Transport Policy 45 (2016) 24–30

Contents lists available at ScienceDirect

Transport Policy

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

Economic savings linked to future Arctic shipping trade are at odds with climate change mitigation

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ARTICLE INFO

Article history:
Received 12 March 2015
Received in revised form
25 June 2015
Accepted 4 September 2015
Available online 20 September 2015

Keywords:
Arctic
Shipping and environment
Greenhouse gases
Emissions
GWP
IMO

ABSTRACT

This paper assesses costs, emissions, and climate impact by freight shipping in the Arctic with main focus on the Northern Sea Route. The entire route lies in Arctic waters, which due to global warming, has become ice free during summer and autumn. The route goes from the Atlantic Ocean to the Pacific Ocean along the Russian Arctic coast and reduces voyage distance by 40% between Northern Europe and Japan. Traditionally, comparisons of the climate impact of transport solutions have been based on fuel consumption and carbon dioxide (CO_2), while other trace emissions in the exhaust gas have been ignored. It is becoming increasingly well-known however, that aerosols, and their precursors emitted from shipping are strong climate forcers, with a magnitude that is intimately connected to the specific region of emission. Taking into account these considerations, we apply region-specific Global Warming Potential (GWP) characterization factors to estimate the relative magnitude of the short-lived climate forcers in the Arctic compared to traditional shipping regions and to the impact of CO_2 emissions in light of reduced overall fuel consumption. The results indicate that there are no general climate benefits of utilizing the Northern Sea Route, even with cleaner fuels, since the additional impact of emissions in the Arctic more than offsets the effect of shorter voyages. In terms of climate change mitigation, managing this trade-off will be challenging, as the Northern Sea Route offers cost savings per ton of freight transported.

1. Introduction

The Arctic is characterized as an area where cold climate and elements like ice, darkness and polar lows provide a rough environment. For thousands of years it was an environment left nearly undisturbed by human activities. More recently, global warming has made a larger part of the Arctic ice-free during the summer months. Fig. 1 shows the area covered by sea ice in March 2012 (left) compared to the ice cover in September 2012 (right), where the magenta line illustrates the median sea ice extend in each of these months from 1979 to 2000. March represents here the month with the largest sea ice extent, i.e. 15 million km^2 and September the month with the smallest ice extent, i.e. 7 million km^2.

The main observation from Fig. 1 is that the area covered by sea ice in September 2012 is reduced by nearly 50% compared to the median for September, i.e. from 7.0 to 3.6 million km^2, which represented a record low ice cover. One year later, i.e. in September 2013 the sea ice cover was 5.0 million km^2 (Bond, 2013). Despite this increase from 2012, the overall trend is that the area covered by sea ice during summer months decreases. The explanation is that higher Arctic sea surface temperatures due to global warming is leading to less sea ice (area extent) during summer months, a time when solar intensity strengthens at Northern latitudes further accelerate the rate of sea ice loss, as more solar energy is absorbed in what are termed rapid feedback by Hansen and Nazarenko (2004). This means that the amount of multiyear sea ice is decreasing, and that an increasing share of the winter sea ice now consists of first year ice, which is thinner than the multiyear sea ice.

If this decrease in sea ice cover continues, we could within the next few decades get three main Arctic sea routes (Rodrigue et al., 2013; Østreng et al., 2013). The first of these is the Northern Sea Route (NSR), which is likely to be ice free first. The route goes from the Atlantic Ocean to the Pacific Ocean along the Russian Arctic coast and reduces voyage distance by around 40% between North of Europe and Japan, i.e. 6–8000 nm, compared to 11–13000 nm through the Suez Canal. The term "ice free" refers to absence of continuous sea ice cover, but part of the voyage will still go through areas with broken sea ice cover of varying density which may require appropriately strengthened hulls and ice breaker support for safe passage. The total number of recorded vessels

