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State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review

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ABSTRACT

CO_2 emissions from maritime transport represent around 3% of total annual anthropogenic greenhouse gas (GHG) emissions. These emissions are assumed to increase by 150–250% in 2050 in business-as-usual scenarios with a tripling of world trade, while achieving a 1.5–2 °C climate target requires net zero GHG emissions across all economic sectors. Consequentially, the maritime sector is facing the challenge to significantly reduce its GHG emissions as contribution to the international ambition to limit the effects of climate change.

This article presents the results of a review of around 150 studies, to provide a comprehensive overview of the CO_2 emissions reduction potentials and measures published in literature. It aims to identify the most promising areas, i.e. technologies and operational practices, and quantify the combined mitigation potential. Results show a significant variation in reported CO_2 reduction potentials across reviewed studies. In addition, no single measure is sufficient to achieve meaningful GHG reductions. Emissions can be reduced by more than 75%, based on current technologies and by 2050, through a combination of measures if policies and regulations are focused on achieving these reductions. In terms of emissions per freight unit transported, it is possible to reduce emissions by a factor of 4–6.

1. Introduction

For centuries, sea transport has been a major facilitator of trades between nations, regions, and continents. More recently, together with trade liberalisation, telecommunication, and international standardisation, it has been a key enabler of globalisation (Hoffmann and Kumar, 2002). Over the past 40 years, maritime transport has increased by 250%, following the same growth rate as global Gross Domestic Product (GDP), and growing more rapidly than energy consumption (170%) and global population (90%) Eskeland and Lindstad, 2016. From a global freight transport perspective, shipping is recognized as an energy-efficient means of transportation compared to road and air transport, due to its large carrying capacity and low fuel consumption per ton transported.

According to the third greenhouse gas study (GHG) of the International Maritime Organization (IMO), shipping emitted 938 Mt CO_2 in 2012, accounting for 2.6% of global anthropogenic CO_2 emissions. This is a reduction compared to the 1100 Mt

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CO_2 emitted in 2007 (3.5% of global emissions) and can be attributed to the increase in vessel size and lower operational speeds (Lindstad et al., 2015a; Smith et al., 2014). Notwithstanding this amelioration, in a business-as-usual (BAU) scenario with a tripling in world trade and no further mitigating measures taken, future emissions are expected to increase by 150–250% over the period 2012–2050 (Buhaug et al., 2009). These emission growth prospects are opposite to what is required to reach a climate target well below 2 °C by the year 2100 (IPCC, 2007). Global GHG emissions have to decrease to net zero and even further to negative values across all sectors by the second half of the century. The decarbonisation level required by each of the sectors is dependent on the widespread adoption of so-called negative emissions technologies and measures, such as bioenergy with carbon dioxide capture and storage and afforestation, to balance sources with unavoidable positive emissions. However, continuous and widespread deployment of negative emissions technologies is currently not happening at the required scale. Consequentially, other sectors need to decarbonize on the premise that negative emissions technologies might not work at scale (Anderson and Peters, 2016).

One approach to reconcile shipping emissions with international commitments on climate change is to treat the shipping sector as if it were a sovereign nation that contributes fair and proportionate to emissions budgets. Following this approach, a reduction of at least 85% relative to 2010 is necessary by 2050 (Anderson and Bows, 2012). This implies that even in a no-growth scenario the CO_2 emissions per unit freight transport from shipping will have to be reduced from approximately 25 to 4 g of CO_2 per ton-nautical mile, i.e. a reduction by a factor of five to six (Lindstad, 2013).

Previous studies of emissions abatement measures in shipping have documented that it is possible to improve energy efficiency and reduce emissions in a cost effective manner, either with zero costs or with net cost savings (Lindstad et al., 2015a; Buhaug et al., 2009; Faber et al., 2009, 2011; Alvik et al., 2010). There are two main types of studies: (i) those estimating the total CO_2 reduction improvement potential for the global shipping sector (e.g. Buhaug et al., 2009; Lindstad, 2013; Alvik et al., 2010), and (ii) those investigating more closely one or a small group of measures together (e.g. Gilbert et al. 2014). Whereas the first type provides oversight, the second type is able to provide more detailed estimates and taking into account distinct contexts of application, such as the studies of speed and its impact on emissions (Corbett et al., 2009; Lindstad et al., 2011; Pélerin et al., 2010). Industrial Research and Development initiatives related to fuel efficiency, GHG emissions reduction, as well as policies for controlling air emissions (Lindstad, 2013; Kontovas and Psaraftis, 2016; Psaraftis, 2016; Eide et al., 2013a) have resulted in a high level of knowledge, awareness, as well as operational adaptations across the maritime sector (Dnv, 2014). However, the quantification of a (theoretical) maximum potential for energy- and GHG reducing measures is complicated by organizational, technical, economic and political barriers for implementation (Jafarzadeh and Utne, 2014; Tillig et al., 2015; Rojon and Dieperink, 2014), as well as variations in applicability of measures for distinct ship types and/or ages (Eide et al., 2013a, 2013b; Tillig et al., 2015; Franc, 2014; Lin, 2012; Guerra and Jenssen, 2014). Whereas overview studies of presenting mitigation measures and scenarios for shipping are available (e.g. Buhaug et al. (2009)), comprehensive reviews are sparse in the scientific literature.

The motivation for this study is to provide a comprehensive overview of the CO_2 emissions reduction potentials and measures published in literature. We aim to identify the most promising measures, i.e. technologies and operational practices, and quantify their mitigation potential. We are well aware of the importance of other pollutants, their impact on both health and climate, and the necessity to consider more than one type of emission when evaluating emission reduction measures (Eide et al., 2013b; Lindstad et al., 2016a, 2015b). For example, while CO_2 emissions from LNG combustion are lower than emissions from HFO combustion, the fugitive emission of methane (a potent GHG) during bunkering or due to slippage in the engine, dampens the GHG reduction potential. However, to be able to utilize the largest body of literature, which often does not consider other GHGs, we chose to focus on measures for mitigating CO_2 emissions as a proxy for GHG reduction.

