, nations, regions, and continents. Together with telecommunication, trade liberalization and international standardization, transport - maritime in particular - has enabled the process we call globalization (Kumar and Hoffman, 2002), entailing productivity gains from specialization and comparative advantages. World trade in the form we know today started around 1850 as global communication developed with steam engines allowing vessels to move without wind, steel hulls enabling larger ships, screw propellers making ships more seaworthy and deep-sea cables allowing traders and ship owners to communicate across the world (Stopford, 2009).

Products are increasingly being manufactured in one part of the world, transported to another country, further refined, and then redistributed to their final country of consumption.

Figure 1 illustrates the strong globalisation of the world from 1970 up to 2012 with all monetary figures adjusted to 2010 levels. First, the growth in sea transport measured in tons transported and ton-miles (freight work) broadly has followed annual global GDP growth of 3 %. Second, growth in the *value* of international trade is twice the annual growth in tons moved, i.e. 6 %. This means that movement of high-value items has increased more than movement of low value cargo such as iron-ore, crude-oil, coal and grain. Third, freight work measured in ton-miles increased as much as tons moved, which implies that average freight distance has been constant. Fourth, fuel consumption in maritime transport has increased less than the freight work, i.e. by 2 % per year, which implies 1 % annual reduction in fuel use and CO_2 emissions per ton nm.