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http://dx.doi.org/10.1016/j.tranpol.2015.09.002
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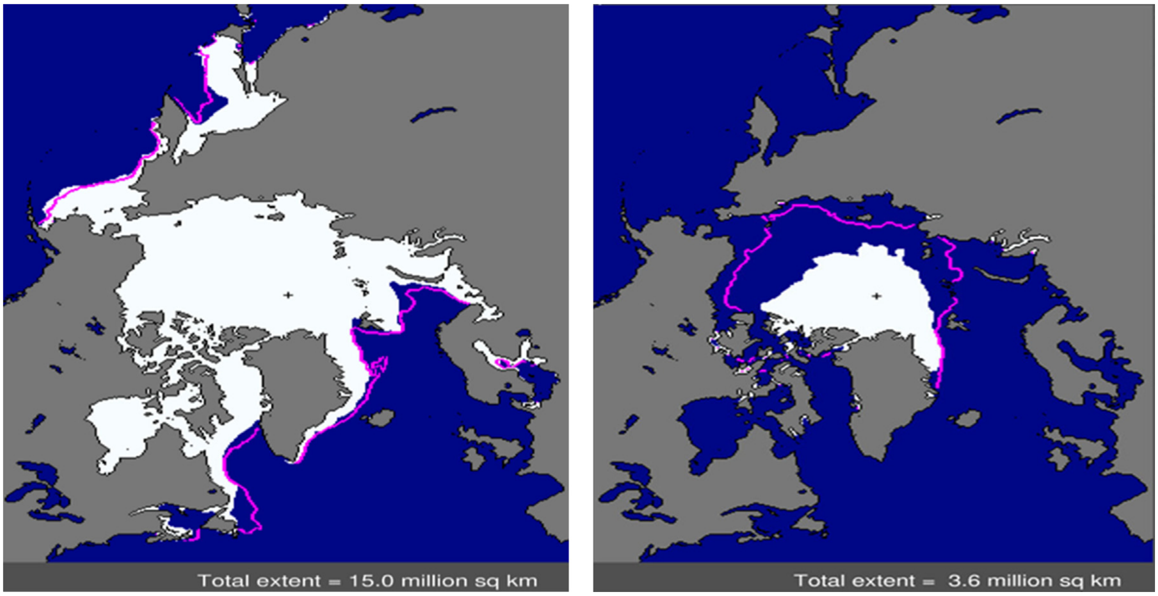

Fig. 1. Total sea ice extent in March (left) and September, 2012 (right). Magenta lines represent the median extent from 1979–2000. (National Snow and Sea ice Data center Boulder, 2012).

passing through the Northern Sea Route was 4, 41, 46, and 71 in 2010, 2011, 2012 and 2013, respectively; the prediction is that this growth in traffic will continue. The second is the Northwest Passage, which might become usable on a regular basis by 2020–2025. The third is the Central Arctic Sea Route, which goes across the Arctic Ocean and links the Bering Strait to the Atlantic Ocean.

Ships emit both to air and sea, and the main source of these emissions is the exhaust gas from fuel combustion in the ships engines. The basic principle of a combustion engine is to compress a large amount of air and mix it with a small amount of fuel. When this mix is ignited it gives mechanical energy transferred through the shaft and hot exhaust gases. Besides CO_2, the gaseous effluent contains: Carbon monoxide (CO), Sulfur oxides (SO_x), nitrogen oxides (NO_x), methane (CH_4), black carbon (BC) and organic carbon (OC). These substances does not only affect climate, but also have adverse health and nature impacts (MARPOL Convention,1973). At medium to high power the combustion engine produces each kWh with the lowest fuel consumption and the lowest emissions. When engines operate at low power, fuel consumption per kWh produced increases.

The emitted CO_2 is a function of the carbon content in the fuel. The emitted SO_x are a function of the Sulfur content in the fuel. The emitted NO_x is a function of fuel type, engine technology, and the engine load relative to its rated power, with the highest emission per kWh at low power (Lindstad and Sandaas, 2014). The emitted BC, formed by incomplete combustion of fossil fuels, is a function of the engine load relative to its rated power, where the BC levels measured per kWh produced are lowest at high power (Kasper et al., 2007; Ristimaki et al., 2010). When power is reduced, BC increases, and at low load it might be 4 to 8 times higher per kWh compared to high loads (Lack and Corbett, 2012). For vessels that use liquid natural gas (LNG) or gas in general as a fuel, leakage of un-combusted CH_4 is a challenge. This leakage, measured in grams per kWh, is lowest at high power and increases at low power (Stenersen and Nielsen, 2010).

Traditionally, assessment of environmental performance of marine transport and ships has been based on fuel consumption converted to amount of CO_2 (Buhaug et al., 2009; Corbet et al., 2009; Lindstad and Mørkve, 2009; Psaraftis et al., 2010; Lindstad et al., 2011), while other trace emissions in the exhaust gas have been ignored (Lindstad and Sandaas, 2014). Current emission regulations provide limits for SO_x and NO_x for health and environmental reasons (MARPOL Convention, 1973) and for CO_2 to mitigate global warming (Eide et al., 2013). Counter-intuitively, the NO_x and the SO_x emissions from ships mitigate global warming (Lauer et al., 2007; Eyring et al., 2009) while the unregulated emissions, i.e. BC and CH_4, contribute to global warming (IPPC, 2013). An emission in one region may lead to a direct climate forcing that differs in magnitude to the same quantity emitted in another region due to regional differences in sea ice extent, solar radiation, and atmospheric optical conditions (Myhre and Shindell, 2013).