In this study, we identify the areas with the highest potential for reduction of emissions as a guide towards furthering the development of low-carbon shipping. In Section 2, we describe the method employed. The CO_2 reduction potentials based on studies with focus on emission reduction achievable at fleet level are presented in Section 3.1. We present the emission reduction potential identified by studies focusing on specific measures in Section 3.2. Subsequently, we discuss the results and the most promising areas regarding mitigation potential as well as uncertainties and gaps in the reviewed literature. In addition, we discuss the need for a more holistic approach, which includes the net contribution to climate change of all the exhaust gases when assessing alternative abatement options and technologies.

2. Methodology

We performed a systematic review of previous studies of fuel and CO_2 emissions reduction measures, based on a comprehensive search and analysis of published studies on shipping energy efficiency and GHG emissions. The review focused on the reported results and not on the methods used. The selection of studies was based on a qualitative assessment of the relevance of the study for estimating CO_2 emission reduction potentials from shipping by different means.

We limited the scope by investigating studies published after the second GHG study of the IMO, published in 2009 (Buhaug et al., 2009), which provides the first most complete overview of emissions reduction potential and is used as main reference for many similar studies (Smith et al., 2014; Faber et al., 2011, 2010; Eide et al., 2013a; Wang et al., 2010). In order to systematically search, analyze, and categorize the results from previous studies, we broadly searched for literature containing a combination of the search terms: ship energy efficiency, GHG or CO_2 emissions from shipping, and ship performance, design, or operations. By reviewing titles and abstracts we filtered the results according to relevance with regards to the aim of the review. We classified the publications based on: type of publication, the primary and secondary focus (e.g. fuel efficiency, CO_2 reduction, other GHGs), the scope of the potential identified (maximum achievable potential or potential from individual measure), the nature of the potential identified (quantitative or qualitative), and the type of measure (e.g. technical, operational). All available data on estimations of emission reduction potential (expressed in fuel efficiency, CO_2 or CO_2-eq reduction) were registered, or calculated based on evidence in the study. In addition, we identified articles providing more insight on emissions and energy efficiency in shipping, though without quantitative estimates of reduction potential.

The literature review converged on approximately 150 studies. Sixty (60) of these studies provide quantitative estimates of CO_2 emission reduction potential, of which fourteen (14) cover the maximum abatement potential at a global or regional fleet level as shown in Table 1, and the rest focuses on one or few individual measures. The remainder of studies provide qualitative complementary insights.

3. Results

3.1. Maximum potential reduction of CO_2 emissions from shipping

This section presents the results from studies focusing on emission reductions achievable at fleet level, based on adoption of available measures within a given time perspective. The main study of potential emission reduction from shipping is the Second IMO GHG Study from 2009 (Buhaug et al., 2009), used as reference for follow-up studies either in terms of potential estimates for individual reduction measures or fleet development scenarios. Efforts post-2009 to assess the global and large scale reduction potential for GHG emissions are led by several SNAME and IMAREST investigations, as well as studies initiated by DNV (now DNV GL) Alvik et al., 2010; Eide et al., 2013a., 2013b; Eide et al., 2011; Hoffmann et al., 2012. In addition, two studies financed by the European Commission's Directorate General *Climate Action* provide valuable input to the state-of-the-art and insight on potential for reduction of emission from European shipping (Lindstad et al., 2015a; Kollamthodi et al., 2013).

Based on reviews of mitigating measures (Lindstad et al., 2015a; Buhaug et al., 2009; Alvik et al., 2010; Faber et al., 2011; Tillig et al., 2015; EMEC, 2010; CNSS, 2011), as well as ongoing industrial projects and in-house knowledge, six groups of measures with high mitigation potential were selected and used to sort and compare the selected studies. These six main groups are: *hull design; economy of scale; power and propulsion* (including energy saving devices); *speed; fuels and alternative energy sources; weather routing and scheduling*. *Hull design* covers aspects related to hull dimensions, shape and weight, which contribute to improve the hydrodynamic performance and minimize resistance. *Economies of scale* is another means of reducing emissions, since larger ships and cargoes tend to be more energy-efficient per freight unit. Typically, when cargo-carrying capacity is doubled, the required power and fuel consumption increases by about two-thirds, thus reducing fuel consumption per freight unit. *Power and propulsion* includes design of power system and machinery, hybrid power solutions, higher propulsion efficiency, waste heat recovery, and reduction of on-board power demand by energy saving devices such as kites and sails. Hybrid power systems enable the efficient exploitation of various energy sources, such as combining batteries with combustion engines to utilize the best of each technology, i.e. batteries can be used as a buffer for covering peak power requirements and to avoid low power operations of combustion engines. *Speed* relates to the operational speed of the vessel, as well as its design speed. Traditionally, ships are often designed to operate at their hydrodynamic boundary speeds, i.e. the speed at which for a given hull the resistance curve starts to rise rapidly with increasing speeds. As power requirement is proportional to the product of speed and resistance, this implies that when a ship reduces its speed, the fuel consumption is reduced and that the biggest fuel reductions are achieved when ships reduce speed in the boundary area. *Fuels and alternative energy sources* covers all aspects related to substituting or complementing bunker fuels HFO-MGO with alternative energy carriers. Emissions of CO_2 can be cut by switching to fuels with lower total emissions, both directly and throughout the fuel cycle including production, refining and distribution. Examples are LNG and biofuels. Hydrogen is gaining increasing attention, as well as renewable energy such as wind and solar. *Weather routing and scheduling* consists of finding the optimum sailing route and speeds, taking into account current, wave and weather conditions, and deliveries according to the contractual agreements or published schedules, to minimize resistance and fuel consumption.

Table 1 shows the potential CO_2 emission reduction at fleet level relative to the estimated BAU emissions for each individual study. The first column gives the reference to the study; the second the applied method; the third the coverage; the following six columns are used for the investigated measures where *x* means that the measure has been included in the study. Then from column 10 follows: fuel price used; fleet reference year; final year of scenario; BAU emissions in the final year; Identified CO_2 emission reduction potential at fleet level in the final year relative to BAU emissions in the final year. In addition, Table 1 includes the median values across all studies for BAU emission estimates as well as minimum and maximum estimated CO_2 reduction potential.

