Ocean Engineering 110 (2015) 94–101

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Maritime shipping and emissions: A three-layered, damage-based approach

Haakon Lindstad [a,*], Gunnar S. Eskeland [b], Harilaos Psaraftis [c], Inge Sandaas [d], Anders H. Strømman [e]

[a] Norwegian Marine Technology Research Institute (MARINTEK), Trondheim, Norway
[b] Norwegian School of Economics (NHH) and SNF and CenSES, Bergen, Norway
[c] Technical University of Denmark, Lyngby, Denmark
[d] United European Car Carriers (UECC), Oslo, Norway
[e] Norwegian University of Science and Technology (NTNU), Trondheim, Norway

ARTICLE INFO

Article history:
Received 23 January 2015
Accepted 15 September 2015
Available online 9 October 2015

Keywords:
Shipping and environment
Abatement cost and options
Greenhouse gases
Heavy fuel oil
IMO and ECA

ABSTRACT

Policy emphasis in ship design must be shifted away from global and idealized towards regional based and realistic vessel operating conditions. The present approach to reducing shipping emissions through technical standards tends to neglect how damages and abatement opportunities vary according to location and operational conditions. Since environmental policy originates in damages relating to ecosystems and jurisdictions, a three-layered approach to vessel emissions is intuitive and practical. Here, we suggest associating damages and policies with ports, coastal areas possibly defined as Emission Control Areas (ECA) as in the North Sea and the Baltic, and open seas globally. This approach offers important practical opportunities: in ports, clean fuels or even electrification is possible; in ECAs, cleaner fuels and penalties for damaging fuels are important, but so is vessel handling, such as speeds and utilization. Globally we argue that it may be desirable to allow burning very dirty fuels at high seas, due to the cost advantages, the climate cooling benefits, and the limited ecosystem impacts. We quantify the benefits and cost savings from reforming current IMO and other approaches towards environmental management with a three-layered approach, and argue it is feasible and worth considering.

1. Introduction

The main source of emissions from sea-going vessels is the exhaust gas from burning fuel in the ship's combustion engines. Upon ignition in the engine, a mix of air and fuel releases mechanical energy which is harnessed for propulsion, and produces hot exhaust gases as a byproduct. Of these exhaust gases, carbon dioxide (CO_2) has only climate effects, while carbon monoxide (CO), sulphur oxides (SO_x), nitrogen oxides (NO_x), methane (CH_4), black carbon (BC) and organic carbon (OC) have both climate and adverse local and regional environmental impacts, e.g. on human health.

Climate impact assessments for marine transport have traditionally been based on amounts of CO_2 emitted from fuel combustion (Corbett et al., 2009; Lindstad and Mørkve, 2009; Psaraftis and Kontovas, 2010; Faber et al., 2009; Lindstad et al., 2011), while other trace emissions in the exhaust gas have been ignored (Lindstad and Sandaas, 2014). 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., 2013). 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 CH_4, contribute to global warming (Jacobson, 2010; Bond et al., 2013; Myhre and Shindell, 2013; Fuglestvedt et al., 2014; Lindstad and Sandaas, 2014). Complicating matters, emissions in one region may lead to a direct climate forcing that differs in magnitude to the same quantity emitted in another region. This is due to regional differences in sea ice extent, solar radiation, and atmospheric optical conditions (Myhre and Shindell, 2013). For example, the deposition of black carbon over highly reflective surfaces such as snow and sea ice reduces the albedo of these surfaces, thereby increasing their surface temperature. This in turn leads to increased melting and additional reductions in snow/sea ice extent and consequently further reductions in the surface albedo, i.e., it is a significant positive feedback loop (Hansen and Nazarenko, 2004; Zender, 2012; Sand et al., 2013; Jacobson, 2010; Bond et al., 2013). Region-specific global warming potential (GWP) characterizations are therefore needed to more accurately quantify the climate

* Corresponding author.
E-mail address: Haakon@marintek.sintef.no (H. Lindstad).

http://dx.doi.org/10.1016/j.oceaneng.2015.09.029
0029-8018/

impact of each emission species. Emission metrics such as GWP, or "*CO_2-equivalent emissions*," have become the common means to quantify and compare the relative and absolute climate change contributions of different emissions species (Shine, 2009). The GWP integrates radiative forcing from a pulse emission over the chosen time horizon, (Borken-Kleefeld et al., 2013). GWP is usually integrated over 20, 100 or 500 years, consistent with Houghton et al. (1990). Longer time horizons place greater weight on compounds with persistent warming (or, in the case of negative values, cooling) effect.

