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The importance of economies of scale for reductions in greenhouse gas emissions from shipping

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ABSTRACT

CO_2 emissions from maritime transport represent 3.3% of the world's total CO_2 emissions and are forecast to increase by 150%–250% by 2050, due to increased freight volumes (Second IMO GHG study, 2009). Fulfilling anticipated climate requirements (IPCC, 2007) could require the sector to reduce emissions per freight unit by a factor of five or six. The International Maritime Organization (IMO) is currently debating technical, operational and market-based measures for reducing greenhouse gas emissions from shipping. This paper also investigates the effects of economies of scale on the direct emissions and costs of maritime transport. We compared emissions from the current fleet (2007), with what can be achieved by increasing average vessel size. The comparison is based on the 2007 levels of trade and predictions for 2050. The results show that emissions can be reduced by up to 30% at a negative abatement cost per ton of CO_2 by replacing the existing fleet with larger vessels. Replacing the whole fleet might take as long as 25 years, so the reduction in emissions will be achieved gradually as the current fleet is renewed.

1. Introduction

The environmental consequences of increasing international trade and transport have become important as a result of the current climate challenge. Products are increasingly being manufactured in one part of the world, transported to another country and then redistributed to their final country of consumption. Since 1990, growth in world trade, of which more than 80% is carried by seagoing vessels (measured by weight), has been higher than ever before and transport volumes have nearly doubled. CO_2 emissions from maritime transport rose from 562 million tons (all tons are metric) in 1990 to 1046 million tons in 2007 (Second IMO GHG study, 2009), which is an 86% increase. This is a high rate of growth, compared to the total global growth in CO_2 emissions from 20,941 million tons in 1990 to 28,846 million tons in 2007 (IEA 2009), which is a 38% increase. Maritime transport emissions are anticipated to increase further by 150%–250% until 2050 on the basis of "business as usual" scenarios with a tripling of world trade (Second IMO GHG study, 2009). Similar growth prospects have also been reported by OECD (2010) and Eyring et al. (2009). These greenhouse gas (GHG) emission growth figures are in sharp contrast to the total reduction of 50%–85% by 2050 that will be necessary to keep the global temperature rise below 2 °C (IPCC, 2007). Just how the annual greenhouse gas reductions should be shared among sectors is a controversial issue, but given a scenario where all sectors accept the same percentage reductions, and that the demand for sea transport follows the predicted tripling of world trade, it can easily be deduced that the amount of CO_2 emitted per ton nautical mile will have to be reduced by at least 85%. This is a reduction by a factor of 5 to 6, which represents a substantial challenge. The question is thus how to make it come about.

Previous studies have documented that it is possible to reduce GHG emissions in a cost-effective manner, i.e. emissions can be cut with net cost savings (DNV, 2010; Longva et al., 2010). These studies can be grouped into two categories; those that investigated the total improvement potential (Second IMO GHG study, 2009; DNV, 2010) and those that looked at what can be achieved by focusing on one or more measures, such as the relationship between speed reduction and emissions (Corbet et al., 2009; Sea at Risk and CE Delft, 2010; Lindstad et al., 2011). The background for the focus on speed reductions is that ships have typically been built to operate at a specific design speed. For large bulk vessels this design speed is around 14 knots (25 km/h), while large container vessels have design speeds of up to 27 knots (50 km/h). The key insight is that the power output required for propulsion is a function of speed to the power of three. This simply

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means that when a ship reduces its speed, its fuel consumption is reduced. The studies that focus on the relationship between speed reductions and emissions have indicated potential reductions of as much as 28% at zero abatement cost and 33% at a cost of 20 USD per ton CO_2 (Lindstad et al., 2011), while the studies of the total improvement potential (Second IMO GHG study, 2009; DNV, 2010) suggest a total reduction potential in the range of 50%–75% without taking gains through economies of scale into consideration.

This contrasts with the fact that historically, emission and cost reductions have been achieved through building larger vessels, commonly termed "economies of scale", and to a lesser degree through the adoption of new technology. In shipping, economies of scale (EOS) usually refer to benefits obtained when smaller vessels are replaced by larger ones. To make qualified suggestions about the effect of increasing average vessel size, knowledge of the current situation is a prerequisite. While rail and road are fairly standardized, with more or less given figures for capacity and speed per unit, the existing maritime fleet consists of vessels of many types and sizes ranging from a few hundred tons to up to hundreds of thousands of tons, while their maximum speed ranges from less than 10 knots (18 km/h) to more than 30 knots (55 km/h), and distances ranges from a few nautical miles (nm) to more than 10,000 nm (18,000 km). Some vessels can only transport one specific product, such as crude oil or LNG. Others, such as product tankers and chemical tankers can transport a wide range of liquid products. The most flexible vessels today are container vessels, which were initially used for transport of finished goods packed in containers, but now also transport raw materials and semi-finished goods. And while container vessels operate as common carriers in liner services calling at a regularly published schedule of ports (like a bus service), most seagoing cargo is still transported by vessels in tramp operation (like a taxi service), where their schedule is a function of cargo availability and customer requests. While a common carrier refers to a regulated service where any company may book transport according to general published rules of the operator, a tramp service in general is a private business arranged between the cargo owner and the operator of the vessel according to a specific contract called a charter party.

Previous studies of economies of scale have tended to focus on the financial benefits of building larger vessels within one particular shipping segment, such as container vessels (Cullinane and Khanna, 2000; Notteboom and Vernimmen, 2009) or LNG Transport (Oil and Gas Journal (2008)).

The International Maritime Organization (IMO) is currently debating technical, operational and market-based measures for reducing greenhouse gas emissions from shipping. In July 2009 the principles for a mandatory Energy Efficiency Design Index (EEDI) and a Ship Energy Efficiency Management Plan (SEEMP) were agreed, and two years later in July 2011 (Resolution MEPC.203 (62)), the EEDI and SEEMP were adopted as parts of the MARPOL Convention (the International Convention for the Prevention of Pollution from Ships). The EEDI uses a formula to evaluate the CO_2 emitted by a vessel per unit of transport as a function of vessel type and size. The formula has been established by grouping vessels built during the past 10 years into vessel types such as container and dry bulk, and then generating the average values and baselines as a function of size and type by a standard excel regression model. Common to all vessel types is that as vessel sizes increase, their emissions decrease. However, the EEDI gives baseline requirements, in which the required emissions reduction when vessel size is doubled is only 14% for a container vessel, 20% for a general cargo vessel, 30% for a dry bulker, 31% for a tanker such as a crude oil carrier and 33% for RoRo car carriers (Roll-on Roll-off vessel). In-depth discussions have challenged a number of aspects of these curves, and it is a fact that while the existing fleet of large container vessels achieve EEDI values well below their current EEDI requirements, large tankers and RoRo vessels lie well above them. The consequence of this is that when the EEDI requirements in the coming 20 years become as much as 30%–35% stricter than they are today, large container vessels can quite easily satisfy them, while it may become much more difficult for large dry bulk, tank and RoRo vessels to satisfy the requirements through technical improvents. It is not within the scope of this paper to offer a detailed technical discussion of the EEDI. However, these examples demonstrate that EEDI can be further developed, and that it is worth investigating how to utilize and encourage economies of scale as an integrated part of EEDI and mitigation policies in general.