The main observations from Table 1 are: the maximum potential for emission reduction spans from 20% to 77%, not including nuclear power as an alternative power source. When including nuclear power as alternative power source, maximum reduction potential reaches 95% (Eide et al., 2013a). Median reduction rates are 35%, 39% and 73% for the years 2020, 2030, and 2050 respectively. The highest range of reduction potential is found in the 2050-estimates, 58–77% (Buhaug et al., 2009; Lindstad, 2013; Eide et al., 2013a), reflecting the time it takes to adopt emission reduction measures. Apart from the

Table 1
Potential reduction in CO_2 emissions from shipping at fleet level, all measures combined.

Author(s)	Method for calculation of potential	Application	Hull design	Economy of Scale	Power& Propulsion	Speed	Fuels & alt. Energy Sources	Routing & Scheduling	Fuel price ($/ton)	Fleet reference year	Final year of scenario	BAU emissions in final year (Mt CO_2)	Identified CO_2 emission reduction potential (%)
Buhaug et al. (2009)	Expert estimates, fleet development scenario model 25 measures	18 ship types, world fleet	x x	 x	x x	x x	 x	x x	500	2007	2020 2050	1294 2595	16–34% 58–75%
Faber et al. (2009)	Same as Buhaug et al. (2009) 29 measures	9 ship types, 40,055 ships	x		x	x	x	x	700	2006	2030	1790	27–47%
Alvik et al. (2010)	Expert estimates 25 measures	59 ship segments, world fleet	x		x	x	x	x		2009	2030	1530	56%
Wang et al. (2010)	Similar to Buhaug et al. (2009) 22 measures	14 ship types, world fleet	x	x	x	x		x	700 900	2007	2020 2030	1421 2205	35–45% 35–45%
Faber et al. (2011)	Updated of Wang et al. (2010)	14 ship types	x		x	x	x	x	700, 900	2007	2020 2030	1204 1982	20–46% 20–46%
Eide et al. (2011)	CO_2 emission scenario model 25 measures	59 ship types, world fleet, 59,800 ships	x		x	x	x	x	350	2008 2008	2020 2030	1191 1533	41% 56%
Hoffmann et al. (2012)	Cost-effectiveness. 25 measures	59 ship segments, world fleet	x		x	x	x	x		2010	2030	1316	30–53%
CCNR (2012)	Model-based. 27 measures	Inland navigation, Western Europe	x	x	x	x	x	x		2010	2050	2.9	58%
Eide et al. (2013a)	Same as Eide et al. (2011) 27 measures	59 ship segments, world fleet, 59,800 ships	x		x	x	x	x	300– 1500	2008	2050	2000	55–95%
Eide et al. (2013b)	Same as Eide et al. (2011) 15 measures (existing ships)	59 ship segments, world fleet, 59,800 ships	x		x	x	x	x		2010	2010	999	25–32%
Lindstad (2013)	Model-based, 5 main measures	11 ship types, 109,000 bt nm	x	x		x		x	120– 1200	2007	2050	2199 2650	77% 76%
Kollamthodi et al. (2013)	Scenario model, 3 main measures	European shipping		x			x			2010 2010	2030 2050	279 403	20% 33%
Heitmann and Peterson (2014)	Abatement costs scenarios, 22 measures	14 ship types	x		x	x	x	x	350– 900	2012	2020	947	22–48%
TNO Lindstad et al. (2015a)	Model-based, 12 measures (existing ships)	10 ship types, world fleet	x	x	x	x	x	x	300– 1200	2012	2030	2007	30–45%
Median											2020 2030 2050	1204 1790 2397	35% 39% 73%

nuclear alternative, the 2050 figures are in line with the estimated maximum potential from the Second IMO study (Buhaug et al., 2009).

Several factors seem to affect the estimated potential for reduction in different ways. First the number and types of measures included in the studies are directly affecting the maximum potential reduction. In addition, it is important to keep in mind that not all reduction measures are additive and can be applied simultaneously. Second, the categorization and aggregation of measures is challenging to compare across the studies. Even across studies including the same set of measures we observe variations in estimated reduction potentials. Third, the baseline year and baseline emissions (2020, 2030, and 2050) affect the magnitude of potential emission reduction. The further ahead in time, the larger the estimated potential for improvement, with a range of 33–48%, 30–56%, and 58–95% respectively for 2020, 2030, and 2050.

The fuel cost given in the fifth last column has no direct effect on the total maximum (technical) potential for emission reduction, but rather on the calculation of cost-efficient potential and no-regret potential. In addition, fuel price is often a determinant for fuel choices in more economically oriented future scenarios (Lindstad et al., 2015a; Kesicki and Strachan, 2011). Table 1 shows a large variation in fuel prices, especially for the more recent studies (Lindstad et al., 2015a; Eide et al., 2013a), highlighting the importance of assessing fluctuations in energy price in order to determine its impact on investment decisions for mitigating measures and varying the threshold for cost efficient measures.

The annual fleet-wide CO_2 emission estimates available in the studies presented in Table 1 are presented in Fig. 1. For each scenario reported in the reviewed studies, the BAU emissions are plotted as well as the low and high emission reduction estimates. To enhance clarity, we shaded the area between low and high emissions estimates for both BAU and reduction scenarios, and added jitter along the x-axis to distinguish between overlapping data points. It is important to stress here that reduction estimates are not solely based on adoption of technical and operational measures, but also reflect the assumptions of the reviewed articles with respect to growth in demand for transport. For example, Buhaug et al. use projections of transport in ton-nautical mile based on the IPCC scenario family (Buhaug et al., 2009), whereas Eide et al. use a fleet development model to estimate size of the fleet based on estimations of growth and scrapping rates (Eide et al., 2013a, 2011).