Climate (Radiative) forcing is the difference of insolation (sunlight) absorbed by the Earth and energy radiated back to space. A positive forcing, i.e. more incoming energy warms the system, while negative forcing cools it. To give an example, the deposition of black carbon over highly reflective surfaces, such as snow and sea ice, reduces its albedo and increases its surface temperature, leading to additional reductions in snow/sea ice extent from enhanced melting and thus additional reductions in the surface albedo (Zender, 2012; Flanner, 2013; Sand et al., 2013; Jacobson, 2010; Bond et al., 2013) Snow and sea ice in extra-tropical alpine, tundra, and the Polar region are therefore essential modulators of Earth's energy balance and global mean surface temperature (Alley et al., 2003; Anderson and Bows, 2008; Lenton et al., 2008; Boé et al., 2009; Anderson and Bows, 2011; Betts et al., 2011; New et al., 2011). Since the impact of each emission species depends strongly on where a vessel operates, region-specific Global Warming Potential (GWP) characterizations are needed to more accurately quantify the climate impact of each emission species. Emission metrics such as GWP, with emission impacts expressed as "CO_2 *equivalents*" have become the common currency to benchmark and communicate the relative and absolute contributions to climate change of emissions of different substances (Shine, 2009). Negative values are used for exhaust gases and particles that have a cooling effect and that positive figures are used for those that have a warming effect. Some of the emission gases are short-lived climate forcers and impact climate over relatively short timescales. Others such as CO_2 have a millennial timescale. The GWP integrates (adds up) radiative forcing from a pulse up to the chosen time horizon which in a sense constitutes a memory of the earlier short lived forces (Borken-Kleefeld et al., 2013). GWP is usually integrated over 20, 100 or 500 years consistent with Houghton et al. (1990), with the latter lending greater weight to the compounds with longer lasting warming effect, or if negative, cooling effect.

Shorter transport distance is one of the drivers for utilizing Arctic routes, while exploration of oil and gas and other valuable minerals in the Arctic area is another. In theory, shorter transport distances reduce freight emissions from shipping, but in reality it is more complicated: First, vessels which can be utilized in these trades are generally smaller than vessels used on the traditional routes through open sea, which implies that additional voyages are required to transport the same yearly tonnage; Second, there will be some remaining sea ice which will increase the power requirement; Third, the challenge with increased shipping traffic in the Arctic is not the amount of emissions emitted in percent of global emissions, but that it is emitted in sensitive areas prone to large impact (Corbett et al., 2010; Fuglestvedt et al., 2014).

The aims of this analysis is therefore to comprehensively compare and assess costs, emissions, and climate impacts connected to trade via the Northern Sea Route versus trades through Indian Ocean and Suez Canal per ton of freight transported. First, the required power is calculated as a function of vessel speed, hull, propeller, sea states, and sea ice conditions for both routes; Second, the costs are calculated; Third, the emissions as a function of power and vessel size is calculated for both routes; Fourth, region-specific Global Warming Potentials (GWP) characterizations are applied to compare the impact of the emissions for the two trading routes; Fifth, the main results and recommendations is summarized in a concluding section.

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, not including port side consequences. The model consists of four main equations: The first describes the power requirement as a function of vessel speed, hull, propeller, sea states, and sea ice conditions; The second describes cost per voyage as a function of required power, voyage length, and vessel characteristics; The third describes the emissions per pollutant per voyage as a function of engine technology, fuel type and fuel consumption; The fourth describes the climate impact for the given time frame as a function of the emissions per pollutant and where they are emitted.

The power model takes into account propeller efficiency η, the power needed for still water conditions P_s, the additional power required for waves P_w, the power needed for wind P_a, the power needed for sea ice P_{ice}, and the necessary auxiliary power P_{aux}, as a function of a vessel's speed and cargo vessel load. This setup is established practice (Lewis, 1988; Lloyd, 1998; Lindstad et al., 2013a, 2014).