While economies of scale are a well-established concept in shipping, this study is the first to investigate the potential reductions in costs and emissions that can be achieved for the whole fleet. The results of the investigation are utilized to suggest how future EEDI and other IMO emission reduction requirements should be set in order to achieve maximum emission reductions through economies of scale. We first establish the employment and performance of the existing fleet (2007), and then compare it with what can be achieved by increasing average vessel size. The comparison is based on the 2007 levels of trade and predictions for 2050.

The model is described in Section 1, its application and the data are presented in Section 2, and the results obtained are discussed in the final section with respect to their implications for policy development.

2. Description of model

The main objective of our model is to calculate emissions and costs for the global fleet as a function of vessel size and fleet mix, with a specific focus on the effect on economies of scale. The system boundaries are set on the vessels themselves and how they are used, for which reason the landside of the terminal and port is excluded. The model is based on a combination of empirical and estimated data. The empirical data are taken from the world fleet as listed in December 2007 in the Lloyds Fairplay database (now the IHS Fairplay database), divided into vessel type and size groups. For each vessel type and size group the operational profile was established on the basis of studies of how vessels in each group are used and the cargoes they carry.

The model consists of four main equations. The first establishes the annual operational profile and freight work of each vessel type and size group. The second calculates annual fuel consumption based on the operational profile and freight work done. The third calculates the amount of CO_2 emitted per nautical mile (nm) sailed, based on the annual fuel consumption and the annual freight work. The fourth equation calculates cost per ton nm.

The annual operational profile in days, T, of a vessel consists of days per cargo voyage multiplied by number of cargo voyages plus days per voyage in ballast multiplied by number of voyages in ballast as expressed by Eq. (1):

$$T = \left[\left(\frac{D_c}{v_c} + T_{l\&d} + T_{s\&w} \right) \Big| N_c + \left(\frac{D_b}{v_b} + T_{s\&w} \right) \Big| N_b \right] \quad (1)$$

where the first term gives the annual number of days used on cargo voyages, where D_c is the distance, v_c is the speed on the cargo voyages, $T_{l\&d}$ is time taken to load and discharge cargo, $T_{s\&w}$ is the time used in slow zones and waiting, N_c is annual number of cargo voyages. The second term gives the annual number of days used on voyages in ballast, which means repositioning the vessel by sailing without any cargo to the next loading port. The annual number of cargo and ballast voyages per vessel type and size used in this study are based on Lindstad et al. (2012). The ratio between cargo voyages and ballast voyages ranges from 1:1 for crude oil transport which is a typical tramp trade to 1:0 in liner trades performed by container vessels or RoRo vessels Christiansen et al. (2007). The explanation is that crude oil carriers transport crude only and hence have to return empty to the oil source after delivery at the refinery, while container vessels and RoRo vessels can transport almost any cargo as long as it can be packed in containers or lifted or rolled on board the vessels. In the formula, D_b is the distance, v_b is the speed on the ballast voyages, $T_{s\&w}$ is the time in slow zones and waiting, N_b is annual number of voyages in ballast.

The annual fuel consumption F of a vessel is the total fuel used on cargo voyages and on ballast voyages, as expressed by Eq. (2):

$$F = K_f \left| \left[\left[\left(\left(\frac{P_c | D_c}{v_c} \right) + P_{l\&d} | T_{l\&d} + P_{s\&w} | T_{s\&w} \right) \middle| N_c \right] + \left[\left(\left(\frac{P_b | D_b}{v_b} \right) + P_{s\&w} | T_{s\&w} \right) N_b \right] \right] \right. \quad (2)$$

where the first term gives the fuel used on cargo voyages, the second term gives the fuel used on ballast voyages and K_f is the amount of fuel (in grams) per produced kWh. In the first term, P_c represents the power used to achieve the speed on cargo voyages, where the power output required for propulsion (when sailing) is a function of the speed to the power of three, which implies that when a ship reduces its speed below its design speed its fuel consumption per nm is reduced. When speed is further reduced the propulsion efficiency drops, the relative impact of wind and waves increases and the net effect is that when the speed drops below 6–9 knots the emissions per nm increase (Lindstad et al., 2011). Then D_c is the distance of the cargo voyages and v_c is the speed on cargo voyages. $P_{l\&d}$ Is the power requirement when loading and discharging and $T_{l\&d}$ is the time used, $P_{s\&w}$ is the power requirement in slow zones and waiting and $T_{s\&w}$ is the time used. In the second term, P_b represents the power used to achieve the speed on ballast voyages, D_b is the distance of the ballast voyages and v_b is the speed on the ballast voyages. $P_{s\&w}$ is the power requirement in slow zones and waiting and $T_{s\&w}$ is the time used. The vessel speeds are based on the speed data per vessel as given by the IHS-Fairplay database, where the speed in general is based on the speed of the vessel when fully loaded, using 75% of its maximum continuous power rating (MCR) under still-water conditions. When sailing in ballast or partly loaded, less than 75% of MCR is needed to achieve the design speed. However, since calm water is the exception in shipping rather than the rule, additional power is required to maintain the design speed when the resistance increases due to wind and waves. Based on these considerations and on a dialog with ship owners, we have used the following values to achieve the design speed; 95% MCR on cargo voyages for bulk, tank and all other vessels modeled with ballast voyages, 80% MCR on their ballast voyages and 90% MCR for container and RoRo vessels. When ship owners slow steam (i.e. reduce speeds below the design speed) to reduce overcapacity in one or more shipping segment these MCR percentages will be lower. Since these speed reductions are usually of the same magnitude for all vessels of similar types, they do not influence the relative difference between small and large vessels within a shipping segment.

The annual amount of CO_2 emitted per ton nautical mile ε is calculated as follows

(Second IMO GHG study, 2009):

$$\varepsilon = \left(\frac{F}{D_c | M | N_c} \right) \middle| K_e \quad (3)$$

where F is annual fuel consumption per vessel as described in Eq. (2), K_e is the CO_2 emitted per unit of fuel burnt and $D_c|M|N_c$ is the annual freight work measured in tons per nautical mile, for which D_c is the distance of the cargo voyage, M is the weight of the cargo and N_c is annual number of cargo voyages.

The cost per ton nautical mile C comprises the annual freight work, the cost of fuel and the annual time charter cost of the vessel as expressed by

$$C = \frac{1}{D_c | M | N_c} \left[(F | C_{Fuel}) + (Capex_v | (k_1 + k_2) + k_3) \right] \quad (4)$$

The first factor, i.e.: $D_c|M|N_c$, transforms the cost from an annual cost per vessel in order to enable comparisons of freight cost per unit for vessels of different sizes and types employed in various trades to be drawn. The cost of fuel is then calculated by multiplying the annual amount of fuel F from Eq. (2) by the average cost of fuel C_{Fuel}, which is calculated based on an average consumption pattern of 90% heavy fuel oil (HFO) and 10% marine diesel oil (MDO). Using one fuel price is a simplification. However, since this mix is given by different geographical environmental requirements and not vessel types it is a proxy which does not really influence the conclusions. Examples of such geographical requirements are the requirement to use low sulphur oil as MDO, or expensive cleaning of the exhaust gas if HFO is used, in the Baltic and North Seas. The annual cost of operating a vessel is based on current new-building prices and where the cost consists of financial items, depreciation and operating costs, expressed as: $(Capex_v|(k_1+k_3)+k_3)$. Where $Capex_v$ is the new-building price of the vessel, k_1% of $Capex_v$ are fixed costs, which consist of financial cost including depreciation and return on own capital, k_2% of $Capex_v$ plus a basic amount k_3 is the variable cost. To summarize, combining Eqs. (1)–(3) enables us to estimate greenhouse gas emissions due to economies of scale as a function of vessel type and size, while Eq. (4) estimates the costs involved.