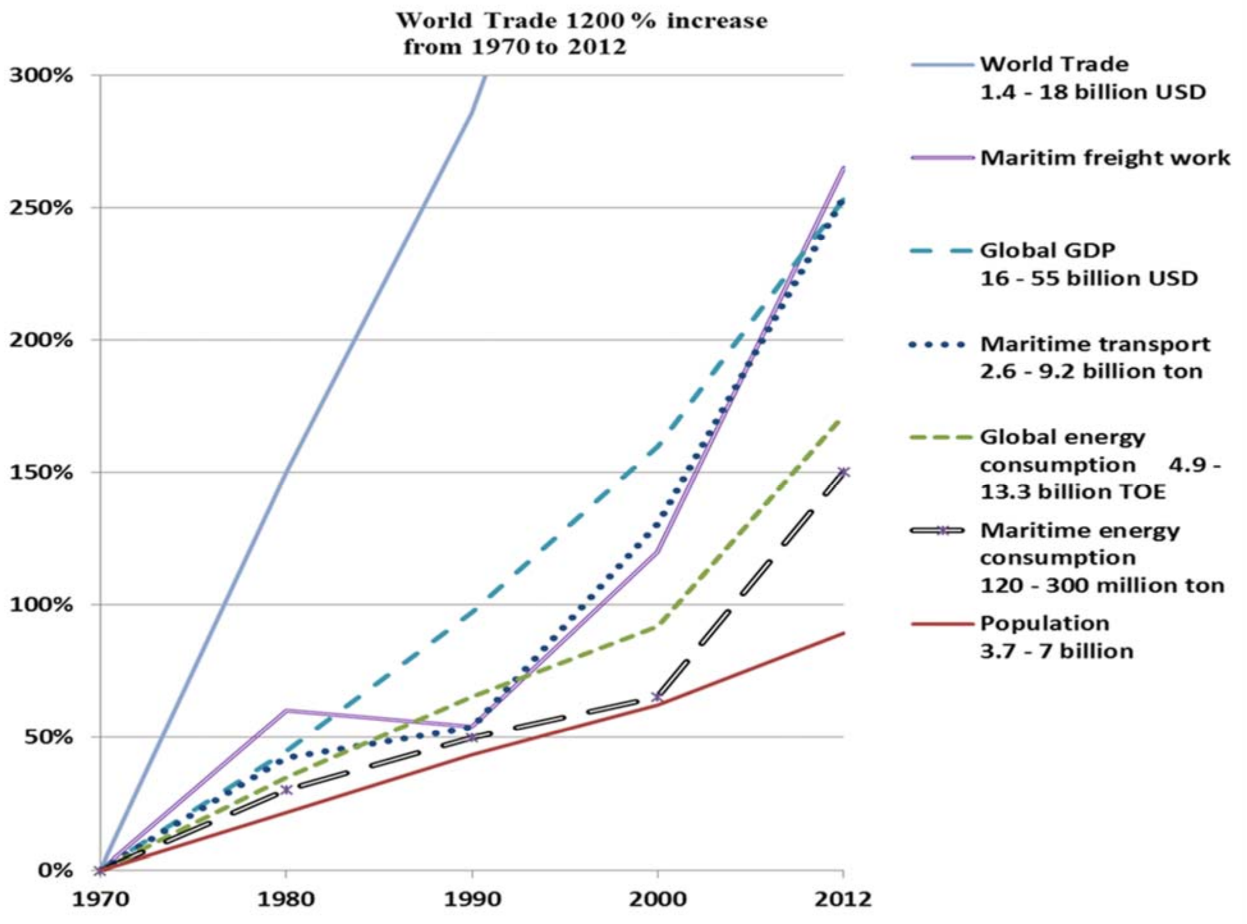

Figure 1: Global development 1970 – 2012. Sources: Lindstad (2013); Eskeland and Lindstad (2016)

The environmental consequences of increased international trade and transport have become important because of the current climate challenge (Rodrigue et. al., 2016). With a business-as-usual (BAU) scenario with continuous transport growth, i.e. around 3% and 1% efficiency improvement, both annually (as seen from 1970) future emissions might increase by 150% – 250 % up to 2050 (Buhaug et al., 2009; Lindstad 2013).

Figure 2 based on Smith et al. (2014) shows shipping emissions up to 2050 for the 16 different scenarios developed by the Third IMO GHG study. These scenarios contain various growth and technology assumptions, however none of them indicates a decrease in emissions up to 2050. In best case (for climate mitigation), emissions will stabilize and in worst case they will increase by 250%. These emission growth prospects are opposite to what is required to reach a climate targets by 2100. Global GHG emissions must decrease to net zero and even further to negative values across all sectors by the second half of this century, as indicated by the slope of the 1.5 – 2-degree scenario IPCC (2013). Nevertheless, it is a controversial issue how the annual greenhouse gas reductions shall be taken across sectors. Given a scenario where all sectors accept the same percentage reductions, the total shipping emissions in 2050 may be no more than 15% - 50% of current levels.

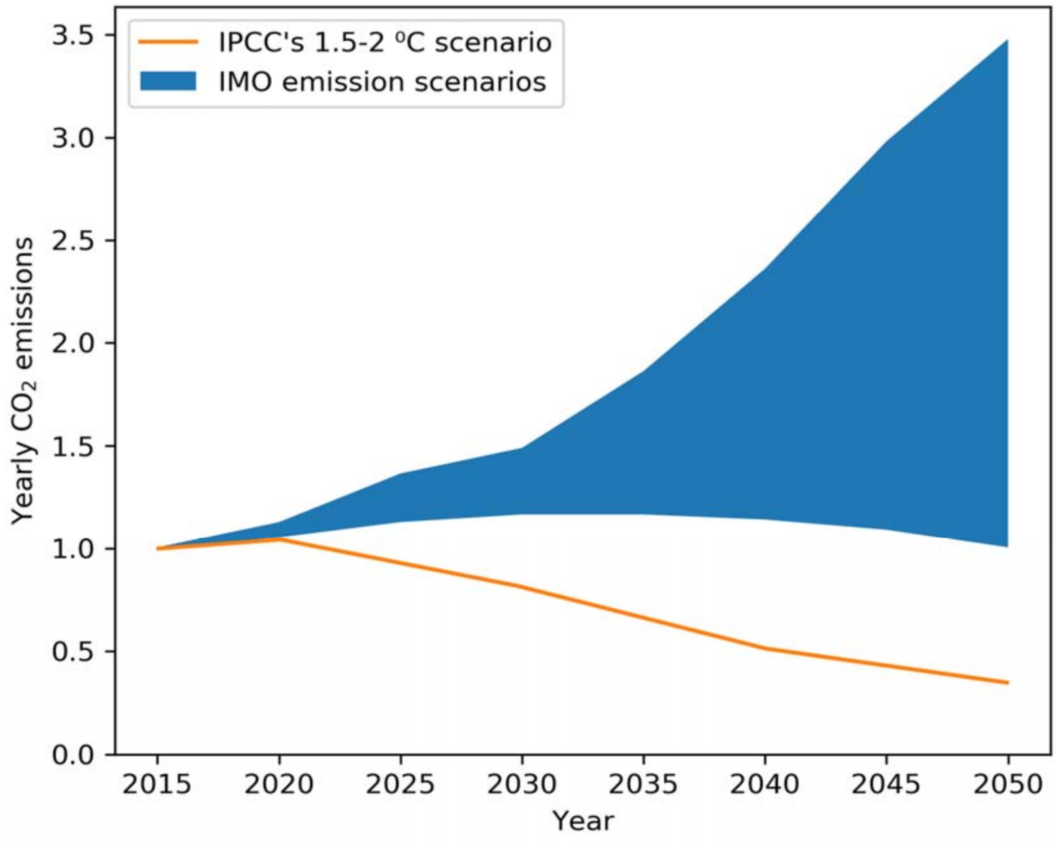

Figure 2: Scenarios for Global Shipping emission. Source: Smith et al. (2014) and IPCC (2013)