Fig. 1 shows an overlap between BAU and reduction scenarios in 2020 and in 2030, reflecting uncertainty in the scenarios as well as different assumptions on the rate of adoption of emission mitigation measures and growth rates of global maritime transport. In the long term, there are no overlaps between BAU and reduction scenarios. However, compared to the 2012 situation (938 Mt CO_2), some of the reduction scenarios amount to a net increase in emissions, whereas other reduction scenarios report a net decrease in annual CO_2 emissions. This is especially clear for the period up to 2030 where one reduction scenario estimates an increase in emissions of more than 65%, where others estimate a decrease of maximum 34%. This signifies the challenge to reduce the absolute emissions of the maritime sector while transport volumes increase. Each increase in transport volume will have to be matched by larger improvements in environmental performance to achieve absolute emissions reduction.

3.2. Estimated CO_2 reduction potential from individual measures

This section presents the estimated reduction potential from individual measures. 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 improved energy efficient design, improved propulsion and power system, and alternative or cleaner fuels. Some measures can be applied as retrofit measures, while others can only be considered for new ships. Operational measures aim at reducing emissions during operations at ship or fleet level. Examples are optimizing speed, voyage planning, fleet management, and on-board energy management. Operational measures are adequate for any ship type, existing or new-built. We have excluded market-based measures from the present review as ultimately they

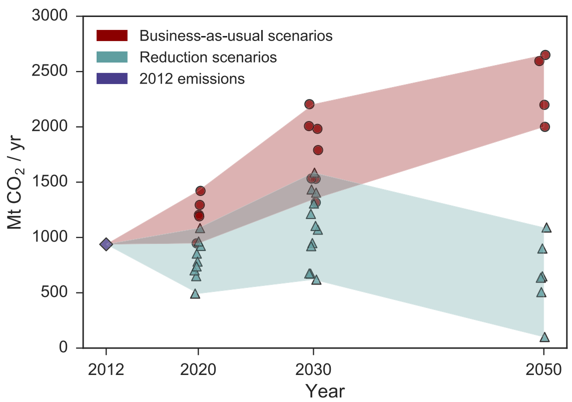

Fig. 1. Annual CO_2 emissions from the global shipping fleet, distinguished by business-as-usual and reduction scenario pathways. Jitter is added to distinguish different data points.

provide an incentive to implement technical and operational measures. Reviews and investigations of such measures can be found in references (Eskeland and Lindstad, 2016; Psaraftis, 2016, 2012; Miola et al., 2011; Russell et al., 2010; Davidson and Faber, 2012; Lindstad et al., 2015c; Carr and Corbett, 2015; Balland et al., 2015; Cullinane and Bergqvist, 2014; Nikolakaki, 2013; Lee et al., 2013).

The main findings on reductions potential at individual measure level are summarized in Table 2. The table presents twenty-two (22) measures or type of measures, for which sufficient, reliable and comparable data are available in the selected literature. These measures are grouped under five main categories: *hull design*, *power and propulsion*, *alternative fuels, alternative energy sources*, and *operations*. Compared to Table 1, this implies that Economies of scale now is one of the measures grouped under hull design; that alternative fuels and alternative energy each are main categories; that *speed* and *weather routing and scheduling* are grouped under *operations.* All references with quantitative estimates of emission reduction potential are given in Table 2. In addition, references providing complementary qualitative insight into the mitigation potential of individual measures are listed in the last column. The range of potential CO_2 emission reduction in percentage represents the absolute minimum and maximum value collected from the literature.

Complementary to Table 2, Fig. 2 shows the CO_2 reduction potential for each of the 22 measures. 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, which and corresponds to the ranges presented in Table 2. In addition, the data points found in each of the studies are plotted using a small circle. Fig. 2 thus gives a graphical overview of the distribution of reduction potentials presented in the literature.

From Table 2 and Fig. 2 we observe a large ranges 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 effectivity of reported reduction potentials. For many measures, the highest reported reduction potential is several times larger than the median value. Eight (8) out of the 22 measures have a 3rd quartile reduction potential of 20% or higher, eight (8) out of the 22 measures have a 3rd quartile reduction potential between 10% and 20 % and six (6) out of the 22 measures have a 3rd quartile reduction potential of less than 10%.

Hull design measures focus primarily on utilizing economies of scale and reducing resistance during operation. The results indicate that novel hull design can contribute considerably to CO_2 emissions reduction. Increasing vessel size reduces emissions per unit transport work and optimizing hull shape for reduced drag can significantly reduce power consumption and consequentially emissions. Additional measures, such as light-weighting, hull coating and lubrication can contribute to improving the performance of hulls further, but their potential as a single measure is limited.

For reduction measures within the power and propulsion system, Fig. 2 shows that some studies report considerable emission reductions. However, the median estimated reduction for measures in power and propulsion system is relatively low. This reflects the challenges and boundary conditions related to implementation of these measures. For example, a truly integrated hybrid drivetrain deviates significantly from a conventional set-up. Meeting all conditions required for optimal implementation, and high emissions reductions, is challenging for such an early stage technology. For some of the more conventional measures, such as efficiency increasing devices, the past decades have already seen considerable improvements and it is likely that further improvements remain marginal as the physical limits are approached.

Fig. 2 shows the highest CO_2 emissions reduction potential for the use of biofuels. However, the systemic effects of large scale adoption of biofuels reach well beyond reduction in CO_2 emissions during combustion. There are two main factors influencing the CO_2 reduction potentials of biofuels. First, the bio feedstock differs in type and quality and is processed in different manners. Variations in CO_2 reduction potential occur due to changes in feedstock, processes, efficiencies, etc. The second factor pertains to the way reduction potential is calculated. Traditionally, emissions from biological origin are assumed to be carbon-neutral as biofuel is of renewable origin and carbon is sequestered during growth of the biomass. However, the carbon-neutrality assumption depends strongly on the rotation periods of the source crop, location of the crops, and direct and indirect albedo changes due to harvesting, all of which have a climate effect. In addition, non-climatic concerns such as competition for scarce land resources make a comparison in terms of only CO_2 emissions overly simplified (Cherubini et al., 2013).