In response to regional and global impacts of emissions, the International Maritime Organization (IMO) is tightening the emission limits for NO_x, SO_x and CO_2 (Lindstad and Sandaas, 2014). First, IMO has defined the coastlines of North America and the North Sea and the Baltic as Emission Control Areas (ECAs). From 2015, the fuel used within these ECAs has a sulphur content restricted to a maximum of 0.1%. From 2020, the limit for fuel Sulphur content outside of ECAs will be 0.5%, down from the current limit of 3.5%. Second, the IMO requires that vessels built from 2016 onwards which operate fully or parts of their time in the North American ECA shall reduce their NO_x emissions by 75% compared to the Tier 2 present global standard for vessels built after 2011 (MARPOL Convention). Third, the energy efficiency design index (EEDI) uses a formula to evaluate the CO_2 emitted per unit of transport, with EEDI limits agreed upon for major vessel types. It is expected that these thresholds stepwise will become 30–35% stricter within the next 15–20 years (Lindstad et al., 2014).

Power generation systems for cargo vessels have generally been designed to ensure that vessels have the power necessary to be seaworthy in rough weather and also in calm water to achieve their design speed by utilizing 75–85% of the installed main engine power (Lindstad, 2013). Historically, fuel costs have been low compared to the total cost of operating the vessel. As these other costs are mostly fixed, i.e., are independent of power output and therefore sailing speed, high speed operation has generally minimized total costs per unit transport, and thus maximized profit. More recently, higher fuel prices and low freight markets have made it profitable to instead reduce fuel consumption through speed reductions (Lindstad, 2013). Since the power output required for propulsion is a function of the speed to the power of three, when a ship reduces its speed, the power required and therefore the fuel consumed per freight work unit is considerably reduced (Corbett et al., 2009; Sea at Risk and CE Delft, 2010; Psaraftis and Kontovas, 2010; Lindstad et al., 2011: Psaraftis and Kontovas, 2013). Accordingly, average operational speeds have been reduced in the later years (Smith et al., 2014) when oil prices have remained around USD 100 per barrel compared to 10–20 USD per barrel in the 1990s and early 2000s.

Since speed reduction drastically reduces power requirements, it has become common to operate from 15% to 40% of the installed power at calm to moderate sea conditions. Although low power output saves energy through the hull's resistance-to-speed relation, fuel consumption per kWh produced increases (Duran et al., 2012) due in part to incomplete combustion. In contrast, at medium to high power production, the combustion engine achieves greatest fuel efficiency and therefore has the lowest emissions per kWh. Relative to total operational costs, the increase in specific fuel consumption per kWh at lower loads makes a small impact on costs. Nevertheless, the emissions of exhaust gases such as NO_x (Duran et al., 2012; Hennie et al., 2012; Ehleskog, 2012; Lindstad and Sandaas, 2014), aerosols such as BC (Ristimaki et al., 2010; Kasper et al., 2007; Lack and Corbett, 2012), and un-combusted CH_4 (Stenersen and Nielsen, 2010; Ehleskog, 2012) increase substantially, due to less favourable combustion conditions.

From an environmental viewpoint, one of the challenges with the current IMO legislation (MARPOL Convention) is that it assumes engine performance at '*ideal lab-conditions*' at medium to high loads and calm water. In reality, vessels today operate more commonly at low to medium power, and only at high power loads in rough seas or other special conditions. As a consequence of the IMO legislation, engine manufacturers tune their engines to meet the IMO emissions standards for NO_x at high power loads, since these high loads are weighted highly in the test cycle. Such tuning generally results in higher NO_x emissions at low loads and also raises fuel consumption at low to medium loads (Hennie et al., 2012; Ehleskog, 2012). The test cycle thus places excessive emphasis on an idealized operational scenario, which results in less efficient combustion and hence higher emissions of all exhaust gases under normal operation.

An important idea is to shift the emphasis from idealized to realistic vessel operating conditions (Lindstad and Sandaas, 2014). This shift leads to a realization that vessel and engine configurations are generally environmentally inefficient in part by having insufficient flexibility. Typically, vessel engines have sub-optimal conversion of fuel to propulsion at very high or low loads and thus have excessive emissions when operating in these states. The engine load 'sweet spot', or range, will for these reasons vary somewhat depending not only on commercial and navigational aspects, but also on how various emissions species are valued and addressed in the regulatory framework. While some of these dependencies will be further developed in subsequent research motivated by this study, a perspective of multi-pollutant control and internalization of environmental externalities forms the basis of our approach (Eskeland, 1994, 1997; Eskeland and Xie, 1998).