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

The cost per voyage comprises the fuel cost and time charter cost (TC) which covers the financial items, depreciation, and operating cost of the vessel, as expressed by Eq. (2):

$$\begin{aligned} C = \downarrow \sum_{i=0}^{n} \left(\frac{D_i}{v_i} \cdot \left(\left(K_{fp} \cdot P_i \cdot C_{\text{Fuel}} \right) + \frac{Capexv_{k_1 k_2}}{24} \right) \right) \\ + \left(D_{lwd} \cdot \left(\left(K_{fp} \cdot P_{aux} \cdot C_{\text{Fuel}} \right) + \frac{Capexv_{k_1 k_2}}{24} \right) \right) \end{aligned} \tag{2}$$

The first term is cost at sea; the second is cost in ports. Sea and ice conditions will vary, handled by sailing sections, each with distance D_i and speed v_i for different sea and ice conditions summing sections from 0 to n. The (D_i/v_i) gives the hours in each section of the voyage. The hourly fuel cost per section is given by $(K_{fp} \cdot P_i \cdot C_{\text{Fuel}})$; where K_{fp} is the fuel required per produced kWh as a function of engine load, P_i is power required, and C_{Fuel} is the cost per fuel unit. In addition to fuel, the cost of operating a vessel comprises financial items, depreciation, and operating cost expressed as $Capexv_{k1k2}$. Here, $Capexv$ is the new-building price of the vessel, k_1 of $Capexv$ gives the daily fixed and variable cost as a percentage of capex and k_2 gives the daily basic fixed amount which is independent of vessel size and its new-building cost. The second term calculates cost in ports for loading, discharging, and waiting based on total days used D_{lwd}.

The emissions ε per pollutant per voyage are calculated as expressed by Eq. (3):

$$\varepsilon = \sum_{i=0}^{n} \frac{D_i \cdot P_i \cdot K_{ep}}{v_i} \tag{3}$$

here K_{ep} is the emission factor for the pollutant as a function of engine load. The relationship to engine load is that emissions per kWh produced increases when engine load is reduced (Lindstad and Sandaas, 2014).

The Global Warming Potential (GWP) for the given time frame per kWh produced and per ton transported per voyage expressed as CO_2 equivalents is calculated by Eq. (4):

$$GWP_t = \sum_{i=0}^{n} \varepsilon_i \cdot GWP_{et} \tag{4}$$

Here, ε_i is emission per pollutant and GWP_{et} is the Global Warming Potential factor for each pollutant for the given time frame.

2.1. Data set

In this study we focus on dry bulk vessels. The explanation is that the dry bulkers perform 40% of total world sea freight work (Lindstad et al., 2012) and a large share of the vessels which have passed through the North East Sea Route since 2010. The main commodities transported by dry bulkers are: Iron ore, coal, grain, fertilizer, alumina, aggregates, and other minerals. A typical small dry bulker will have a dead weight (dwt) of 20–25000 ton, where dwt expresses the maximum amount of cargo the vessel can carry, while the largest ones has dead weight of up to 400,000 ton. Table 1, based on Lindstad et al. (2014) presents the characteristics of typical Panamax and Capesize vessels which are used in trades between Asia and Europe.

In this study we have assumed equal operational profiles and 50/50 between loaded and ballast sailings (Lindstad et al., 2012, 2013a). This implies that the vessels either will go back empty or be ballasted a similar distance to be loaded again and in both cases, our cost figures includes loading and discharging. For wind and weather patterns we use a simplified model containing 30% with 4 m head waves and 70% in calm water (Lindstad et al., 2013b, 2014). The wind speed u_a is taken as zero in calm water and 14 m/s in the 4 m head waves condition, rewarding performance in rougher sea without neglecting calm sea performance.

In a good freight market, i.e. where the revenues are significantly higher than the cost of operating the vessels, the owners would operate these vessels at 85–90% of full power which would give an average speed of 13 knots (Lindstad, 2015). However, in today's market with overcapacity, lower freight rates, and high fuel costs, 10–11 knots will be a more typical average speed (Smith et al., 2014). With calm water, 10 knots speed implies that the required power is less than 30% of max continuous power (Lindstad, 2015). With rougher sea, i.e. 30% of the time, higher power

Table 1
Main characteristics of dry bulk vessels.

	Panamax	Capesize
Length-lpp (m)	220.0	287.0
Beam (m)	32.3	45.0
Draft (m)	14.5	18.2
Displacement (ton)	92000	203000
Dead weight (ton)	80000	180000
Installed power (kW)	10500	16500
Block coefficient	0.87	0.84
Design speed	15	15
Newbuilding cost (MUSD)	30	50

will be required to achieve 10 knots speed. Roughly speaking, this implies that half of the fuel consumption will be emitted at low power and the other half at high power. Regarding sea ice conditions, part of the voyage through NSR will go through areas with broken sea ice cover of varying density which increases power consumption compared to still water conditions. In addition vessels will generally have to wait for sea icebreakers to lead the vessels through some parts of the Northern Sea Route; one week (7 days) is therefore added to the roundtrip time.