3. Application and analysis

The aims of the analysis were first, to identify the emissions and costs for individual ship classes for the existing fleet, and then, to investigate the effects of economies of scale on the direct emissions and costs of maritime transport as a function of vessel size and fleet mix for the entire global fleet.

3.1. Selection of types of vessel and size groups

This study includes all cargo vessels as listed in the IHS-Fairplay database (www.ihs.com) in December 2007, but excludes vessels which are built for a combination of passenger and cargo, such as Ro-Pax vessels which transports passengers, cars and cargo on board trailer units. In terms of emissions, the vessels that are excluded emit 20% of the total CO_2 emitted by maritime transport. This means that the vessels included according to our calculations emitted 820 million tons of CO_2 in 2007. This is within the same range as the total emissions calculated for these vessels by the IMO 2009 GHG study. The cargo vessels can be grouped into the three subgroups of dry bulk, general cargo and tank, based on cargo type and on how the cargo is handled and transported, although there is some overlap (competition for cargoes) between dry bulk and general cargo and between general cargo and tankers. The following section offers a brief introduction to the different vessel types and the cargoes that they carry.

Dry bulk commodities are in solid form and can be handled mechanically by grabs, conveyor belts, bucket units or pneumatic systems. Typical dry bulk commodities are iron ore, coal, grain, cement, fertilizers and aggregates. General cargo is all cargo types which cannot be handled by grabs, conveyor belts, pumps or pipeline systems. General cargo is transported by general cargo vessels, container vessels, reefer vessels and Ro-Ro vessels. Container vessels are purpose-built for transport of standardized containers. However, since containers are of different types, e.g. reefer, tank, bulk and standard, container vessels can carry not only general cargo, but also dry bulk commodities and petroleum products and chemicals. General cargo vessels are typically used for transport of pallets, bulk products in Big Bags, forest products, steel and aluminum, but also containers. Reefer vessels carry perishables such as fruit and fresh food and frozen products, while Ro–Ro vessels are used for new and used cars, heavy vehicles and project cargo, but also trailer units with cargo and goods. Wet bulk cargoes typically consist of liquefied products and gas that are mainly transported in wet bulk tankers, such as crude oil, liquefied petroleum gas (LPG) and liquefied natural gas (LNG), or a family of similar products such as refined oil products by product tankers and chemical products by chemical tankers.

Each of these types of vessel includes vessels of various sizes; however, while the largest reefers are around 20,000 dead weight tons (dwt), the largest crude oil tankers are more than 300,000 dwt. The dead weight is the measure in metric tons of how much weight a ship can carry. To model the existing operational patterns, all vessel types were divided into two to six size groups where the small vessels for all vessel types are those between 0 and 15,000 dwt. The smallest vessel typically operates in short sea trades or coastal shipping trades (Second IMO GHG study, 2009). For all vessel types, the largest vessels are grouped together. For reefers, where the largest vessels are only 20,000 dwt this gives only two size groups, while six size groups are needed to describe the operational trade pattern of dry bulkers, whose largest vessels have an average size of 172,000 dwt. This process enabled us to calculate values for the smallest vessel, the largest and the average within each group. Table 1 summarizes the main characteristics of the operational patterns of both dry bulk vessels and all other types of cargo vessels. The table shows vessel type and size in the first column, number of vessels in the second column, average dead weight per vessel in the third column, net payload per vessel in the fourth where the weight of the bunkers and the tare weight of the cargo containment units has been subtracted from the dead weight (Container and Ro–Ro). These are followed by average utilization, average design speed, duration of cargo voyages, annual number of cargo voyages, annual number of ballast voyages, average engine size, annual freight work done, which is the sum of all quantities carried measured in weight over all the distances, annual CO_2 emitted and grams CO_2 per ton nm. To familiarize the reader with the table we take dry-bulk Capesize vessels as an example (first line in Table 1). The average size of a Capesize vessel is 172,000 dwt and when bunker oil, water and supplies have been loaded they can load 169,000 t, a capacity that is utilized 97% on average. The main Capesize trades are from Australia to Japan/Korea/China in Asia or to Western Europe, and from Brazil to Asia and Western Europe. The average sailing distance is 7500 nm one way, the design speed is 14 knots and the time used from start of loading until end of discharge is 33 day, including average waiting times. Capesize vessels sail an average of six voyages with cargo and five in ballast a year, due to imbalance of trades. A combination of cargo and ballast voyages is usual in all tramp trades. While in liner trades, represented by container and Ro–Ro vessels, there are no ballast voyages, but also lower utilization, since very few of these vessels are fully loaded on a roundtrip basis.

The main observations from Table 1 are that the largest vessels are mainly used on the longest voyages while the smallest are mainly used on the shortest voyages. Most freight work is performed by the largest vessels, including Panamax size groups, while the ‘coastal vessels’ below 15,000 dwt perform some 5% of all sea transport work. The largest vessels of all types emit less CO_2 per ton nm, where the ratio of largest to smallest is 1:13 in dry bulk (7–91 g of CO_2 per ton nm) and 1:3 in the container segment (28–80 g of CO_2 per ton nm). This implies that increasing average vessel sizes will help to lower emissions. However, we would point out that the relationships between ship size and emission is not linear, but rather reflects a power–law relationship with diminishing marginal emission reductions as vessel size increases. To illustrate this, as the dry bulk vessel size increases from 26,000 to 46,000 dwt, the emissions per ton nm are reduced by 33%, while an increase from 46,000 to 72,000 dwt offers only a further 17% reduction.