While there is no question that SO_x and NO_x emissions must be reduced when the vessel is close to land, sensitive ecosystems and densely populated areas, the main objective of this paper is to investigate if it is possible to fulfil the requirements for reducing harmful emissions in ports and coastal areas without giving away the overall cooling effect of maritime transport. The employed model is described in Section 2, its application and data are presented in Section 3, the analysis and results in Section 4 and the results obtained are discussed in the final section with respect to their implications for policy development.

2. Methodology

We need assessment of costs, fuel consumption and emissions (see Lindstad et al., 2014) limiting our attention to the vessels and their use, excluding activities while in port. The model consists of four main equations, of which the power element describing fuel consumption is the most important. The power function (Eq. (1)) (Lewis, 1988; Lloyd, 1988; Lindstad et al., 2013) considers the power needed for still water conditions, P_s, the power required for waves, P_w, the power needed for wind, P_a, the required auxiliary power, P_{aux}, and propulsion efficiency, η. This setup is established practice (Lewis, 1988; Lloyd, 1988; Lindstad et al., 2013).

$$P_i = \frac{P_s + P_w + P_a}{\eta} + P_{aux} \tag{1}$$

Eq. (2) calculates voyage cost as a function of required power, voyage length, and vessel characteristics.

$$C = \sum_{i=0}^{n} \left(\frac{D_i}{v_i} \cdot \left((K_{fp} \cdot P_i \cdot C_{Fuel}) + \frac{TCE}{24} \right) \right) + \left(D_{lwd} \cdot \left((K_{fp} \cdot P_{aux} \cdot C_{Fuel}) + \frac{TCE}{24} \right) \right) \tag{2}$$

The first term represents cost at sea while the second term determines cost at port. During a voyage, the sea conditions will vary and this is handled by dividing each voyage into sailing sections, with a distance D_i for each sea condition influencing the vessels speed v_i and the required power P_i. The hourly fuel cost per section is given by $(K_{fp} \cdot P_i \cdot C_{Fuel})$, where K_{fp} is the fuel required per produced kWh, which is a function of engine load, and C_{Fuel} is the cost per fuel unit. In addition to fuel, the trip cost includes financial items, depreciation, and operating costs, which are expressed as Time Charter Equivalent (TCE). The second term is cost at port, where D_{lwd} is the total number of hours spent at port.

Emissions ε, per pollutant per voyage are calculated as expressed by

$$\varepsilon = \sum_{i=1}^{n} \frac{D_i \cdot P_i \cdot K_{ep}}{v_i} \tag{3}$$

Here, K_{ep} is the emission factor for the pollutant as a function of engine load. Emissions per kWh produced increase when engine load is reduced.

GWP per kWh produced and per ton transported are calculated by

$$GWP_t = \sum_{i=1}^{n} \epsilon_e \cdot GWP_{et} \tag{4}$$

Here, ε_e represents emissions of pollutant i and GWP_{et} is the GWP factor for each pollutant within the given time frame.

3. Application and data set

Currently, the IMO has defined two ECAs with the goal of reducing locally and regionally harmful emissions. These ECAs are North America (US and Canada) and Europe (North Sea and Baltic Sea). This study therefore focuses on vessels operating between Northern Europe and the eastern coast of North America, i.e., trade routes connecting ports in the two present ECA areas. This implies that the total voyage distance could range from less than 3000 to more than 5000 nautical miles (nm, where 1 nm = 1852 m), of which the voyage distance carried out within the either ECA could range from 400 nm to over 2000 nm. For example, the distance from Zebrugge in Belgium to New England is around 3000 nm, of which 400–600 nm will be within the ECA sectors. Similarly, the distance from German or Polish ports in the Baltic to U.S. East Coast ports is typically around 4000 nm, with 1000 nm falling within the ECA sectors, while the distance from the Swedish and Finnish ports in the North of Baltic to the same East Coast ports is around 5000 nm, with more than 2000 nm travelled within the ECA sectors. We have chosen here to use a total transport distance of 4000 nm, of which 1000 nm are within ECA areas as the benchmark for comparison in this study.