In unit terms to reach the 1.5 – 2 degrees target, the CO_2 emissions under a business as usual scenario should be reduced from 20 – 25gram of CO_2 per ton-nautical mile in 2007 to 4gram or less of CO_2 per ton-nautical mile in 2050 (Lindstad 2013), i.e. an 80 – 85% reduction.

2. MODEL DESCRIPTION

The model enables a full evaluation of fuel consumption, costs and emissions as functions of vessel operation, abatement options and fuel prices; see Lindstad et al. (2011, 2014, 2015a, 2015b, 2017).

A vessel's fuel consumption is given by Equation (1).

$$F = \sum_{i=1}^{n} \left(\frac{D_i}{v_i} \cdot P_i^{dmvs} \cdot K_{fp} + T_{lwd} \cdot P_{lwd} \cdot K_{fp} \right) (1)$$

During a voyage, the sea conditions will vary and we divide each voyage into sailing sections, with a distance D_i, speed v_i and power P_i^{dmvs} as a function of vessel design d, speed v , total weight carried m and sea conditions s. K_{fp} is fuel per produced kWh as a function of engine load, T_{lwd} is time spent in port loading, discharging, and waiting and P_{lwd} is average power used in port.

The cost per freight unit transported, i.e. per ton-mile is given by Equation (2):

$$C = \frac{1}{D \cdot M} \cdot \left(\left(\sum_{i=1}^{n} \frac{D_i}{v_i} + T_{lwd} \right) \cdot (TC + C_{abatement}) + F \cdot C_{Fuel} \right) (2)$$

The first factor transforms cost to cost per ton-mile: M is the weight of the cargo and D is distance sailed with cargo. Large bulkers and tankers typically sail one way fully loaded and return empty in ballast, while liner vessels usually tend to be neither empty nor completely full. Total days per voyage is given by sailing days $\sum_{i=1}^{n} \frac{D_i}{v_i}$ and days in port T_{lwd}. The vessel's daily cost is given by its operational and financial costs plus the cost for the abatement option. Fuel cost is a function of consumed fuel F and the fuel price C_{Fuel}.

Emissions, ε per pollutant, comprises fuel and freight work as expressed by Equation (3):

$$\varepsilon = \left(\frac{F}{D_c \cdot M \cdot N_c}\right) \cdot K_{ep}(3) \ ,$$

K_{ep} is the emission factor for each exhaust gas as a function of power and fuel type. D_c is the distance of the cargo voyage, M is the weight of the cargo and N_c is the annual number of cargo voyages. SOx and CO_2 are always strictly proportional to fuel consumption by fuel type, while the other pollutants increase relative to fuel consumption when engine operates at high or low power.

Metrics that weight emitted greenhouse gases according to their global warming potential (GWP), and report them in terms of "*CO_2 equivalents* have become a standard (Shine, 2009). Equation (4) gives total GWP impact per energy unit produced and ton transported.

$$GWP_t = \sum_{i=1}^{n} \varepsilon_e \cdot GWP_{et} \ (Eq. 4)$$

were, $\varepsilon_e$represents emissions per exhaust gas i and GWP_{et} is the GWP factor for each pollutant within the given time frame, i.e. usually, 20 or 100 years consistent with Houghton et al. (1990).

3. MITIGATION MEASURES IN THE LITERATURE

Maritime emission and reduction measures are commonly divided into two main categories: technical and operational (Psaraftis, 2016). Technical measures focus for example on energy savings through more energy efficient designs, improved propulsion and power system, and alternative or cleaner fuels. Some technical measures can be applied as retrofit measures, while others will practically and economically be considered only when building new vessels. Operational measures aim at reducing emissions during operations both for existing and newbuilt vessels.