Historically, large seagoing vessels have used heavy fuel oil with a sulfur content of up to 3.5% while smaller vessels have used distillates with sulfur content of up to 1.0%. Increased environmental concern in recent years has challenged this practice. The International Maritime Organization (IMO) has approved regulations which limit the maximum Sulfur content to 0.1% for fuel used in Emission Control Areas (ECA) such as North Sea and the Baltic beginning in 2015. The rules also limit the maximum sulfur content to 0.5% globally from 2020. The higher sulfur fuels can continue to be used if engine exhaust is treated by scrubbers which reduce the SO_x in the exhaust gas to specified limits. In this study we focus on three fuel alternatives: Light Fuel Oil (LFO), i.e. a heavy fuel oil where the sulfur content has been reduced from 2.7% to 0.5%; Marine gas oil (MGO) with a sulfur content up to 0.1% and Liquid Natural Gas (LNG) with a sulfur content of less than 0.01%, which both satisfies the requirements for operations in ECAs after 2015; LFO and MGO are used in traditional diesel engines while LNG is burnt in diesel dual fuel engines. Dual fuel means that the engine can run on traditional fuel such as LFO or MGO in addition to LNG, where the LNG is injected either at high or low pressure. In this study only high pressure LNG dual fuel engines is considered, since these engines burns nearly all the methane gas. In combination with exhaust gas recirculation (EGR) the high pressure dual fuel engine satisfies the requirement for the 75% reduction of NO_x from new-built vessels from 2016 which shall operate in Canadian or US waters, i.e. IMO Tier III. 600 USD per ton is used as a fuel cost, and the daily time charter cost (TC) is based on 2014 newbuilding prices with $Capexv_{k_1}=9\%$ and $Capexv_{k_2}=3000$ USD per day. For a Panamax with a new building price of 30 million USD, this gives a daily cost of 10,500 USD. For a Capesize which has more than twice the carrying capacity of the Panamax, i.e. 180,000–210,000 ton and a new-building price of 50 million USD, this gives a daily cost of 15,300 USD. Presently, Capesize vessels are not used in NSR trades due to their size and sea draft. This implies that the economy of scale effect by employing larger vessels, i.e. Capesize instead of Panamax is only available for trades through Suez Canal. It should here be noted that these new-building cost and daily time charter cost are based on traditional diesel engines and the use of LFO or MGO. For LNG there will be an additional new building cost of 8–10 MUSD (Lindstad et al., 2015), due to the more advanced engine and the expensive storage and handling system which is required for storage of the required amount of LNG bunker. This implies that the energy equivalent price per ton of LNG has to be lower than the price of the traditional diesel based fuels if the LNG option shall be a commercially viable option.

Table 2 presents the emission factors, K_{ep}, in grams per kWh used in this study for each of the fuels and the values used by previous studies of shipping emissions (Buhaug et al., 2009; Corbett et al., 2010; Peters et al., 2011). For each fuel option, "high" indicates emissions at medium to high power, i.e. from 50% upwards and "low" indicates emissions at low engine loads, i.e. from 35% downwards. It should be noted that in the three previous studies the Sulfur values is based on heavy fuel oil with a Sulfur content of 2.7% while in this study the highest content is 0.5% in the LFO.

Table 2 presents that CO_2 and SO_x emissions at low loads are around 10% higher than at high loads; CH_4 emissions are generally doubled at low power; NO_x emissions increase 50% to 100% at low power; the ratio of BC emissions at low power to BC emissions at high power is greater than for any other emission species.

Table 3 presents the GWP values (IPCC, 2013) for each of the emission species for the world and for the Arctic. The world figures are the average for the four regions: East Asia; EU plus North Africa; North America; and South Asia. Negative values are used for exhaust gases and aerosols that have a cooling effect, and that positive figures are used for those which have a warming effect. Some of the emission species are short-lived climate forcers and impact climate over relatively short timescales. Others, such as CO_2, have a millennial timescale and we have therefore chosen to calculate with both a 20 year time horizon and a 100 year time horizon.

3. Results and discussion

We first investigated the climate impact as a function of power load by combining the emissions obtained by Eq. (3) with the region specific GWP factors presented in Table 3, starting with a 20 year time horizon. Assessments based on the 20 year time horizon

Table 2
Emission factors in gram per kWh.