The vessels typically carrying out these trade routes are general cargo vessels transporting break bulk such as paper, pulp, timber, steel products, project cargo or even unitized cargo such as containers. These vessels are also smaller than those operating other deep-sea trade routes, i.e., Asia–Europe, Asia–North America, or Australia–Asia. The smaller vessel size may be attributed to a combination of smaller lot sizes, multiple port visits, transport of finished or partially fabricated goods rather than large loads of raw materials, port restrictions, and reduced cargo consolidation (Lindstad et al., 2012). The cargo-carrying capacity of these vessels ranges from 6000 to over 25,000 t. We use a general cargo vessel with 17,000 deadweight ton (dwt) as the basis for this study. This vessel has the following specifications: length of 135 m, beam 22 m, draft 10 m, main engine 7500 kW, service speed of 15 knots at 75–80% maximum continuous power (MCR) and a maximum speed fully loaded of 16 knots at calm water conditions. The typical new-build price for such a vessel is 25 MUSD. We have assumed an average capacity utilization of 60% of both volume and weight for a roundtrip voyage. Wind and weather data were simplified under the assumptions of 30% voyage time spent in 2–5 m head waves, 5% with head waves over 5 m and 65% in calm water conditions. Based on North Atlantic wind and weather data (Bales et al., 1981), it could be argued that this profile should have more time spent in rough sea conditions. We believe, however, that our assumptions are reasonable since the round-trip consideration effectively negates the increased power required in headwind conditions, as power requirements for travel in tailwinds are similar to or lower than calm water conditions.

In this study, we compare alternative engine power configurations and fuels to examine the potential for reducing harmful emissions in coastal areas and ports while limiting global warming, if not retaining the historical overall cooling effect of shipping. The traditional power setup consists of one large engine for propulsion and one or two auxiliary engines. This setup may be replaced with currently available technology in two alternative configurations. The first is a hybrid configuration consisting of multiple engines while the second alternative is an advanced engine control system that enables the main engine to operate in the ECA compliant mode in the ECA and the most energy-efficient mode outside the ECA. For both multiple-engine and advanced engine control system on a single engine, generators operating at variable engine speeds produce auxiliary electricity. In addition, both configurations use batteries for peak load shaving in order to boost power when needed and in port while idling. The main advantage with multiple-engine configurations is that the full capacity is delivered with a combination of individual engines operating in the high power zone, where fuel consumption per kWh is lowest. The combination of multiple engines with batteries for energy storage and peak shaving gives reduced environmental impact. The main advantage with an advanced engine control system on a single main engine is that the capital expenses are lower than for the multiple-engine configuration.

The fuels to be compared are heavy fuel oil (HFO—2.7%) with maximum sulphur content up to 3.5%, heavy fuel oil where the sulphur content has been reduced to 0.5% (HFO—0.5%) or marine diesel oil (MDO) with a sulphur content of 0.5%, light fuel oil (LFO) or marine gas oil (MGO) with sulphur content up to 0.1% and liquefied natural gas (LNG). HFO and LFO are used in traditional diesel engines, while LNG is used in diesel dual-fuel engines. Dual-fuel engines can operate on traditional fuels such as HFO, LFO, MGO or on LNG, where the LNG is injected at either high or low pressure. In this study, we have chosen to focus on high-pressure LNG injection systems since these engines nearly achieve complete combustion of the methane, contrasting low pressure systems that emit considerable amounts of un-combusted methane. Methane is a greenhouse gas with a global warming impact (GWP_{100}) 30 times stronger than CO_2 per gram emitted (IPCC, 2013).

Table 1 shows the emission factors, K_{ep}, in grams per kWh used for each fuel type according to the NO_x regulation the vessel must meet. “Tier 2” NO_x regulations are the established global requirements for vessels built after 2011, while “Tier 3” regulates NO_x emissions for vessels built 2016 onwards that operate fully or partly in the North American ECA. “Tier 1”, which is not shown in Table 1 are for vessels built between 2001 and 2011. A notation of “None” in the IMO Tier column indicates that the engine is optimized for minimizing fuel consumption, and therefore does not satisfy even Tier 1 requirements. For each fuel, “high” indicates emissions at medium to high engine loads, i.e., 50–90% of maximum power (MCR) and “low” indicates emissions at low engine loads, i.e., 15–30% MCR. The two bottom rows in the table show the GWP for each emitted species, respectively for a 20 and a 100-year horizon. These GWP values are the average of the following four regions: East Asia, EU plus North Africa, North America, and South Asia. Although the studied trade route occurs between only two of these regions, the average of all four of these regions is used. However, we acknowledge that climate and atmospheric science are continuously developing with figures being adjusted and refined. Positive GWP values denote emission species that have a warming effect while negative values indicate exhaust gases and aerosols that have a global cooling effect. Some of the emissions species are short-lived and thereby have climate impacts over relatively short timescales. Others, such as CO_2, have a millennial time scale. Our inclusion of global warming impacts (GWI) at both 20- and 100-year time horizons in this study enables an assessment of how time horizon influences the results.

Table 1 shows, that CO_2 and SO_x emissions per kWh at low loads are approximately 10% higher than at high loads. Furthermore, CH_4 emissions are doubled at low power for the fuel oils and increases by a factor of five in the LNG option, NO_x emissions increase by 50% at low power, and the ratio of BC emissions at low

Table 1
Emission factors in grams per kWh.