Bouman et al 2017 identified twenty-two (22) types of measures for which sufficient, reliable and comparable data are available in the peer-reviewed literature. Figure 3 shows the CO_2 reduction potential for each of the 22 measures. For each, a solid bar indicates the typical reduction potential area, i.e. from 1st to 3rd quartile of the dataset, and a thin line indicates the whole spread. In addition, the data points are shown by a small circle. Moreover, the study grouped the measures in five main categories: *hull design*, *power and propulsion*, *alternative fuels*, *alternative energy sources*, and *operations*.

From Figure 3 we observe a large range in emission reduction potential per measure reported by the individual studies. Some of the variability can be explained by differences in assumptions and benchmarks across the selected studies, but it also indicates large uncertainty as to the reported reduction potentials.

If all options depicted in Figure 3 could be combined, which is a highly hypothetical exercise, the emission reductions would be over 99% based on 3rd quartile values, 96% based on the median, and 82% based on 1st quartile values. A more likely feasible combination would be: Vessel size; Hull shape; Ballast water reduction; Hull coating; Hybrid power/propulsion; Propulsion efficiency devices; Speed optimization; Weather routing and Trim/Draft optimization. Assuming relatively large independence between the individual measures, combining these options can lead to emission reductions of 80% based on 3rd quartile values, 59% based on the median, and 34% based on 1st quartile values.