3.2. *Reduction in greenhouse gas emissions through economies of scale*

As we pointed out in the Introduction, economies of scale in shipping is the term usually used to refer to the benefits obtained by replacing smaller vessels by larger vessels. The potential of economies of scale to reduce greenhouse gases and costs can be evaluated by calculating the average for existing vessels and comparing it with what can be achieved by replacing the existing fleet with larger vessels. We point out that the rise in vessel size is an ongoing process, which gradually increases the average vessel size by introduction of new vessels which are larger than the existing ones and by replacing old vessels which are being scrapped with similar or a larger size one. Examples of such increases are the new Chinamax dry bulkers (400,000 dwt) which will be more than twice the average size of today’s largest bulkers; the Capesize vessels (172,000 dwt). Similarly, the new Maersk’s triple-E class container vessels (216,000 dwt) will be twice the average size of today’s largest container vessels. When these larger vessels are introduced, more ports will be served by feeder vessels. However, since the feeder distances are much shorter than the deep-sea distances, the increase in emissions due to this change will still be much smaller than the savings on the deep-sea legs. Feeder vessels and their operations are perhaps best known as an integrated part of the ocean services provided by the big container lines. However, feeder vessels and operations are already used in a number of different trades, where cargoes are collected and/or delivered at a number of ports by smaller vessels and brought to larger ports served by ocean-going vessels. Although in theory new vessels can be much bigger than existing vessels, there will be limitations, due to draft and port restrictions both for ocean going vessels and for feeder and coastal vessels in smaller ports. And when physical constraints themselves do not set the limits, national rules for pilotage and port fees will in some cases result in significant cost increases and operational disadvantages when a ship exceeds a certain size. Examples are ships exceeding a length of 200 m in Japanese ports or a given dead weight size in Norwegian ports. A general consequence of such rules is that vessels are either kept below the limits or built significantly larger. Moreover, logistics requirements and the size and cost of carrying stocks will tend to work against using vessels that are too large. The explanation is that with constant freight volumes, the introduction of larger vessels will tend to reduce sailing frequencies, and when sailing frequencies are reduced the total lead time from factory gate to customer will be longer.

Given all these considerations and the predictions for trade growth until 2050, we use the average size of today’s largest vessels (2007) of each type as shown in Table 1 to calculate what can be achieved by economies of scale. For dry bulkers this means Capesize vessels with an average size of 172,000 dwt. For container vessels it means 8500 TEU vessels with an average size of 106,000 dwt. In comparison, the current average sizes are

Table 1
Operational patterns and quantity of CO_2 emitted per ton nm as a function of vessel size and type.

Vessel type	**Number of vessels**	**Average vessel size in dwt (ton)**	Net payload capacity (ton)	Utili-sation when loaded	Distance per voyage (nm)	Speed (knots)	Duration of cargo voyage (days)	Number of cargo voyages	Duration of balast voyage (days)	Number of balast voyages	Average engine size (kW)	Freight work (**billion ton miles**)	CO_2 emitted (**gram per ton nm**)
Dry bulk Capesize 120′+	**782**	**172,000**	169,000	97%	7500	14	33	6	30	5	15,430	**5770**	**7**
Dry Bulk 80–120’	**119**	**94,000**	92,000	97%	6500	14	29	7	26	5	1970	**480**	**10**
Dry Bulk Panamax 60–85’	**1447**	**72,000**	71,000	95%	5500	14	28	8	25	5	9800	**4290**	**10**
Dry Bulk Handymax 35–60’	**1937**	**46,000**	45,000	95%	5,000	14	25	9	22	5	8210	**3730**	**13**
Dry Bulk Handysize 15–35’	**1920**	**26,000**	25,000	90%	3000	14	16	15	14	7	6660	**1940**	**20**
Dry Bulk coastal 0–15’	**1318**	**4300**	4000	85%	787	12	6	36	5	20	1950	**130**	**91**
General Cargo 15′++	**1215**	**25,000**	24,000	90%	3000	15	16	15	13	8	8080	**1180**	**24**
General Cargo 0–15’	**16,065**	**3100**	2800	85%	500	12	5	46	4	24	1580	**1200**	**59**
Container 8500 TEU +	**206**	**106,000**	85,000	70%	11,000	25	31	11	27	0	67,370	**1480**	**28**
Container 5500–8500 TEU	**175**	**80,000**	64,000	70%	11,000	25	31	11	27	0	60,280	**950**	**33**
Container 3000–5500 TEU	**1068**	**55,000**	44,000	70%	7000	23	24	14	20	0	37,210	**3220**	**34**
Container 2000–3000 TEU	**789**	**33,000**	27,000	70%	2500	21	10	32	9	0	20,000	**1190**	**34**
Container 1000–2000 TEU	**832**	**21,000**	16,400	70%	1,000	19	8	45	6	0	12,660	**430**	**49**
Container 0–1000 TEU	**1328**	**9100**	7300	70%	650	17	6	49	5	0	6230	**220**	**80**
Reefer 15′++	**22**	**16,000**	14,500	90%	4000	21	14	16	12	10	14,970	**20**	**61**
Reefer 0–15’	**1204**	**5200**	4700	90%	1501	16	7	29	5	19	4830	**250**	**81**
RoRo 35′++	**20**	**45,000**	36,000	70%	8500	18	30	12	27	0	20,30	**50**	**27**
RoRo 15’–35’	**409**	**20,000**	15,800	70%	1800	19	11	33	9	0	14,170	**260**	**54**
RoRo 0–15’	**1981**	**4200**	3400	70%	437	14	4	80	4	0	4980	**160**	**227**
Crude oil 200′++	**506**	**295,000**	289,000	99%	9000	15	42	4.5	37	4.5	24,830	**5860**	**7**
Crude oil 120–200’	**356**	**152,000**	147,000	99%	6000	15	29	6	26	6	17,160	**1990**	**10**
Crude oil 75–120’	**660**	**103,000**	100,000	99%	2500	15	16	12	14	12	12,730	**1880**	**15**
Crude oil 15–75’	**410**	**52,000**	50,000	98%	897	15	11	18	9	18	9090	**350**	**27**
Crude oil 0–15’	**121**	**3600**	3500	98%	300	12	6	25	5	25	1930	**3**	**114**

Products 75'++	**47**	**112,000**	108,000	85%	5000	15	29	9	24	4	14,580	**180**	**13**
Products 15–75'	**737**	**46,000**	37,100	85%	3637	15	23	10	20	5	8960	**1030**	**24**
Products 0–15'	**4122**	**2500**	2100	85%	149	11	12	20	10	12	2930	**30**	**95**
Chemical 40'++	**533**	**48,000**	45,000	85%	5,000	15	25	11	21	3	9360	**1070**	**18**
Chemical 15–40'	**839**	**28,000**	22,200	85%	2897	15	21	12	18	4	7820	**710**	**33**
Chemical 0–15'	**2496**	**4900**	4000	85%	435	12	7	31	5	16	2270	**140**	**118**
LNG 60'++	**229**	**76,000**	75,000	99%	8000	20	31	6	27	6	27,090	**820**	**33**
LNG 15'–60'	**26**	**38,000**	30,700	99%	3923	18	21	10	18	10	14,910	**30**	**47**
LNG 0'–15'	**10**	**8600**	8200	99%	700	16	9	18	8	18	5800	**1**	**113**
LPG 45'++	**118**	**53,000**	51,000	99%	5000	17	21	9	18	9	13,400	**270**	**22**
LPG 15'–45'	**128**	**27,000**	21,500	99%	2031	16	13	15	11	15	10,060	**100**	**39**
LPG 0–15'	**857**	**3500**	2800	99%	320	13	5	34	4	34	2550	**40**	**172**
Total	**45,000**	**24,000**				14						**41,000**	**20**

52,000 dwt for dry bulkers and 34,000 dwt for container vessels. The assumed 2050 fleet of dry bulkers will then consist of Chinamax dry bulkers, dry bulkers with a size between Chinamax and Capesize, the current Capesize vessels, a new bulk size around 125,000 dwt utilizing the new Panama lock extension from 2014, and vessels from 50,000 dwt and downwards to serve smaller ports and trades. With an average lifetime of 25 years per vessel the benefits of building larger vessels will appear gradually, but the whole fleet could still be renewed before 2050.