	IMO tier	CO_2	BC	CH_4	CO	N_2O	NO_x	SO_2	OC	NET GWP_{20}
Previous studies										
Buhaug et al. (2009)		595	0.067	0.06	1.4	0.02	14.8	10.3	0.2	
Peters et al. (2011)		595	0.067	0.06	1.4	0.02	14.8	10.3	0.2	
High power										
HFO—2.7% S	None	540	0.05	0.05	1	0.02	15.0	9.5	0.20	−1009
	Tier 2	570	0.05	0.05	1	0.02	12.0	10.0	0.20	−1003
HFO—0.5% S	Tier 2	570	0.05	0.05	1	0.02	12.0	2.0	0.20	98
	Tier 3	600	0.05	0.05	1	0.02	2.5	2.1	0.20	262
LFO—0.1% S	Tier 2	570	0.05	0.05	1	0.02	12.0	0.4	0.20	351
	Tier 3	600	0.05	0.05	1	0.02	2.5	0.4	0.20	529
LNG—Dual fuel HP	Tier 2	450	0.005	0.5	1	0.02	9.0	0.1	0.20	364
	Tier 3	450	0.006	0.5	1	0.02	2.5	0.1	0.20	439
Low power										
HFO—2.7% S	None	600	0.2	0.1	2	0.02	22.5	10.5	0.22	−1037
	Tier 2	630	0.2	0.1	2	0.02	18.0	11.0	0.23	−1014
HFO—0.5% S	Tier 2	630	0.2	0.1	2	0.02	18.0	2.2	0.22	228
	Tier 3	660	0.2	0.1	2	0.02	3.7	2.3	0.22	454
LFO—0.1% S	Tier 2	630	0.2	0.1	2	0.02	18.0	0.5	0.22	490
	Tier 3	660	0.2	0.1	2	0.02	3.7	0.5	0.22	743
LNG—Dual fuel HP	Tier 2	490	0.05	1.0	2	0.02	12.0	0.1	0.22	397
	Tier 3	490	0.06	1.0	2	0.02	3.7	0.1	0.22	549
GWP_{20} factors		1	1200	85	5.4	264	−15.9	−141	−240	
GWP_{100} factors		1	345	30	1.8	265	−11.6	−38	−69	

GWP factors based on World average excluding Artic: BC—Collins et al. (2013); CH_4—IPCC (2013); CO—Fry et al. (2012); N_2O—IPCC (2007); NO_x—Fry et al. (2012); SO_2—IPCC (2013); OC—IPCC (2013).

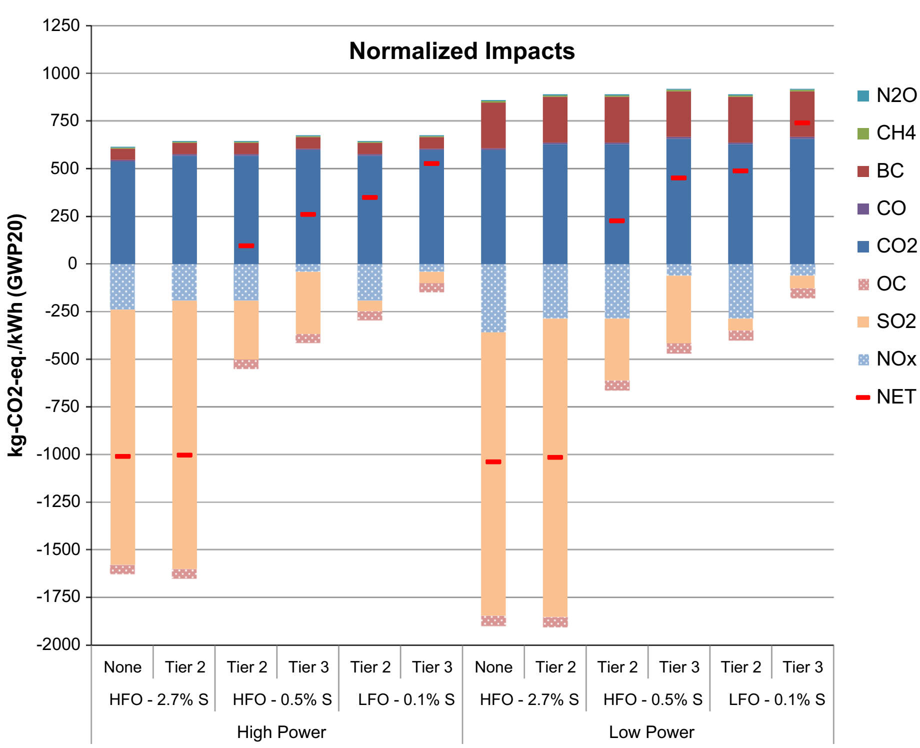

Fig. 1. Global warming impact over 20-year horizon in kg CO_2-equivalent per 1000 kWh as a function of operating power, fuel type, and NO_x regulation (Tier).

power to BC emissions at high power increases more drastically than for any other emissions species.