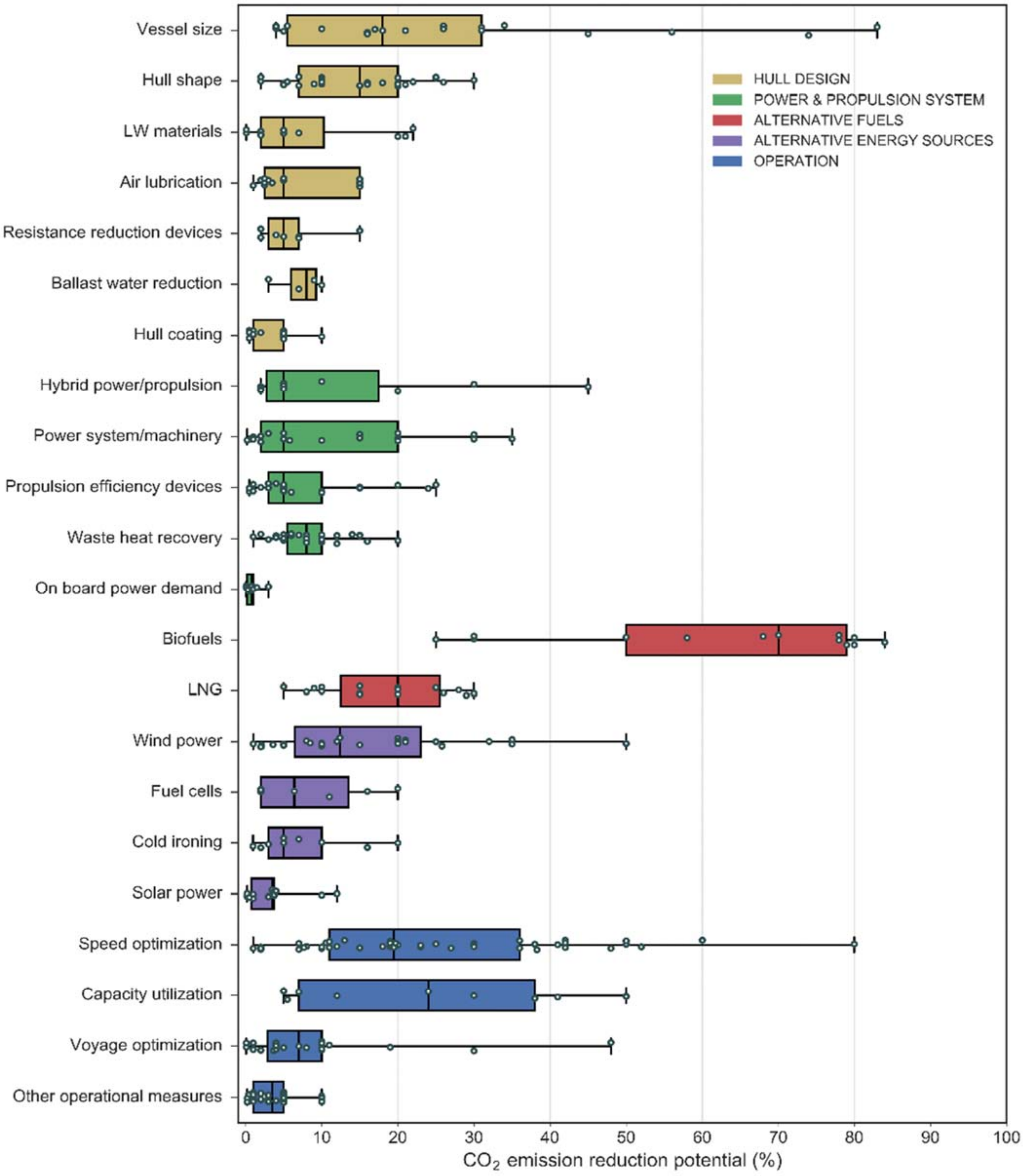

Figure 3: CO_2 emission reduction potential from individual measures. Source: Bouman et al 2017.

4. MITIGATION MEASURES IN THE SHIPPING INDUSTRY

Here we discuss to what extent the reduction measures from the literature are used by the industry. The first observation is that each of the 22 measures are used on at least one vessel. Second, the operational measures, represented by the four blue bars at the bottom of figure 3, are relevant both for existing and new vessels. These are really the core of running a shipping business to make a profit, and are thus partly or fully employed across the industry. Third, economies of scale through larger vessels and operational speed reductions are the only ones for which we have seen large scale utilization, even though these simple measures also have potential to deliver a lot more.

First larger vessels. The key observation is that when the ship's cargo-carrying capacity is doubled, the required power and fuel use typically increases by about two thirds, so fuel consumption per freight unit is reduced. The vessel's building cost increases with about half of the increase in cargo capacity, and also costs of crew, maintenance and management rise less than proportionally with cargo capacity. Table 1 (Lindstad et al 2015c) shows how average vessel size has increased from 2007 to 2015 based on IHS Markit data (www.ihs.com) and ISL data (ISL 2014). From 2007 to 2015, the average cargo vessel size has increased from 22 500 to 31 500 ton. Moreover, it can be observed that the its's the average size which has increased most. The explanation is the large increase in number of dry bulkers, which has an average size more than twice the average for the fleet.

Second, reducing operational speeds, The explanation is that the power output required for propulsion is a function of the speed to the power of three and beyond (Silverleaf and Dawson, 1966). This implies that when a ship reduces its speed, the power required and therefore the fuel consumed per transported unit is considerably reduced (Corbett et al., 2009; Psaraftis and Kontovas, 2010; Lindstad et al, 2011, Psaraftis and Kontovas, 2013). Table 2 show the development of average vessel size, design and operational speeds per vessel type from 2007 to 2012 (Smith et al. 2014; Lindstad et al. 2015c).

Table 1: Average vessel increase 2007 - 2015

Vessel type	Average vessel size (dwt) 2007	2012	2015	Change
Dry Bulk	52 500	68 600	69 300	32%
General Cargo	4 600	5 300	6 200	35%
Container	34 200	41 600	44 300	30%
Reefer	5 400	5 700	6 000	11%
RoRo&Vehicle	7 200	7 600	8 900	24%
Crude oil tank	178 700	183 500	185 800	4%
Product tank	9 800	10 700	10 700	9%
Chemical tank	15 800	18 000	19 000	20%
LNG&LPG	22 800	27 600	29 000	27%
RoPax	1 400	1 600	1 800	29%
Average	22 500	30 800	31 500	40%

Table 2: Design and operational speeds 2007 – 2012

Vessel type	Average vessel size (dwt) 2007	2012	Design speed 2007	2012	Operational speed 2007	2012
Dry Bulk	52 500	68 600	14.1	14.8	12.2	11.5
General Cargo	4 600	5 300	12.1	12.5	10.0	9.3
Container	34 200	41 600	20.3	21.3	16.3	14.6
Reefer	5 400	5 700	16.2	16.2	16.2	13.4
RoRo&Vehicle	7 200	7 600	16.3	16.3	15.0	15.0
Crude oil tank	178 700	183 500	15.5	15.7	13.8	11.9
Product tank	9 800	10 700	12.3	12.4	10.6	9.4
Chemical tank	15 800	18 000	13.4	13.6	12.1	11.1
LNG&LPG	22 800	27 600	14.9	15.6	13.1	12.9
RoPax	1 400	1 600	17.9	16.6	13.8	10.7
Average	22 500	30 800	14.1	14.6	12.0	11.1