Switching to LNG as a fuel can lead to relatively high emissions. Consisting mostly of methane, the CO_2 emissions during LNG combustion are considerably lower than those of other fossil fuels and this is reflected in the reduction potential. However, leakage of methane from the engine, a potent GHG, could pose a challenge not captured in Fig. 2. In addition, as a carbon based fuel of fossil origin, combustion of LNG still results in continued CO_2 emissions. Considering that the residence time of CO_2 in the atmosphere is thousands of years (Archer et al., 2009), and that there is a clear carbon budget associated with the goals set forward in the Paris agreement, a one-sided focus on LNG as a mitigation option risks lock-in of the sector into a high-carbon infrastructure not commensurate with required commitments in the long term (Gilbert, 2014).

For the measures focusing on alternative sources of energy we observe high reduction potentials for wind power and low potential for solar power. The utilization of sails, kites, and photovoltaic cells to capture these additional energy sources is strongly dependent on the ship case in which the technology is applied. Such measures are most efficient for smaller ship sizes on specific routes with high solar incidence and wind potential, as the total amount of energy that can be generated by these measures on-board is constrained by the surface area necessary for each of these measures. Conversely, cold ironing can theoretically be applied to ships of any size. It can reduce local air pollution considerably, especially in countries with clean electricity mixes. However, there appears to be little agreement between studies as to its CO_2 reduction potential, which is necessarily a function of the fraction of travel time spent in port. Few data are available in the review for application

Table 2
Measures and potential effect on energy efficiency and emissions reduction (CO_2).

Type of measure	Main measures reviewed	Short description	Potential CO_2 reduction	References to studies providing estimates	Additional studies
Hull design	Vessel size	Economy of scale, improved capacity utilization	4–83 %	Lindstad (2013), Faber et al. (2011), Gilbert et al. (2014), Tillig et al. (2015), Wang et al. (2010), Miola et al. (2011), Wärtsila (2009), Stott and Wright (2011), Lindstad et al. (2012, 2016b), Gucwa and Schäfer (2013), Lindstad and Eskeland (2015), Halfdanarson and Snåre (2015), Pauli (2016), Zöllner (2009)	Buhaug et al. (2009), Lindstad (2013, 2015), Cullinane and Khanna (2000), Sys et al. (2008), Wu and Lin (2015), Styhre (2010), Bittner et al. (2012)
	Hull shape	Dimensions & form optimization	2–30%	Lindstad et al. (2015a, 2013a, 2014), Buhaug et al. (2009), Lindstad (2013), Faber et al. (2011), Gilbert et al. (2014), Tillig et al. (2015), Lin (2012), Wang et al. (2010), CCNR (2012), Miola et al. (2011), Wärtsila (2009), Stott and Wright (2011), Lindstad and Eskeland (2015), Ulstein (2009)	
	Lightweight materials	High strength steel, composite	0.1–22%	Buhaug et al. (2009), Faber et al. (2011), Tillig et al. (2015), Wang et al. (2010), CCNR (2012), Miola et al. (2011), Wärtsila (2009), Hertzberg (2009)	Job (2015), Sánchez-Heres (2015), Shipping and Marine (2015)
	Air lubrication	Hull air cavity lubrication	1–15%	Buhaug et al. (2009), Faber et al. (2009, 2011), Tillig et al. (2015), Wang et al. (2010), CCNR (2012), Miola et al. (2011), Wärtsila (2009), Wang and Lutsey (2013)	
	Resistance reduction devices	Other devices/retrofit to reduce resistance	2–15%	EMEC (2010), CCNR (2012), Miola et al. (2011), Wärtsila (2009)	
	Ballast water reduction	Change in design to reduce size of ballast	0–10%	Lindstad et al. (2015a), Tillig et al. (2015), Miola et al. (2011), Wärtsila (2009)	
	Hull coating	Distinct types of coating	1–10%	Buhaug et al. (2009), Faber et al. (2009, 2011), Lin (2012), Wang et al. (2010), Miola et al. (2011), Wärtsila (2009), Wang and Lutsey (2013), Maddox Consulting (2012)	
Power & propulsion system	Hybrid power/ propulsion	Hybrid electric auxiliary power and propulsion	2–45%	Lindstad et al. (2015a), Faber et al. (2011), Tillig et al. (2015), Wang et al. (2010), CCNR (2012), Wärtsila (2009), Lindstad and Sandaas (2014, 2016), Sciberras et al. (2015)	
	Power system/machinery	(Incl. e.g. variable speed electric power generation)	1–35%	Buhaug et al. (2009), Faber et al. (2011), Tillig et al. (2015), Lin (2012), Wang et al. (2010), CCNR (2012), Miola et al. (2011), Wärtsila (2009), Wang and Lutsey (2013), Maddox Consulting (2012), Baldi (2013)	Doulgeris et al. (2012), Solem et al. (2015)
	Propulsion efficiency devices		1–25%	Lindstad et al. (2015a), Buhaug et al. (2009), Faber et al. (2009, 2011), Gilbert et al. (2014), Psaraftis (2016), Tillig et al. (2015), Lin (2012), Wang et al. (2010), CCNR (2012), Wärtsila (2009), Wang and Lutsey (2013), Maddox Consulting (2012)	
	Waste heat recovery		1–20%	Lindstad et al. (2015a), Faber et al. (2009, 2011), Gilbert et al. (2014), Psaraftis (2016), Tillig et al. (2015), Lin (2012), Wang et al. (2010), EMEC (2010), CCNR (2012), Wärtsila (2009), Wang and Lutsey (2013), Maddox Consulting (2012), Baldi (2013), Future (2012), Baldi et al. (2013), Choi and Kim (2013a, 2013b), Baldi and Gabrielii (2015), Deniz (2015)	
	On board power demand	On board or auxiliary power demand (e.g. lighting)	0.1–3%	Lindstad et al. (2015a), Faber et al. (2009, 2011), Tillig et al. (2015), Wang et al. (2010), Wärtsila (2009), Wang and Lutsey (2013), Maddox Consulting (2012)	