4. Analysis and results

We first investigate the climate impact (GWI) expressed in CO_2-equivalents, as a function of power load by combining the emissions obtained in Eq. (3) with the region-specific GWP factors, starting with a 20-year time horizon for HFO 2.7%, HFO 0.5% and LFO 0.1%, as shown in Fig. 1. The figure includes the GWI for each assessed fuel and engine technology at low and high power loads. Emissions contributing to global warming are positive values in the figure while those contributing to global cooling are negative values; the red horizontal lines denote net warming or cooling effect. Fig. 2 shows comparable results for a 100-year time horizon (GWI_{100}).

Fig. 1 shows that the warming impact (GWI_{20}) is lowest at high power loads, for all fuel and engine configurations. Beyond this, the main observations are that HFO 2.7% gives a large net cooling effect; HFO 0.5% and LFO 0.1% give a warming effect, and the stricter NO_x regulation significantly and invariably raises the warming effect.

Comparing Figs. 1 and 2, the differences between the assessed options are smaller for a 100-year time horizon. Over this longer time horizon, the impact of the CO_2 emissions becomes dominant in comparison to the shorter-lived species. Another observation is that with a 100-year horizon, the effect of HFO 2.7% goes from cooling to being neutral, the warming effect of HFO 0.5% and LFO 0.1% increases further, and the favourable role of dirty fuels is retained.

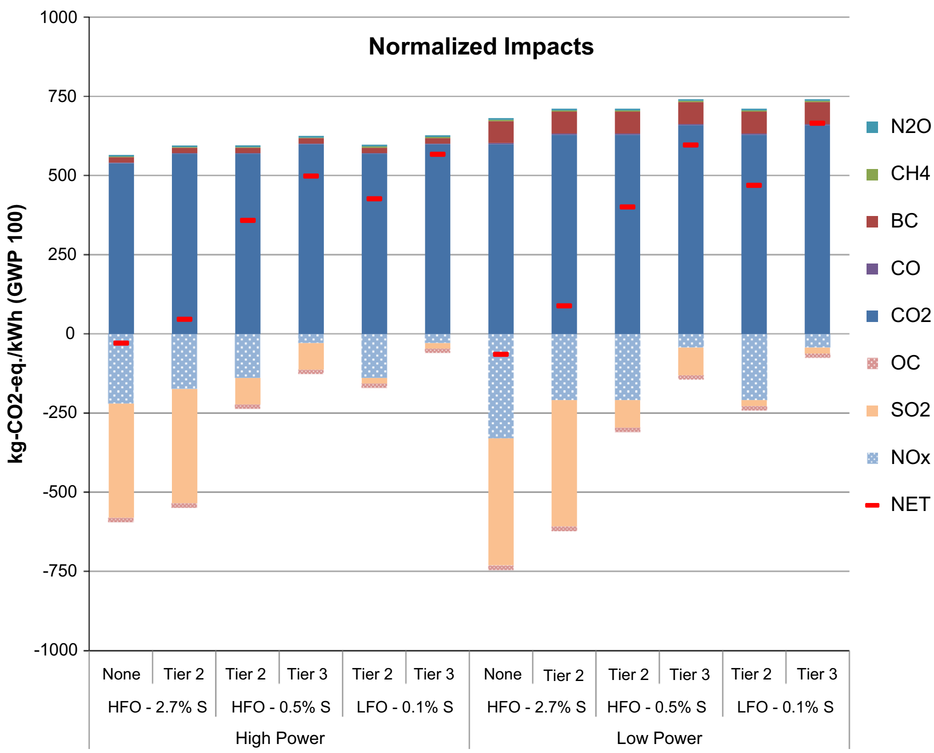

Fig. 2. Global warming impact over 100-year horizon in kg CO_2-equivalents per 1000 kWh produced as a function of operating power, fuel type, and NO_x regulation (Tier).

Table 2
Key figures for the investigated options in a 20 and a 100-year perspective.