The economies of scale calculations were performed in two steps, as shown in Table 2. First, for 2007 we compared the average performance of each vessel type based on the current pattern of operation, with what it would have been if the average vessel size had increased from the current average (2007 fleet) up to the average size of the largest vessels used today (2007). To exemplify for dry bulk, the current average size (2007 fleet) is 53,000 dwt while the average size of the largest type of dry bulkers, the Capesize vessels is 172,000 dwt. This based on the assumption that the mathematical average vessel within each group represents the average values for each vessel type. Secondly, we did the same for 2050, based on anticipated freight work and volumes per vessel type. Our 2050 projections for freight volumes and freight work are based on growth in GDP in line with the IPCC (2007) B1 scenario, growth in freight work, which is 80% of the growth in GDP and growth in container shipping, which will continue to be three times as high as in other shipping segments (Second IMO GHG study, 2009). Similar growth predictions for container ships trade and emissions have also been made by the Ocean Policy Research Foundation (2008). Compared with other IPCC (2007) scenarios, the B1 scenario, which has an annual growth of 3.1%, lies between high-growth scenarios such as A1T (4%) and low-growth scenarios like B2 (2.4%). With these assumptions, freight work will grow from 41,000 billion ton nm in 2007 to 109,000 billion ton nm in 2050.

Table 2 shows that the total freight work performed in 2007 was 41,000 billion ton miles, produced by 45,000 vessels with an average size of 24,000 dwt. If the 2007 fleet had been replaced by an economies of scale (EOS) fleet with an average size of 98,000 dwt, the number of vessels would have fallen to 11,000. This would reduce CO_2 emissions per ton nm from 20 to 14 g, and reduce annual emissions from 820 million tons to 570 million tons CO_2 which is a 31% reduction. By 2050, the freight work based on the IPCC (2007) B1 scenario will have grown to 109,000 million tons. If this work had been performed by the 2007 fleet mix, 12,300 vessels would have been required, while only 23,000 vessels would be needed with an EOS fleet whose average size has increased from 98,000 dwt to 106,000 dwt due to the greater share of freight work performed by container vessels. The negative effect of the greater share of total freight work done by container vessels is that the quantity of CO_2 per ton nm mile increases compared to 2007 figures from 20 to 24 for the 2007 fleet and from 14 to 18 for the EOS fleet. However, increased environmental concern might slow down the anticipated strong growth in container shipping and hence give a freight distribution among vessel types in 2050 more in line with 2007 figures. If the average vessel size increases significantly but fails to reach 106,000 dwt the savings will be reduced, although by less than might be expected, since 50% of the reduction in emissions comes from the first doubling of average vessel size from 24,000 to 48,000 dwt, and the remaining 50% comes from increasing average vessels size from 48,000 to 106,000 dwt.

3.3. Reduction in costs through economies of scale

The potential for reducing costs through economies of scale was estimated using the same vessel size assumptions as for emission reduction in the previous section. This means

Table 2
Quantity of CO_2 emitted per ton nm as a function of vessel size and type.

Vessel type	Freight work (billion ton miles)	No. of vessels 2007 fleet	Average vessel size 2007 fleet (ton (dwt))	Average vessel size EOS fleet (ton (dwt))	No. of vessel EOS fleet	CO_2 emitted per freight unit 2007 fleet (gram per ton nm)	CO_2 emitted per freight unit EOS fleet (gram per ton nm)	Annual CO_2 emitted 2007 fleet (million ton)	Annual CO_2 emitted EOS fleet (million ton)
Key figures 2007									
Dry bulk	16,137	7523	53,000	172,000	2295	11.4	7.0	184	113
General cargo	2382	17,280	4600	25,000	3165	42.2	24.4	100	58
Reefer	258	1226	5400	16,100	412	84.8	65.3	22	17
Container	7501	4398	34,000	106,000	1418	34.8	28.2	261	212
RoRo	485	2410	7200	45,000	388	75.8	25.7	37	12
Crude oil	10,061	2053	143,000	295,000	994	9.7	7.0	98	70
Oil products	1257	4906	10,200	112,000	445	25.0	13.3	31	17
Chemicals	1919	3868	15,800	48,000	1281	25.4	17.8	49	34
LNG	852	265	70,000	76,000	243	33.9	33.3	29	28
LPG	401	1103	11,600	53,000	239	34.8	22.5	14	9
Sea river	16	1169	1136	7,466	178	31.3	11.5	3	1
Total freight	41,000	45,000	24,000	98,000	11,000	20.0	13.8	820	570
Key figures 2050									
Dry bulk	29,853	16,250	53,000	172,000	4725	11.4	7.0	340	208
General cargo	4,407	37,325	4600	25,000	5293	42.2	24.4	186	108
Reefer	477	2,648	5400	16,100	706	84.8	65.3	40	31
Container	46,131	32,721	34,000	106,000	6270	34.8	28.2	1 604	1301
RoRo	897	5,206	7200	45,000	403	75.8	25.7	68	23
Crude oil	18,613	4,434	143,000	295,000	1875	9.7	7.0	181	130
Oil products	2325	10,597	10,200	112,000	696	25.0	13.3	58	31
Chemicals	3550	8355	15,800	48,000	2064	25.4	17.8	90	63
LNG	1576	572	70,000	76,000	516	33.9	33.3	53	52
LPG	742	2382	11,600	53,000	381	34.8	22.5	26	17
Sea river	30	2163	1136	7466	329	31.3	11.5	6	2
Total freight	109,000	120,000	24,000	106,000	23,000	24.4	18.1	2 650	1970

calculating the average costs of existing vessels and then comparing them with the costs which can be achieved by building bigger vessels. When comparing costs, different cost-accounting principles can be employed, but irrespective of principles, some cost items will be variable and others fixed. A variable cost is an expense that fluctuates based on activity level, while a fixed cost does not fluctuate with activity level. For a ship-owner, vessels that are owned or are leased on long-term contract represents the main fixed cost, while the cost of fuel is a variable cost. Between these two cost types, we have the cost of crew and the management cost of operating the vessel, which is not a fully variable cost, but is still usually treated as a variable cost. Regarding cost accounting principles used in comparing the existing fleet with an EOS fleet, we have at least three options. The first is to compare the fleets on the basis of total variable and fixed costs for the required transport capacity, based on the cost of new-building in 2011. The second is to use the average second-hand price of the existing fleet in combination with the 2011 variable cost to compare with new-building of the EOS fleet. The third option is to take a marginal approach for the existing fleet, comparing only its variable cost against total variable and fixed cost for the EOS fleet. The first cost option gives us the relative cost advantage with an EOS fleet compared to the existing fleet in a long-term view. The second enables us to compare the competitiveness of the existing fleet against an EOS fleet gradually entering the market. The third option tells us whether the existing fleet will at least be able to cover its variable costs when the EOS fleet enters the market. It should be noted that freight rates and hence the transport cost in shipping have historically been highly volatile, ranging from low levels that do not even cover all variable costs to high levels that are more than 5 to 10 times the total costs. However, in a 25-year perspective, which is the average lifetime of a vessel, the profitability of major shipping companies will be similar to that of other large companies. We have calculated costs per ton nm using Eq. (4) with costs and percentages as outlined below. The cost of fuel C_{Fuel} is based on an average consumption pattern of 90% HFO at a price of 600 USD/ton and 10% MDO at a price of 900 USD/ton, which gives a fuel price of 630 USD/ton based on average 2011 prices. The annual time-charter equivalent cost per vessel is calculated on the basis of the 2011 new-building price $Capex_v$ as provided by IHS Fairplay (Table 3), and where 8% of $Capex_v$ covers the fixed cost, and 3% of $Capex_v$ plus a basic amount of 2000 USD per day, covers the variable costs. The basic amount takes into account the fact that even for small and cheap vessels there are some costs which have to be covered. In total, this is sufficient to pay for the operation of the vessel, its technical and operational management, its depreciation and the return on the capital employed.