Alternative fuels	Biofuels		25–84%	Lindstad et al. (2015a), Faber et al. (2009, 2011), Gilbert et al. (2014), Eide et al. (2013a), Wang et al. (2010), Bengtsson et al. (2012), Brynolf et al. (2014a)	Brynolf et al. (2014a, 2014b), Bengtsson (2011), Bengtsson et al. (2014), Kristensen (2012), Grahn et al. (2013), Taljegard et al. (2014)
	LNG		5–30%	Lindstad et al. (2015a), Buhaug et al. (2009), Faber et al. (2009, 2011), Gilbert et al. (2014), Psaraftis (2016), Eide et al. (2013a), Wang et al. (2010), CNSS (2011), Baldi et al. (2013), Bengtsson et al. (2012), Brynolf et al. (2014a, 2014b), Einang (2009), Seddiek (2015)	Jafarzadeh et al. (2012), AEsoy et al. (2011), Einang (2007), Chryssakis et al. (2014), Thomson et al. (2015)
Alternative energy sources	Wind power	Kite, sails/wings	1–50%	Lindstad et al. (2015a), Buhaug et al. (2009), Faber et al. (2009, 2011), Gilbert et al. (2014), Psaraftis (2016), Tillig et al. (2015), Wang et al. (2010), EMEC (2010), CNSS (2011), Wärtsila (2009), Wang and Lutsey (2013), Clauss et al. (2007), Smith et al. (2013), Traut et al. (2014), Teeter and Cleary (2014)	Nuttall (2013), B9Shipping (2016), Ecoliner (2016), SkySails (2015), Schmitz and Madlener (2015), Dadd et al. (2011)
	Fuel cells		2–20%	Lindstad et al. (2015a), Faber et al. (2009, 2011), Gilbert et al. (2014), Kotb et al. (2013)	Alvik et al. (2010), Welaya et al. (2013), Ludvigsen and Ovrum (2012)
	Cold ironing	Electricity from shore	3–10%	Lindstad et al. (2015a), Gilbert et al. (2014), Lin (2012), CCNR (2012), Miola et al. (2011), Chatzinikolaou and Ventikos (2013)	Alvik et al. (2010)
	Solar power	Solar panels on deck	0.2–12%	Lindstad et al. (2015a), Buhaug et al. (2009), Faber et al. (2009, 2011), Gilbert et al. (2014), Wang et al. (2010), CNSS (2011), Wärtsila (2009), Wang and Lutsey (2013), Sjöbom and Magnus (2014)	Qiu et al. (2015), Nuttall (2013), Cotorcea et al. (2014), Lock (2013), Glykas et al. (2010)
Operation	Speed optimization	Operational speed, reduced speed	1–60%	Lindstad et al. (2015a, 2011, 2016b, 2013b), Buhaug et al. (2009), Lindstad (2013), Faber et al. (2009, 2011, 2010), Gilbert et al. (2014), Corbett et al. (2009), Tillig et al. (2015), Lin (2012), Wang et al. (2010), CNSS (2011), CCNR (2012), Miola et al. (2011), Wärtsila (2009), Lindstad and Eskeland (2015), Wang and Lutsey (2013), Maddox Consulting (2012), Chatzinikolaou and Ventikos (2013), Norlund and Gribkovskaia (2013)	Psaraftis and Kontovas (2013), Yin et al. (2014), Woo and Moon (2014)
	Capacity utilization	At vessel and fleet level (fleet management)	5–50%	Buhaug et al. (2009), Lindstad (2013), Faber et al. (2009), Gucwa and Schäfer (2013), Lindstad et al. (2016b)	
	Voyage optimization	Advanced weather routing, route planning and voyage execution	0.1–48%	Buhaug et al. (2009), Faber et al. (2009, 2011), Wang et al. (2010), Miola et al. (2011), Wärtsila (2009), McCord et al. (1999) Lindstad et al. (2015a, 2013b), Lindstad (2013), Psaraftis (2016), Tillig et al. (2015), Lin (2012), CCNR (2012), Wang and Lutsey (2013), Maddox Consulting (2012), Johnson and Styhre (2015)	Fagerholt et al. (2009, 2010), Bausch et al. (1998), Álvarez (2009), Fagerholt (2001), Norstad et al. (2011), Kontovas (2014)
	Other operational measures	Trim/draft optimization, Energy management, Optimized maintenance	1–10%	Buhaug et al. (2009), Faber et al. (2009, 2011), Tillig et al. (2015), Lin (2012), Wang et al. (2010), CCNR (2012), Miola et al. (2011), Wärtsila (2009), Wang and Lutsey (2013), Maddox Consulting (2012), Seddiek (2015)	Johnson and Styhre (2015), Ranheim and Hallet (2010), Rialland et al. (2014), Poulsen and Sornn-Friese (2015)