Power production	Buhaug et al. (2009)	Corbett et al. (2010)	Peters et al. (2011)	Light fuel oil – LFO 0.5% Sulfur		Marine gas oil – MGO 0.1% Sulfur		LNG – High pressure dual fuel engine	
Poluttant				High	Low	High	Low	High	Low
CO_2	595	609	595	570	630	570	630	430	480
CH_4	0.06		0.06	0.05	0.10	0.05	0.10	0.20	1.00
N_2O	0.02		0.02	0.02	0.02	0.02	0.02	0.02	0.02
SO_x	10.3	10.3	10.3	2.2	2.4	0.45	0.50	0.10	0.40
NO_x	14.8	14.8	14.8	12.0	18.0	12.0	18.0	2.00	4.00
CO	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
BC	0.067	0.067	0.067	0.050	0.200	0.025	0.150	0.005	0.050
OC	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Table 3
Global Warming Potential (kg-CO_2-equivalents/kg emission).

Emission type	CO_2	BC	CH_4	CO	N_2O	NO_x	SO_2	OC
GWP_{20} world factors	1	1200	85	5.4	264	−15.9	−141	−240
GWP_{20} Arctic factors	1	6200	85	5.4	264	−31	−47	−151
GWP_{100} world factors	1	345	30	1.8	265	−11.6	−38	−69
GWP_{100} Arctic factors	1	1700	30	1.8	265	−25	−13	−43

Negative values shown in Table 3 have a cooling effect and positive has a warming effect.

is most relevant if the focus is on identifying fuels and technologies which give the largest reduction in climate impact within the next decades. This is also consistent with policies focusing on the need for a reduction in GHG emissions of around 50–85% in 2050, compared to current levels to achieve a stabilization of the temperature at 2 °C above pre-industrial levels (IPCC, 2013). Fig. 2 shows the climate impact with a 20 year horizon when operating in the Arctic and when operating in the rest of the world at high and low power. Here the CO_2 equivalent impact is shown vertically for each of the assessed fuel and engine technologies at low and high power shown horizontally. Emissions which contribute to warming are grouped above the zero line and those which contribute to cooling are below the line with the net effect of warming and cooling emissions shown as the red horizontal line.

In general, Fig. 2 shows that the climate impact is lowest per kWh at high power for all fuel and engine options. At low power, the increase in climate impact is much larger in Arctic than in non-Arctic areas. In non-Arctic areas, LFO has the lowest net impact of all of the assessed options both at high and low power, due to the cooling effect of the emitted sulfur and nitrogen oxides. In Arctic areas the MGO has the lowest impact at high power while the High Pressure LNG solution has the lowest warming impact at low power. Fig. 3 shows the climate impact with a 100 year horizon when operating in the Arctic and when operating in the rest of the world at high and low power.

Comparing Fig. 3 with Fig. 2 shows that there is a much larger difference between the assessed options with a 20 year time horizon compared to a 100 year time horizon. The explanation is that with a longer time horizon, the impact of the CO_2 emissions becomes the dominant warming mechanism relative to the shorter-lived (in atmosphere) emission species. This implies that if we compare trades through Northern Sea Route with trades through Suez Canal based on a 100 year horizon, the large difference in distance will result in a smaller impact of NSR. However, since we might be close to an Arctic tipping point (Lenton et al., 2008; Boé et al., 2009) there are good arguments for making such assessment based on a much shorter time horizon, i.e. the 20 year impact. In Fig. 4 we compare trades through Suez with trades through Northern Sea Route (NSR) with trades through Suez based on equal vessel sizes, i.e. using Panamax dry bulkers in both trades for each of the fuel options.

The figure shows that Northern Sea Route (NSR) gives the lowest cost, i.e. 18 USD per ton of goods transported versus 29 USD per ton transported through the Suez Canal. NSR also gives the lowest CO_2 only emissions, i.e. the marine blue area in each of the bars, per ton transported. However, if the comparison instead is done based on CO_2 equivalents (GWP_{20}), the climate impact for per ton transported through Suez is lower than when using the NSR for all the investigated fuels. For LFO used in Suez trades the impact is 20 kg-CO_2-eq. per ton transported as shown by the red net line compared to a climate impact of 65 kg-CO_2 eq. in trades through NSR; Switching fuel from LFO to LNG in NSR trades reduces the climate impact of the NSR trade to 40 kg-CO_2 eq. which still is twice the impact level of using LFO in Suez trades measured per ton transported.