5. HOW LEGISLATION ENCOURAGE OR DIS-ENCOURAGE GHG REDUCTION

Presently, the policy objectives behind regulations for NO_X and SO_X relate to human health and ecosystems. CO_2 regulation, in contrast such as the Energy Efficiency Design Index (EEDI), is motivated by the need to reduce global warming. Other exhaust gases in shipping internationally are unregulated. Separate regulations for each exhaust gas exists, despite the fact that the emissions are interlinked both through the reductions measures and through their environmental impacts. One example is that the present approach to NO_X reductions through technical standards neglects that the reductions tends to come at the cost of higher fuel consumption (Lindstad et al., 2015b), and thus CO_2 emissions. Similarly, stricter SO_X rules tend to raise fuel consumption on a well to propeller basis, i.e. either when refineries remove sulphur from heavy fuel oils (HFO), or in scrubber operation and increased speeds at sea due to the higher capex with onboard abatement options (Lindstad et al., 2017).

As CO_2 is regulated through the energy efficiency design index (EEDI), the policy aims to address directly the ratio between the CO_2 emitted and the freight work. The EEDI verification – as a new vessel is built - takes place under assumptions of i) design speed; ii) design loads, and iii) still water conditions. This are important abstractions from real-life conditions; calm sea is the exception in shipping and - even at calm water – vessels generally operate at speeds different from design speed, depending inter alia on fuel prices and market conditions.

A major challenge if the emission reductions envisaged for CO_2 shall be achieved through EEDI will be to identify EEDI compliant solutions which are energy- and emission-efficient for power outtake under realistic operational conditions, from lying idle at berth in port to realistic combinations of sea states, including ensuring that the vessels have the required power in critical situations in high sea states.

In Lindstad and Bø (2018) the effect of different abatement measures are investigated as EEDI compliance methods. An Aframax tanker (110 000dwt) is used as the case study vessel, and the measures evaluated are slender hull design, LNG, and hybrid propulsion. Tankers typically sail one way fully loaded and return empty in ballast, which gives an average capacity utilization of 50% for a roundtrip voyage. The vessels spend around 200 days at sea, 100 days loading, discharging, leaving or entering ports or in speed-restricted zones such as estuaries and canals, and the remaining 65 days idle in port or waiting at anchor.

One of the results from this study is shown in Figure 4. Here the first column shows the increase in newbuilding cost for the alternative abatement measures compared with the baseline vessel. The second column shows increased yearly cost, combining amortized CAPEX from column 1 with operational costs such as fuel expenditures. The third column shows the reduction in Greenhouse gas (GHG) emissions expressed as CO_2-equivalent on an annual basis. The fourth column shows GHG abatement cost per ton of GHG reduced (CO_2eq.).

The red colour is used for today's standard design which has a main engine of 13 000 kW. This vessel fulfils the EEDI requirements for 2015, i.e. 10% reduction compared to 2013. From 2020, 20% reduction is required and from 2025, 30 % reduction is required compared to 2013.

Main observations from Figure 4 are the large spread in cost and GHG emissions. For the cost the annual cost increases ranging from less than zero with the 11 000kW slender design in 2020 up to 0.8 MUSD per year for the most expensive options in 2025. For the GHG emission the reductions range from 5 %, i.e. when applying only the standard LNG technology to 25 – 27 % when combining a slender hull form with best LNG technology and a hybrid power setup.

However, shipping lines are in business to make a profit, which suggests that their ranking will be based on cost minimizing, i.e. the slender vessel with a 11 000kW engine to meet the 2020 EEDI standard, and the slender vessel with the 9 800KW engine and a hybrid power plant to meet the 2025 EEDI standard. Consequently, the real reductions of GHG emissions through the EEDI scheme might be less than half of what is indicated by the test.