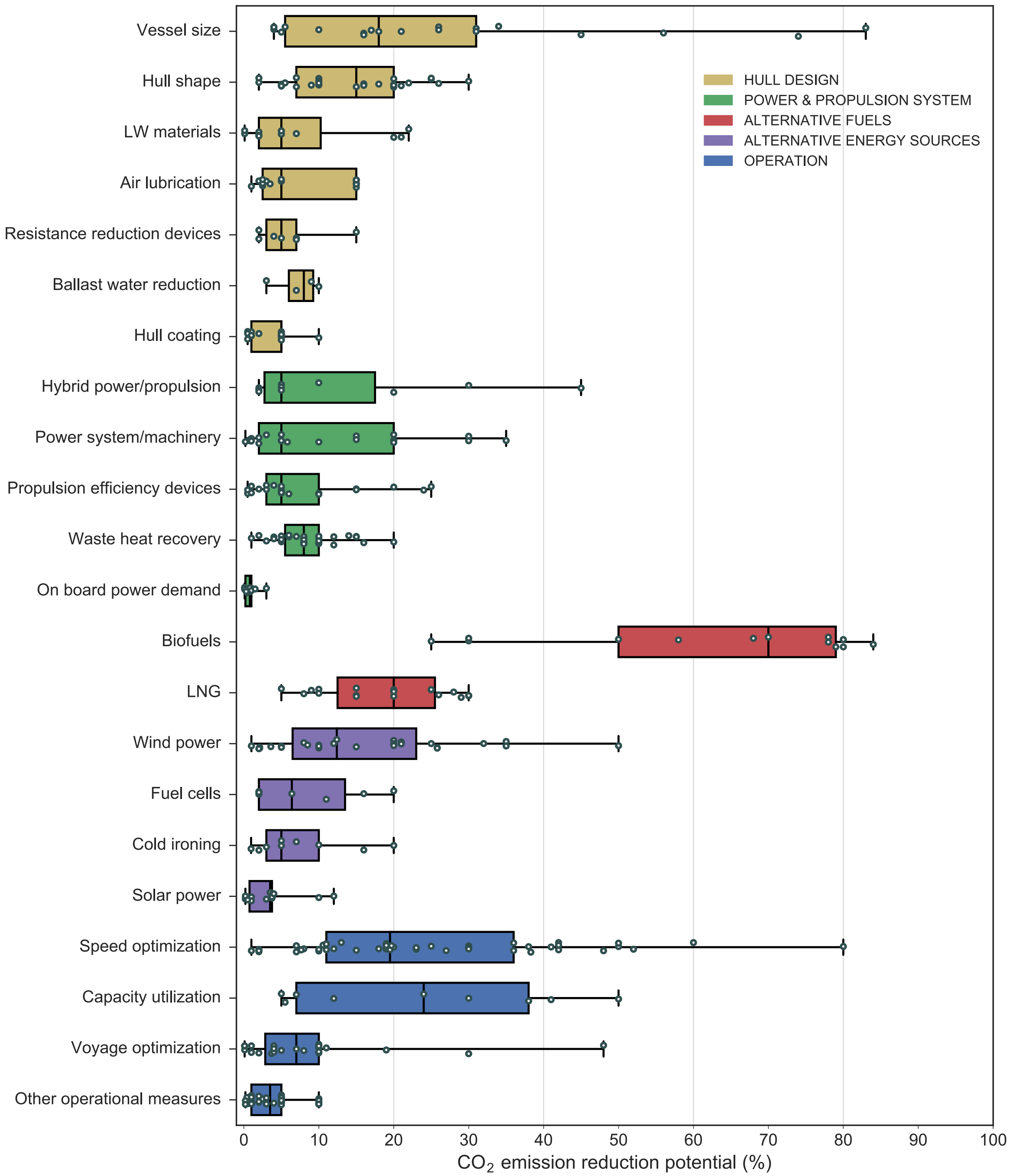

Fig. 2. CO_2 emission reduction potential from individual measures, classified in 5 main categories of measures.

of fuel cells for power generation. As an additional means of power generation, its effects might be marginal, but the question remains if a system could be designed in which most power comes from a fuel cell.

As ship resistance is directly correlated with shipping speed, it is no surprise that speed optimization is another measure where relative high reductions in fuel consumption and emissions can be achieved. However, many data points lie well beyond the 3rd quartile boundary, suggesting low agreement in the literature on the reduction potential. Capacity utilization shows a high median value, but the large range as well as relatively low amount of data points increases the uncertainty towards its potential as a reduction measure. For voyage optimization, most studies indicate a potential less than 10 percent, but few outliers report higher potentials well beyond the 3rd quartile boundary.

If all options depicted in Fig. 2 could have been combined, which is a highly theoretical exercise, the emission reductions would be over 99% based on 3rd quartile values, 96% based on the median, and 80% based on 1st quartile values. However, many of the presented options are mutually exclusive. In addition, some of the reported reduction potentials are not directly additive due to interdependency of the measures. Nonetheless, there is a large number of practical and economically feasible combinations of measures. One of these combinations would be: Vessel size; Hull shape; Ballast water reduction; Hull coating; Hybrid power/propulsion; Propulsion efficiency devices; Speed optimization and Weather routing. Assuming relatively large independence between the individual measures, combining these options can lead to emission reductions of 78% based on 3rd quartile values, 55% based on the median, and 29% based on 1st quartile values.

Introducing alternative fuels to the above combination of measures would increase the reduction potential to 67–88% and 85–96% for respectively median and 3rd quartile values, and depending on the mix between LNG and biofuels. However, the reduction potential in the use of biofuels is based on the assumption of carbon neutrality of fuel from biological origin.

In total these results indicate that there is a potential for reducing emissions by 75–85 %, i.e. a factor of 4–6 per freight unit transported, based on current technologies and based on the 3rd quartile values. If we instead use the median values, an emission reduction of between 50 and 60% per freight unit transported up to 2050 is more realistic.

4. Discussion

This study has reviewed over 150 studies to provide a comprehensive overview of the GHG emissions reduction potentials for maritime transport and measures published in literature. Its aim was to identify the most promising areas, i.e. technologies and operational practices and quantify their combined mitigation potential. A direct comparison of the results presented in the reviewed studies comes with inherent uncertainty, as methodologies across studies differ and reduction potentials are identified with respect to different baselines.

The CO_2 reduction potentials based on studies with focus on emission reduction achievable at fleet level in Section 3.1 range from 33 to 77% against a 2050 scenario baseline, indicating a high potential. Moreover, if the emission reduction is based on studies focusing on specific measures as in section 3.2, this potential increases to 80% or more based on the studies that identified the highest emission reduction potentials, i.e. 3rd quartile values. If the 3rd quartile values are replaced with the median, the reduction potential is reduced to 50% and upward per freight unit transported. These numbers are in line with a previous study by Gilbert et al. investigating the reduction potential of combined measures to decarbonize vessels. Newly built bulk carriers and tankers are quantified with a potential in the range of 81–98%, and containers ships with an even higher range of 92–98%. It should be noted, however, that upper bounds assume high reductions through use of biofuels (Gilbert et al., 2014).