We calculated economies of scale on the basis of these new building costs, operational patterns and transport work as established in the previous sections. This calculation was first performed in order to find the relative cost advantage using an EOS fleet relative to the existing fleet, based on full fixed and variable costs for both fleets as shown in Table 4.

Table 4 shows that costs per million ton nm with the 2007 fleet are lowest for crude oil carriers, with a cost of 3500 USD. In

Table 3
New-building cost per vessel as a function of vessel type and size.

Vessel type	Average vessel size 2007 fleet (ton (dwt))	Engine size 2007 fleet (kWh)	Average new building price 2007 fleet (Million USD)	Average vessel size EOS fleet (ton (dwt))	Engine size EOS fleet (kWh)	Average new building price EOS fleet (Million USD)
Dry bulk	52,500	8000	32	172,000	15,000	59
General cargo	4600	2100	11	25,300	8000	27
Reefer	5400	5000	15	16,100	15,000	29
Container	34,200	22,000	44	106,000	67,000	98
RoRo	7200	7500	32	44,600	20,000	93
Crude oil	142,900	15,000	65	295,200	25,000	98
Oil products	10,200	2700	15	112,100	15,000	57
Chemicals	15,800	4500	28	47,600	9000	54
LNG	70,100	25,000	162	76,300	27,000	170
LPG	11,600	4500	28	53,300	13,000	64

Table 4
Comparing total cost for the existing fleet (2007) with total costs for an EOS fleet in 2007 and 2050.

Vessel type	2007 Freight work (Billion ton miles)	2050 Freight work (Billion ton miles)	Cost with 2007 fleet (USD per million ton nm)	Cost with EOS fleet (USD per million ton nm)	Total cost in 2007 with 2007 fleet (Million USD)	Total cost in 2007 with EOS fleet (Million USD)	Total cost in 2050 with 2007 fleet (Million USD)	Total cost in 2050 with EOS fleet (Million USD)
Dry bulk	16,137	29,853	4200	2400	68,000	39,000	125,000	72,000
General cargo	2382	4407	22,400	9800	53,000	23,000	99,000	43,000
Reefer	258	477	28,400	19,200	7000	5000	14,000	9000
Container	7501	46,131	10,200	7800	77,000	59,000	471,000	360,000
RoRo	485	897	36,400	13,900	18,000	7000	33,000	12,000
Crude oil	10,061	18,613	3500	2500	35,000	25,000	65,000	47,000
Oil products	1257	2325	14,200	5100	1800	6000	33,000	12,000
Chemicals	1919	3550	12,700	8000	24,000	15,000	45,000	28,000
LNG	852	1576	12,500	12,200	11,000	10,000	20,000	19,000
LPG	401	742	17,200	9100	7000	4000	13,000	7000
Total	41,000	109,000			318,000	193,000	918,000	605,000
Cost in USD per million ton nm					7800	4700	8400	5600
Potential reduction with economy of scale						39%		34%

an EOS fleet, dry bulk vessels would have the lowest cost per million ton nm at 2400 USD, followed by crude oil tankers, with a cost of 2500 USD. Combining these unit costs with the freight work performed in 2007 and 2050 gives us the total costs in each year for both the 2007 fleet and the EOS fleet. In 2007, the total cost would be 318,000 million USD with the actual 2007 fleet and 193,000 million USD with the EOS fleet, which is a 39% reduction. In 2050, the total becomes 918,000 million USD with the 2007 fleet and 609,000 million USD with the EOS fleet, i.e. a 34% reduction. When 2007 and 2050 are compared the figures also show that the cost per million ton nm will be 10% higher in 2050 with the 2007 fleet and 20% higher with the EOS fleet. The reason is the foreseen growth in the total share of the freight work performed by container vessels, which have higher unit costs and emissions than the fleet average.

While this section has shown the benefits of replacing smaller vessels with larger ones when the existing vessels reach the end of their lifetime, additional calculations are needed offer recommendations for short- and medium-term decisions. Since we do not know the remaining value of the existing vessels, we make the assumption that it is significantly lower than the value of new-buildings and that the fixed cost per transported unit will be only 50% of the fixed cost per transported unit for a similar new-built vessel. Table 5 shows the results of this comparison, which is based on the 2007 freight work for all three cost options.

Table 5 shows that the total costs for the EOS fleet are lower than the variable costs of using the existing fleet. For dry bulkers this means that the variable costs for an average 2007 vessel is 3000 USD per million ton (4200 USD in total cost), while the total cost for an EOS dry bulker is 2400 USD per million ton. This implies that in trades that can accommodate larger vessels due to transport volumes and that are not limited by port restrictions, smaller vessels cannot compete against large new buildings. However, this does not imply that smaller vessels in general should be scrapped and replaced with larger new buildings, since smaller vessels will still be needed due to port limitations and the demand for transporting smaller volumes. But it does suggest that ship-owners should consider scrapping older vessels unless they match an EOS size, and replace them with newer second-hand vessels of similar or larger size, or with larger new-buildings. Regarding age, the average expected lifetime of cargo ships is around 25 years, while well-maintained vessels can operate longer. However, as a vessel becomes older, ordinary maintenance costs become larger, while costly upgrades may be needed in order to retain the class societies' certificates that are required to operate. In a good market with high freight rates, ship-owners can easily absorb these additional costs, while under normal market conditions, the profitability of keeping versus replacing an older vessel with a newer vessel will be evaluated at least annually. This is similar to the aviation industry, where airlines replace older aircraft which need overhauls and additional maintenance with newer aircraft with lower variable costs due to reduced fuel consumption and lower maintenance.

When we compare the significant cost savings made by increasing the average vessel size against the additional potential cost increases in ports related to infra- and supra- structure, for feedering and for increased stock, a few comments can be made. The first is that most ports can accommodate a certain rise in the average vessel size they serve without any modifications. Larger vessels like the Chinamax bulkers will only be used for trades between a limited numbers of ports. The second is that with the new Panama Canal locks from 2014, vessels can be much beamier and hence carry up to 50% more cargo and still be used in most ports that serve current Panamax vessels. The explanation of this is that the main restriction in most ports is the sea draft (measured from the surface of the water to the deepest part of

Table 5
Comparing the cost for the existing fleet (2007) with the full cost for an EOS fleet.