Engine setup	Built year	Fuel	Region	NO_x tier	Fuel in ton per voyage	Annual fuel cost 2015	Fuel Cost Increase	GWI_{20} in kg per ton transported	Annual ton CO_2 eq. GWP_{20}	GWI_{100} in kg per ton transported	Annual ton CO_2 eq. GWP_{100}
Standard	2000	2.70%	Atlantic	None	156						
			ECA		51	1242 000		−1120	−22394	−43	−851
Standard	2011	2.7% 0.1%	Atlantic	Tier 2	165						
			ECA		57	1503 000	261000	−646	−12923	195	3904
Hybrid	2016	2.7% 0.1%	Atlantic	Tier 2	156						
			ECA	Tier 3	54	1422 000	180000	−726	−14523	172	3449
Standard	2016	2.7% 0.1%	Atlantic	Tier 3	173						
			ECA		57	1551 000	309000	−547	−10937	327	6547
Hybrid	2020	0.5% 0.1%	Atlantic	Tier 2	156						
			ECA	Tier 3	54	1656 000	414000	245	4897	439	8770
Hybrid	2020	LNG	Atlantic	Tier 2	156						
			ECA	Tier 3	54	1260 000	18000	418	8355	430	8595
Standard	2020	0.5% 0.1%	Atlantic	Tier 3	173						
			ECA		57	1551 000	309000	471	9425	612	12240

Fuel prices: 2.7%(HFO)=300 USD/ton; 0.5%(LFO)=375 USD/ton; 0.1(MGO)=450 USD/ton;
LNG=300 USD/ton (all fuel prices per TOE); Annual CO_2 emissions only approximately 13 000 tons.

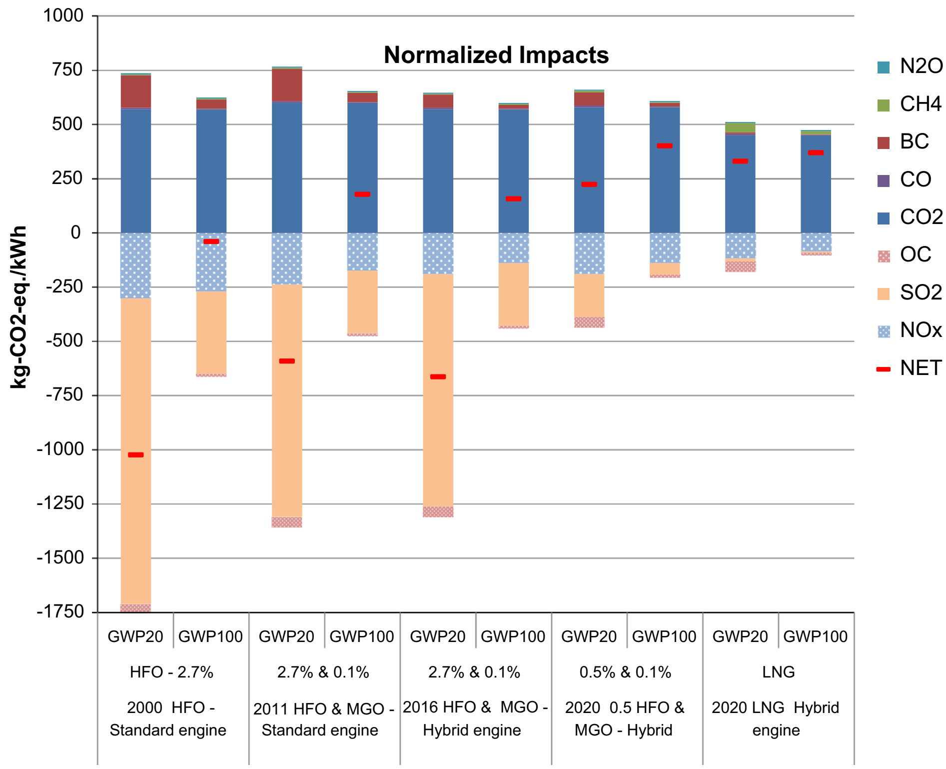

Fig. 3. Average Global warming impact over 20- and 100-year horizon in kg CO_2-equivalents per 1000 kWh for the investigated trades (25% of distance in ECA) as a function of fuel, legislation year and power setup (standard or hybrid).