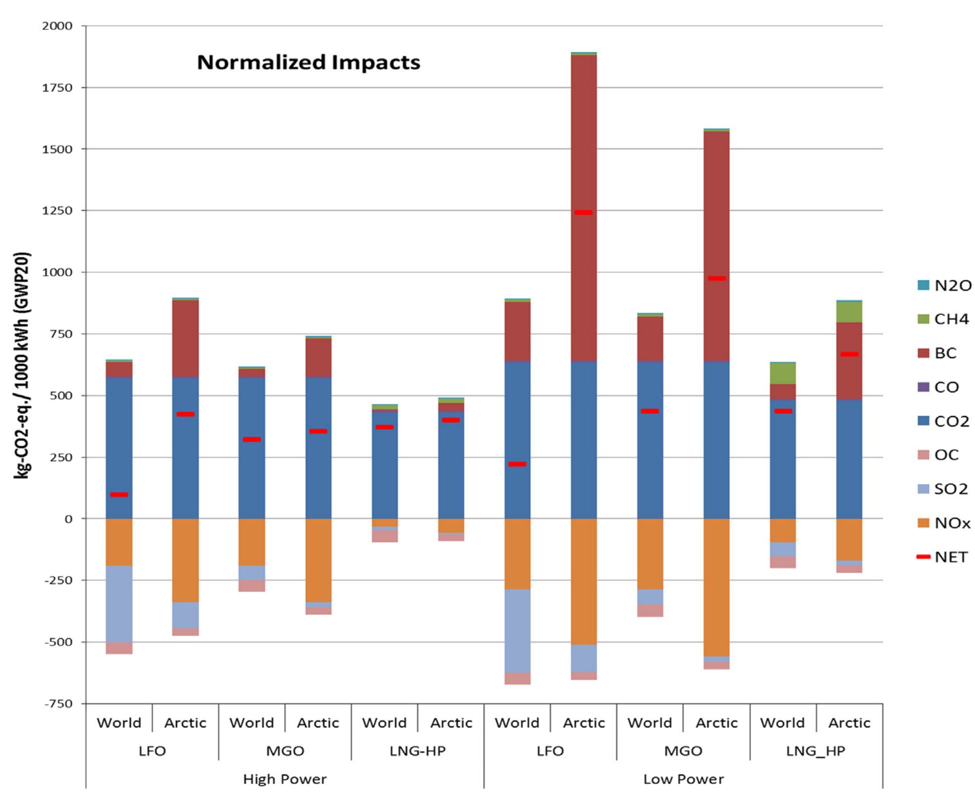

Fig. 2. Kg CO_2 eq. impact per 1000 kWh with a 20 year time horizon (GWP_{20}) as a function of power, fuel, and operational area.

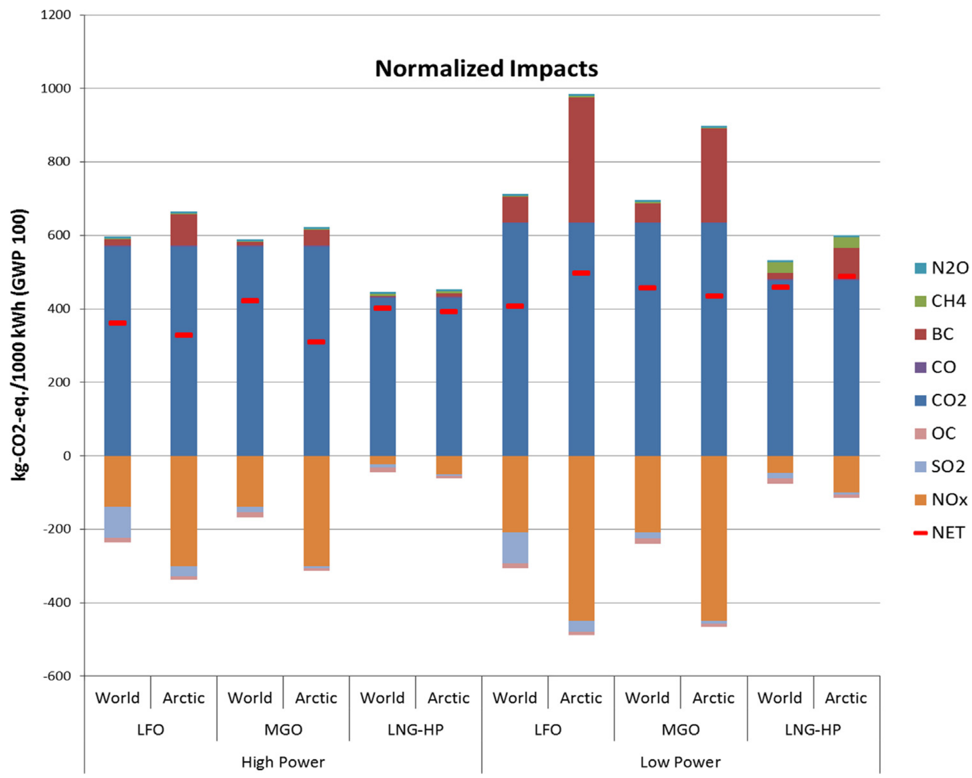

Fig. 3. Kg CO_2 eq. impact per 1000 kW h with a 100 year time horizon (GWP_{100}) as a function of power, fuel, and operational area.