Vessel type	2007 Freight work (Billion ton miles)	Variable and fixed cost 2007 fleet based on —new buildings (1) (USD per million ton nm)	Variable and fixed cost 2007 fleet (2) (USD per million ton nm)	Variable cost only 2007 fleet (3) (USD per million ton nm)	Variable and fixed cost EOS fleet (USD per million ton nm)	Total cost with 2007 new built fleet (1) (Million USD)	Total cost with 2007 existing fleet (2) (Million USD)	Total variable cost 2007 fleet (3) (Million USD)	Total cost in 2007 with EOS-fleet (Million USD)
Dry bulk	16,137	4200	3600	3000	2400	68,000	58,000	48,000	39,000
General cargo	2382	22,400	19,300	16,100	9800	53,000	46,000	38,000	23,000
Reefer	258	28,400	25,500	22,500	19,200	7000	7000	6000	5000
Container	7501	10,200	9200	8100	7800	77,000	69,000	61,000	59,000
RoRo	485	36,400	30,000	23,500	13,900	18,000	15,000	11,000	7000
Crude oil	10,061	3500	3000	2500	2500	35,000	30,000	25,000	25,000
Oil products	1257	14,200	11,900	9600	5100	18,000	15,000	12,000	6000
Chemicals	1919	12,700	10,500	8200	8000	24,000	20,000	16,000	15,000
LNG	852	12,500	10,500	8500	12,200	11,000	9000	7000	10,000
LPG	401	17,200	14,200	11,200	9100	7000	6000	4000	4000
Total	41,000					318,000	275,000	228,000	193,000
Cost in USD per million ton nm						7800	6700	5600	4 700

the vessel) rather than beam or length. The third is that in some trades, the larger vessels used on the deep-sea legs will mean that fewer ports can be served, which will contribute to increased feedering. However both for dry bulk and container trade we might see the same as in aviation, where the largest Airbus A-380 aircraft is used on major routes with high frequencies like Singapore–London and Singapore–Frankfurt, while Singapore–Copenhagen is served by aircraft of half their size, three to four days a week. Translated to shipping, this means that major ports which cannot be served by mega-vessels will continue to be served directly by large vessels, while the ultra-large vessels will be used in major ports that can accommodate them. The fourth is that with the foreseen growth in trade, vessel sizes can be increased without reducing the sailing frequencies and without increasing the average days in stock for the commodities. The fifth is that port states can implement legislation in combination with a cost structure which will work as a barrier to the introduction of larger vessels. Although this challenge should not be ignored, we regard it primarily as a safety point. Our judgment is that due to completion between port states and ports, they will try to do whatever they can within the physical limitations to accept larger vessels as long as their safety threshold are met. Adding all this up, our conclusion is that compared to the potential savings of using significantly larger vessels, the additional cost are small.

3.4. Abatement costs with an EOS fleet

The main purpose of calculating abatement costs is to enable different emission reductions options both within shipping and between sectors to be compared. Since most abatement options come at a cost that exceeds the economical benefits, abatement costs tend to be positive. In the shipping sector, research has shown that there are emission reductions options which can be adopted at negative abatement cost (Second IMO GHG study, 2009; Faber et al, 2009; DNV 2010). However, Russell et al. (2010), claim that these studies fall short in identifying, characterizing and assessing the impact of the range of decisions faced by individual ship owners and collectively based on current and future market conditions, and that these studies do not take profit and opportunity cost into consideration. Our understanding is that previous work has been based on assuming an ongoing operation with long-term vessel ownership, ignoring that a large proportion of the shipping market is much more focused on asset play, with buying and selling vessels driven by profit and opportunity assessments. Taking the long-term view, abatement costs can be calculated by combining the cost savings and potential reductions in emissions produced by introducing larger vessels, as shown in Table 6. These abatement costs have been calculated on the basis of comparing the freight levels required to cover the fixed and variable costs of the 2007 fleet versus the EOS fleet, assuming that in the long run, freight rates for different commodities will reflect their different transport costs. These abatement costs lie within a range from −361 USD per ton CO_2 for container vessels to −739 USD per ton CO_2 for RoRo vessels. This is based on a scenario in which smaller vessels are replaced by larger vessels when they are scrapped, while scrapping relatively new small vessels to reduce emissions would give a positive abatement cost.

3.5. Sensitivity analysis of cost variables

Fuel prices and new building costs are the two main exogenous variables in the sensitivity analysis. The results regarding cost reductions through economies of scale in Section 3.3 are based on a fuel price of 630 USD/ton and 2011 new-building prices. However, both the fuel price, which is a function of the oil price, and

Table 6
Abatement costs as a function of economies of scale.

Vessel type	Cost with 2007 fleet (USD per million ton nm)	Cost with EOS fleet (USD per million ton nm)	2007 Freight work (Billion ton miles)	2050 Freight work (Billion ton miles)	2007 Emission reduction with EOS fleet (Million ton CO_2)	2050 Emission reduction with EOS fleet (Million ton CO2)	Abetment cost per ton CO_2 (USD)
Dry bulk	4200	2400	16,137	29,853	42	78	−689
General cargo	22,400	9800	2382	4407	71	131	−423
Reefer	28,400	19,200	258	477	5	9	−472
Container	10,200	7800	7501	46,131	49	303	−361
RoRo	36,400	13,900	485	897	15	51	−739
Crude oil	3500	2500	10,061	18,613	24	27	−423
Oil products	14,200	5100	1257	2325	27	27	−415
Chemicals	12,700	8000	1919	3550	15	45	−620
LNG	12,500	12,200	852	1576	0	1	−598
LPG	17,200	9,100	401	742	5	9	−663
Total	7800	4700	41,000	109,000	250	680	

Table 7
Sensitivity analyses for cost variables.

Scenario	Average cost in 2007 with 2007 fleet (USD per million ton nm)	Average cost in 2007 with EOS fleet (USD per million ton nm)	Reduction in 2007 with EOS (USD per million ton nm)	Average cost in 2050 with 2007 fleet (USD per million ton nm)	Average cost in 2050 with EOS fleet (USD per million ton nm)	Reduction in 2050 with EOS (USD per million ton nm)
Base case, oil price=630 USD/ton	7800	4700	3100	8400	5600	2800
Oil price 315 USD/ton	5700	3300	2400	5900	3800	2100
Oil price 1260 USD/ton	11,700	7400	4300	13,200	9100	4100
New building price 50% of today	6200	3800	2400	6900	4700	2200
New building price 200% of today	10,600	6400	4200	11,200	7300	3900

new-building prices have been extremely volatile during the past ten years. It is therefore relevant to test out the robustness of the conclusions by varying the 2011 costs of fuel and new-building from 50% of current levels to up to 200%. Table 7 shows that lower costs would reduce the cost difference between the 2007 fleet and the EOS fleet in absolute terms, while higher costs would increase it. However, since the saving with the EOS fleet ranges between 30 and 40%, we can conclude that economy of scale is a robust strategy that would be profitable at all foreseeable fuel and new-building prices.