Three main conclusions can be drawn: first, it is possible to reduce emissions per freight transport unit by 75% and above up to 2050. Second, reaching such a level is based on the studies that showed reduction potential in the high end, i.e. the 3rd quartile values. Third, achieving such high reduction is necessary to ensure absolute reductions in annual CO_2 emissions of the sector, as the continued future growth of maritime transport offsets the gains made in individual cases. In addition, a remaining challenge is to be able to realize the required GHG reductions, while at the same time meet customer demands and remain competitive in comparison to other transport modes, i.e. road, rail, and aviation.

CO_2 is not the only greenhouse gas emitted by the shipping sector. Surprisingly few studies focusing on GHGs cover more than carbon dioxide (Smith et al., 2014; Eide et al., 2013b; Sciberras et al., 2015; Baldi et al., 2013; Brynolf et al., 2014b; Seddiek, 2015; Paxian et al., 2010; Lack and Corbett, 2012; Ma et al., 2012). Studies considering tighter regulations of NO_x and SO_x emissions in the ECAs rarely focus on the impact on CO_2 emissions or the total GHG effect. It appears that, for most key pollutants, emissions reduction go hand in hand with reductions in CO_2 emissions, e.g. through a combination of fuel switching (i.e. to low sulphur fuel or natural gas) and abatement equipment. However, several authors report an increase in CO_2 equivalent emissions as a function of stricter NO_x and SO_x regulations (Eide et al., 2013b; Lindstad et al., 2016a, 2015b; Gilbert, 2014; Ma et al., 2012). Current regulations provide emission limits for CO_2 for its climate change effects and for NO_x and SO_x for their health and environmental effects (Eide et al., 2013b). This represents a conflict, since the NO_x and SO_x emissions that are regulated for environmental reasons tend to mitigate global warming (Lauer et al., 2007; Eyring et al., 2010), while the unregulated emissions, i.e., BC and methane, contribute to global warming (Lindstad and Sandaas, 2016; Jacobson, 2010; Bond et al., 2013; Myhre et al., 2013; Fuglestvedt et al., 2014). These effects are not captured by the current study, but do warrant further investigation.

The ranges and grouping of data points presented in Fig. 2 give an indication on the level of agreement between studies, while the total number of data points indicate the amount of evidence. Together, agreement and amount of evidence can be used to express and communicate confidence levels in a qualitative way, where the highest level of confidence is given for measures with high agreement and robust evidence (Mastrandrea et al., 2010). While reviewing a sizeable total number of studies, there are fewer articles per measure. Combined with relatively low levels of agreement between studies, this affects negatively the confidence with which high-potential measures can be selected.

Based on the above, there is a need for more transparent research that is able to address simultaneously the climate mitigation potential and other environmental issues related to international maritime transport. For example, the climate effects of a shift from HFO to LNG including the interplay between reduced SO_2 emissions, reduced CO_2 emissions, and fugitive methane emissions are not well understood. The uncertainty and variation in the mitigation options presented in the previous sections have to be reduced in order to aid the maritime community in making the best choices for sustainable development of maritime transport. Research has to address multiple aspects simultaneously in order to prevent double counting of efficiencies and measures. This allows for a closer look at both individual measures and their feasibility of application, as well as a combination of measures in hybrid solutions. In addition, expanding the scope to a wider transport network would provide a better picture of the environmental impact and potential for reduction of emissions from maritime transportation in relation to other transport modes and with regard to total impact from transport. Such a multimodal and logistics perspective has been raised by Lindstad (2013), Lindstad et al. (2016b), Bergqvist and Cullinane (2013), Cui and Li (2015), Cullinane (2014).

While the shipping sector has engaged in establishing policies to reduce emissions, the rate of implementation and level of commitment implies that it is likely that more policies and regulations are needed to achieve the high emission reductions (Lindstad, 2013; Gilbert et al., 2014). The Energy Efficiency Design Index (EEDI) from the International Maritime Organization (IMO) is one example of such legislation. The EEDI, which now is applicable for all vessels built from 2013 onwards, is an energy efficiency requirement that puts thresholds on the CO_2 emitted per ton of goods transported for a fully loaded vessel as a function of its size and its type. These threshold values will gradually become stricter and the only way to meet the requirement will be to improve the design, the power system, or through adopting low-carbon fuels. A push for tougher baselines will hence contribute to larger emission reductions.

5. Conclusion

To limit the rate of global warming the maritime sector is faced with the challenge to drastically reduce its GHG emissions in the coming decades. Sector-wide reductions are further complicated by the projected increased demand for maritime transport services. To reduce emissions, the sector has many technological and operational measures at its disposal. In this article, we extensively reviewed the literature to identify measures with high CO_2 reduction potential and quantify the range of reported reduction potentials for 22 individual measures, as well as the maximum reduction potential identified by literature describing fleet-wide reduction scenarios.

Our results indicate that no single measure is sufficient by itself to reach considerable sector-wide reductions. Though there are single measures for which high reduction potentials are reported (e.g. the use of biofuels or speed optimization), the wide range of identified potentials suggests only moderate agreement across studies. To present a more balanced analysis we focused on median and 3rd quartile values within the reviewed dataset. We identified eight measures with a 3rd quartile potential of 20% or higher, eight measures with a 3rd quartile potential between 10% and 20%, and six measures with a 3rd quartile potential of less than 10%.

Based on the reviewed studies, we conclude that a significant emission reduction over 75% is achievable by swift adoption and combination of a large number of individual dependent and independent measures. In other words, it is possible to reduce GHG emissions by a factor of 4–6 per freight unit transported with current technologies within 2050. As an example, we presented one combination of measures leading to emission reductions of 78% based on 3rd quartile values. However, many more combinations are possible and we hope that this article can act as a starting point for identifying successful combinations of emissions reduction measures.

The overall success of these emissions reductions technologies and measures is dependent on the growth rates of maritime transport. Policies, regulations, and legislation, such as the EEDI, can facilitate reduction of GHG emissions by the sector, but successful implementation has to be supported by high-quality studies addressing multiple effects and measures simultaneously in order to avoid counteracting and inefficient adoption of mitigation measures.

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