From a climate change perspective, the results from both the 20- and 100-year horizons show that the reduction of SO_x and NO_x emissions through IMO legislation will have a net negative effect since sea transport sector will be contributing to global warming rather than its cooling or neutral effect before the new rules. While there is no question that SO_x and NO_x emissions must be reduced when the vessel is close to land, sensitive ecosystems and densely populated areas, one aim of this paper is to see if it is possible to fulfil the requirements for reducing harmful emissions in ports and coastal areas without giving away the overall cooling effect of maritime transport. As previously described, this may be possible by replacing the traditional power setup consisting of one large engine for propulsion and one or two auxiliary engines with one of two alternatives. The first option is a hybrid setup consisting of multiple engines while the second option is a state-of-the-art engine with an advanced engine control system. Both options enable the vessel to operate in ECA-compliant mode within the ECA, and the most energy efficient mode when outside of the ECA. In the following sections, we calculate that both options give similar benefits, however, there is a need for further investigation of their benefits and disadvantages, and their respective capex cost.

Table 2 shows the annual cost and climate impact for each of the investigated fuel and engine combinations based on 10 roundtrip voyages per year with and average sailing speed of 10–11 knots, which is typical for these vessels according to Smith et al. (2014). The first column shows engine setup, the second building year of the vessel, the third fuel type, the fourth operational region, the fifth fuel consumption per voyage outside and inside ECA, the sixth annual fuel cost based on 2015 prices, the seventh fuel cost increase compared to only HFO (2.7%) and no NO_x regulations, then follows Global warming impact per ton transported with a 20 year time horizon and annual CO_2 eq. emissions for one vessel, followed by the same figures with a 100 year time horizon.

These results indicate: First that the climate impact was lowest for the 2000 built vessels, i.e. before any NO_x or SO_x legislation was implemented; Second that continued use of HFO (2.7%) outside the ECA's and clean fuels retains a significant climate cooling effect; Third hybrid power solutions reduce fuel costs compared to standard engine setups for all investigated fuel combinations; Fourth, globally reducing maximum allowed Sulphur content to 0.5% eliminates the net cooling effects for all investigated options and the net result is a significant contribution to global warming. As an illustration, continued use of HFO 2.7% Sulphur outside of the ECA (in combination with clean fuels within the ECA), will retain the global cooling effect of shipping while satisfying the need for reduced harmful emissions close to land. We can notice that continued use of HFO (2.7%) outside the ECA gives the lowest climate impact also with the longer time perspective of GWP_{100}.

To further clarify and explain the climate consequences of the current IMO proposal, Fig. 3 shows the CO_2-equivalent emissions, now presented in average CO_2 equivalent kilograms per thousand kWh for different years and rules for NO_x and Sulphur. For the 2011 vessel, we assume 0.1% Sulphur in the ECA's, to enable a direct comparison with the 2016 vessel that in addition satisfies the Tier 3 NO_x requirements. For 2000 and 2011 vessels, performance is based on standard engines, while the 2016–2020 vessels are based on hybrid engine setups using state of the art technology to minimize fuel consumptions, emissions and environmental impact. This clearly is optimistic, but even with the best technology the figure clearly illustrates that CO_2 eq. emissions per kWh increases significantly from 2020 due to the global reduction in the Sulphur cap to 0.5%.

5. Conclusions

This study challenges the traditional environmental regulations approach for shipping activities. We investigate the possibility of fulfilling the requirements for low levels of harmful emissions in ports and coastal areas without sacrificing the benefits at high seas of low cost bunker oil and its overall climate cooling effect. Continued use of HFO 2.7% Sulphur outside of the ECA in combination with clean fuels within the ECA is indicated both to retain the global cooling effect of shipping and to reduce harmful emissions close to land.

This indicates that IMO and other authorities should reconsider decisions to globally reduce allowable Sulphur content in fuels from 3.5% to 0.5% by 2020. Burning dirty fuels at high seas in an engine optimized for fuel economy (hence also raising the NOs), gives climate cooling benefits, and this more than compensate for the warming effect of reducing harmful SO_x and NO_x emissions close to land and human populations. Another problem with the IMO approach is that engines tuned to comply with ECA emission restrictions risk increasing greenhouse gas emissions, perhaps an irony of placing a 'local first' focus on environmental regulations. In addition, this study indicates that hybrid power setups give lower environmental impact than the standard engine solutions and a lower annual fuel bill. However at current fuel prices, which are 50% of the 2012–2014 average, the economic argument for investing in more advanced engine solutions weakens. One potential incentive to be considered forward is that vessels burning fuels with high Sulphur content beyond 2020 have to install either hybrid engine systems or advanced engine control systems linked to verifiable automatic reporting systems to ensure that the dirty fuel is burned only at high seas, and that the vessel complies with SO_x and NO_x obligations in the current and future ECAs. Implementation of such systems currently is entirely feasible technically.

We hope this study contributes to a discussion of how environmental policies in the marine transport industry can best move forward.

Acknowledgements

This study has been financed by the Norwegian Research Council (Grant no. 239113) through the *Hybrid and other configurations for environmentally friendly transport* project.

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