4. Discussion and conclusions

The main objective of this paper was to investigate potential reductions in cost and emissions by utilizing economies of scale. The results demonstrate that emissions can be reduced by as much as 30% at a negative abatement cost by replacing the existing fleet with larger vessels. Replacing the whole fleet might take as long as 25 years, so the reduction in emissions will be achieved gradually as the current fleet is renewed.

When the results were compared with data from other studies of reductions in emissions and costs, they were found to be within a similar range as those for container vessels presented by Cullinane and Khanna (2000), Notteboom and Vernimmen (2009). Few studies of other vessel types exist, although figures are available that demonstrate the importance of economies of scale for emission reduction per freight unit since the Second World War (Second IMO GHG study, 2009). Our results confirm the potential for reducing emissions if we build bigger vessels in the future than we have done to date. Where abatement costs are concerned, our finding of minus 450 USD per ton CO_2 at a fuel price of 630 USD/ton is higher than previous studies have found (Second IMO GHG study, 2009; Faber et al, 2009; DNV 2010). When we compare the potential for emission reduction at a negative abatement cost, these studies indicates a reduction potential of around 30%, while our results suggest up to 30% from economies of scale alone. Since none of these studies have included the effect of economies of scale we conclude, on the basis of our results and those of Cullinane and Khanna (2000), Notteboom and Vernimmen (2009) that the importance of economies of scale has been underestimated by previous studies of abatement cost and reduction potential.

As mentioned in the Introduction, CO_2 emissions from maritime transport represent 3.3% of the world's total CO_2 emissions, and they are forecast to increase by 150%–250% until 2050, on the basis of "business as usual" scenarios with a tripling of world trade (Second IMO GHG study, 2009). In response to these challenges, the International Maritime Organization (IMO) is currently debating technical, operational and market-based measures for reducing greenhouse gas emissions from shipping. Progress has been made, and in July 2009 the principles of EEDI and SEEMP were agreed, while in July 2011, EEDI and SEEMP were adopted as part of the MARPOL Convention (Resolution MEPC.203 (62)). In a recent study commissioned by IMO (MEPC.63/INF.2), the potential reduction in emissions from EEDI and SEEMP versus business as usual scenarios was evaluated by Lloyds Register and DNV. The figures indicate that these two measures will reduce emissions per transported unit by almost 40% versus "business as usual" in 2050, and that EEDI would contribute 75% of the reduction. This is based on the assumption that more efficient technology is or will be available within the next few years. That the EEDI baselines fully represent the average for each ship type from very small to the largest vessels and that existing vessels will be replaced by vessels of similar size. In spite of these reductions, total emissions in 2050 are predicted to be twice the 2007 level, given a tripling of world trade.

It is our view that the study has taken an optimistic approach regarding the effect of new technology, but it is in line with previous assessments made by the Second IMO GHG study (2009). Regarding EEDI baselines, Greece has highlighted some of the problems for larger vessels (MEPC.62/6/19). The Greek evaluation shows that most modern large tankers currently lie well above the proposed baseline and that the same is true for large dry bulk vessels. This conclusion has also been drawn by IMarEST (MEPC.60/4/33) and by Kruger for RoRo vessels (GHG-WG.2/2/22). The treatment of larger vessels is clearly a challenge, since our study has shown that emissions can be reduced by up to 30% at negative abatement cost by replacing smaller vessels with larger ones. Since the effect of economies of scale is not included in the study by Lloyds Register and DNV, it comes in addition to what can be achieved with the EDDI and SEMP measures. Combined emissions could be reduced by more than 50%. However, the current treatment of larger vessels in EEDI is a challenge. This due to the fact that large dry bulk, tank and RoRo vessels built during the last 10 years lie on average around 10% above the current EEDI requirement, which implies that when the EEDI values in 2030 is reduced by a further 30%, the required improvement for these larger vessels will need to be 40%. Since the technology that will enable these reductions to be made is a function of vessel size and speed rather than of vessel type, EEDI reductions beyond what technology can give, can only be achieved by installing less power (smaller engines), thus reducing design speeds. A serious challenge is that power reductions on large dry bulkers and tankers can also have implications for safety, since their existing power levels partly are a function of what is required to keep the vessel under command in rough seas. On the other hand, large container vessels, which are already well below the requirements will need to improve by much less than 30%.

In a technical world, the obvious solution to maximizing emission reductions through combining economies of scale, EEDI and SEEMP would have been to improve the EEDI baselines by employing more advanced regression models in combination with technology assessments of current versus potential technologies. However, IMO's GHG discussions started on the basis of the non-binding commitment under the Kyoto protocol regime; progress has been slow and Resolution MEPC.203 (62) was not reached by consensus. So instead of making it complex, one solution might be to propose that when vessels reach a certain size, the EEDI requirement becomes a fixed value for all vessels above that size. One way to set this cut-off point for each ship type could be to set it so that 80% of vessels fall within the standard EEDI and 20% within the fixed area. Such an amendment of the EEDI scheme would bring several benefits; it would reward economies of scale and the associated emission reductions; large new-buildings would still have to be made much more energy-efficient than their older counterparts;, it would stop the debate in IMO about punishment of larger vessels, and it would offer more equal treatment of all vessels. Most importantly, it would enable larger vessels of all types to be built with sufficient power to maintain seaworthiness and maneuverability under all weather conditions.

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Appendix. Nomeclature

C cost per freight unit, USD/ton nautical mile (all tons are metric)

$(Capex_v|(k_1+k_3)+k_3)$ annual cost of a vessel, where $Capex_v$ is the new-building price of the vessel, k_1% of $Capex_v$ is the fixed cost which consists of financial costs including depreciation and return on own capital, k_2% of $Capex_v$ plus a basic amount k_3 is the variable (operational) cost, USD

C_{HFO} cost of heavy fuel oil, USD/ton

C_{MDO} cost of marine diesel oil, USD/ton

D_b distance per voyage in ballast, nm = nautical miles

D_c distance per cargo voyage, nm = nautical miles

DWT maximum cargo capacity of a vessel, tons

EOS economies of scale

ε quantity of CO_2 emitted per ton nautical miles, grams

F_b fuel consumption on sailings in ballast, tons

F_c fuel consumption on cargo sailings, tons

$F_{l\&d}$ fuel consumption during loading and discharging, tons

$F_{p\&s}$ fuel consumption in port and slow zones (e.g. canals and entering and leaving port), tons

$K_e=317$ CO_2 emitted per unit of fuel burnt; based on Endresen (2007)

$K_f=190$ quantity of fuel used per unit of work produced, g/kwh

M weight of cargo, tons

N_c annual number of cargo voyages

N_b annual number of voyages in ballast

N_v number of vessels

P_b power required on voyages in ballast, kWh

P_c power required on cargo voyages, kWh

$P_{l\&d}$ power required for loading and discharging, kWh

$P_{s\&w}$ power required in slow zones and when waiting, kWh

T_b time used per ballast voyage, (days, hours, minutes)

T_c time used per cargo voyage, (days, hours, minutes)

$T_{l\&d}$ time per voyage for loading and discharging, (days, hours, minutes)

$T_{s\&w}$ time per voyage in slow zones and waiting, (days, hours, minutes)

v_b vessel speed on ballast legs(1 knot = 1852 m/h), knots

v_s vessel speed on cargo legs (1 knot = 1852 m/h), knots

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