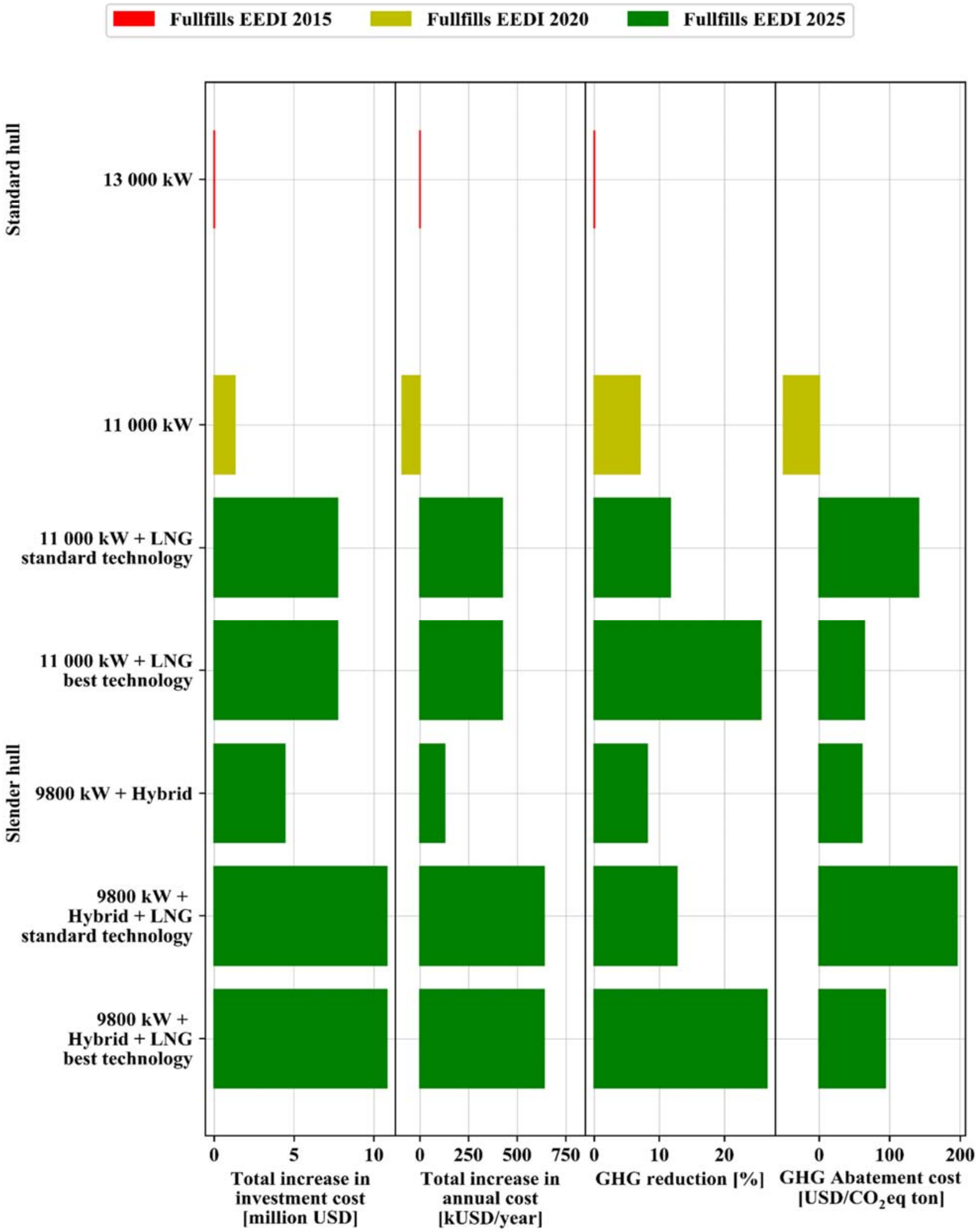

Figure 4: Investment cost, yearly cost, CO_2-eq emission and abatement cost per ton of CO2 for an Aframax crude oil tanker. Based on Lindstad and Bø (2018).

6. CONCLUSIONS

It is an important intervention point when a vessel is being commissioned, to influence its emissions through its lifetime in a cost-effective fashion. These interventions will then be based on assumptions about how the vessel is used.

For international shipping, apart from technologies (drivetrain, fuel, hybrid, hull), very important factors in future emissions will be the vessel size and speed, and it is thus problematic that policies such as EEDI will embody: i) unrealistic operative assumptions (like still water, and speed); ii) more generous EEDI limits for smaller vessels, thus to some extent failing to incentivize sufficiently a further move towards larger vessels; iii) speed limitations through power limitations, thus rendering vessels poorly equipped for power in situations of need and/or resulting in vessels operating at full power in normal conditions; iv) a slowdown in new-buildings resulting in a slowdown in modernization of the fleet, to some extent resulting in existing vessels being active longer and used more intensively.

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