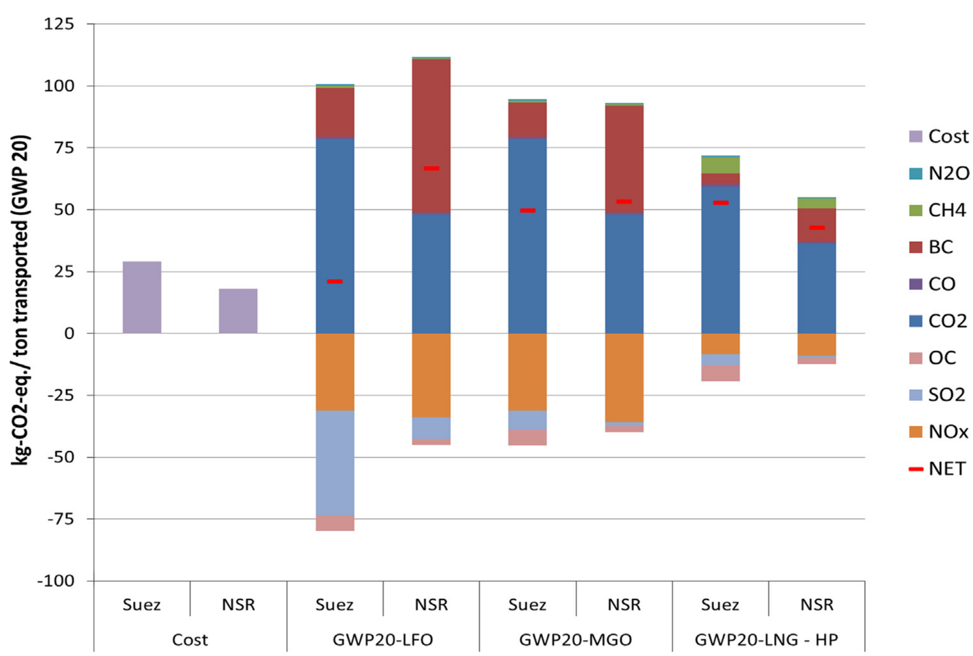

Fig. 4. Cost and kg CO_2 equivalent (GWP_{20}) per ton transported per fuel type for Suez versus NSR trades.

4. Conclusions

The main objective of this study has been to assess costs, emissions, and climate impact of trade by Northern Sea Route between Northern Pacific and Europe. Based on our analysis, the following conclusions are drawn: First, the GWP approach results in a larger differentiation between the alternative options than the CO_2 only approach; Second, the GWP approach gives the opportunity to model the real impact of reduced operational speeds, i.e. low power operations; Third, the GWP approach enables modeling the impact of various options as a function of chosen technologies and fuels in sensitive areas such as the Arctic; Fourth, in a world where urgent action is required to mitigate global warming, the traditional CO_2 only approach should be replaced by the GWP concept to ensure that the best climate mitigation options are selected; Fifth replacing the traditional CO_2 only approach with GWP would be fully in line with the basis for the UNFCCC agreement.

However, replacing the CO_2 only approach for climate assessments will be challenging, since the current emission regulations by the International Maritime Organization provide limits for SO_x and NO_x for health and environmental reasons and for CO_2 to mitigate global warming, while all other trace exhaust gas emissions are unregulated. The explanation for this is than in the late 1980s, when IMO started its work on prevention of air pollution from ships the focus was on harmful emissions and their impact on humans and nature only.

The overall results indicate that there are no general climate benefits of utilizing the Northern Sea route even with cleaner fuels, since the additional impact of emissions in the Arctic more than offsets the effect of shorter voyages. In terms of climate change mitigation, managing this trade-off will be challenging as the Northern Sea Route offers cost savings per ton of freight transported.

Acknowledgments

We are grateful to Dr. Matthias P. Nowak, Senior Scientist at MARINTEK for valuable support.

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