ASSESSMENT OF THE RELATIVE CLIMATE IMPACT OF ALTERNATIVE MARITIME FUELS AND ENGINE TECHNOLOGIES – 30th of SEPTEMBER 2019

Background

SINTEF OCEAN has been asked by Viking Cruises to evaluate the following statement: *Assess the relative climate impact of various alternative fuel systems taking the impact of all exhaust gases into consideration, not limiting it to impact of* CO_2*,* CH_4 *and* N_2O*.*

Summary

For emissions to air this memo confirms that a ship operating on heavy fuel oil and fitted with scrubbers has equal or lower actual emissions to air of CO2, SOx, NOx, Black Carbon (BC) and particulate matters than the same ship running on marine diesel.

Emission to air

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 thermal energy, which is harnessed for propulsion, and produces hot exhaust gases as a by-product. 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) and particulate matters have both climate and environmental impacts on human health and nature. Here particulates include black carbon (BC) and organic carbon (OC) in addition to PM_{10} and smaller.

Presently NO_X and SO_X are regulated due to human health and local pollution and CO_2 is regulated due to global warming while the remaining exhaust gases are un-regulated. This represents a conflict, since NOx and SOx emissions tend to mitigate global warming (Lauer et al, 2007; Eyring et al 2010), while the unregulated emissions, 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, 2016). Complicating matters, emissions in one region may lead to a direct climate forcing that differs in magnitude from 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 increased melting and reductions in snow/sea ice extent.

Metrics that weight emitted gases according to their global warming potential (GWP), to report them in terms of "*CO_2 equivalents*", have become standard currency to benchmark and communicate the relative and absolute contributions to climate change (Shine, 2009). GWP gives negative weights to emitted exhaust gases and particles that have a cooling effect, and positive weights to those that have a warming effect. GWP is usually integrated over 20 or over 100 years, where the longest time horizon gives greater weight to CO_2, which stays up in the atmosphere for hundreds of years.

Historically, shipping emissions were not perceived as a problem since vessels are operated at sea far from humans. In the 1970s, several studies confirmed the hypothesis that air pollutants could travel several thousands of kilometres before deposition and damage occurred.

In the late 1980s, the International Maritime Organization (IMO) started its work on prevention of air pollution from ships, and in 1997 the air pollution Annex (VI) was added to the International Convention for the Prevention of Pollution from Ships (MARPOL Convention). The first regulation of air pollutions from ships, which came into effect in the late 1990s was not strict and could easily be met. That has now changed with stricter rules coming into force in the period from 2015 to 2021:

- First, IMO has defined the coastlines of North America and the North Sea and the Baltic as Emission Control Areas (ECA's). From 2015, the fuel used within these ECAs has a sulphur content restricted to a maximum of 0.1 %. From 2020, the maximum limit for fuel Sulphur content outside of ECAs will be 0.5 % (down from the current limit of 3.5 %).

- Second, IMO requires that vessels built from 2016 onwards which operate fully or parts of their time in the North American ECA shall reduce their NOx emissions by 75 % compared to the Tier 2 for vessels built after 2011 (MARPOL Convention). From 2021, the Tier 3 NOx rules will also be applicable in the North Sea and Baltic ECA.

- 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 to 35 % stricter within the next 15 – 20 years (Lindstad et al 2014).

Fuels and Abatement options

Large seagoing vessels currently use heavy fuel oil (HFO) with a sulphur content of up to 3.5%, while smaller vessels use distillates with sulphur content less than 1.0 %. Inside the ECA's all vessels must comply within the 0.1% Sulphur limit, either through low Sulphur fuels or through exhaust gas scrubbers. Maritime transport consumes 7 - 8% of a Global oil production of around 4 billion ton in total. HFO represents 75% of the maritime consumption (IHS 2018), which means that shipping consumes around a third of the 600 – 800 tons of residual oil coming out from the refineries. Diesel represents nearly 25 % of the consumption and LNG represents 2 % (Lindstad et al., 2017).

- The advantage of HFO for the ship-owners is its low price compared to distillates. For the refineries, selling residual fuel has been an alternative to making large investments (in process equipment), to convert more of the residual fuel to distillates or to low sulphur or desulphurised fuel oils (LSHFO).

- While LNG and LPG are an option for new-buildings it becomes too costly for retrofitting existing vessels due to the need for new fuel tanks and engine modifications or replacements. (Acciaro, 2014; Lindstad et al., 2015).

- For these reasons the existing fleet have three main abatement options to comply with the Global Sulphur cap of 0.5% from 2020 onwards: HFO & Scrubber; a desulphurised heavy fuel oil (HFO<0.5%S); or using a distillate, such as marine diesel oil (MDO).

Table 1 shows typical fuel consumption per vessel as a function of vessel type and size for vessels types which currently typically use HFO (Lindstad and Eskeland 2016). In total this adds up to around 30 000 vessels.

Table 1: Global Fuel consumption for vessels types which currently use HFO

Ship type and sizegroup - dwt indicates average vessel size	No. of vessels	DWT (ton)	Installed Power (kW)	Average 2012 speed (knots)	Design speed (knots)	Days at sea 2012	Annual fuel with 2012 speed (ton)	Annual fuel with Design speed (ton)
General Cargo 7' dwt	2 900	7 300	3 300	10.1	13.6	166	1 800	2 900
General Cargo 22' dwt	2 000	22 500	7 400	12.0	15.8	174	4 400	6 900
Reefer 6' dwt	1 100	5 700	5 000	13.4	16.8	173	5 100	7 200
Ro-Ro & Vehicle 12' dwt	1 300	11 800	10 100	14.7	19.2	243	9 200	10 000
Ferry - RoPax > 2' GT	1 200		15 500	14.0	21.6	215	7 000	15 000
Dry Bulk 42' dwt	5 400	41 700	10 100	11.7	15.1	170	4 000	6 000
Dry Bulk 75' dwt	2 300	82 000	10 000	11.9	15.3	191	6 000	10 000
Dry Bulk 180' dwt	1 200	177 000	17 300	11.7	15.3	202	9 600	14 800
Dry Bulk 270' dwt	300	271 400	22 200	12.2	15.7	202	11 400	17 000
Chemical Tanker 15' dwt	1 000	15 300	5 000	11.7	14.1	182	3 500	5 000
Chemical Tanker 43' dwt	1 200	42 600	9 300	12.3	15.0	183	7 900	10 600
Tanker 9' dwt	900	8 600	3 200	8.8	12.8	148	2 400	4 600
Tanker 44' dwt	650	43 800	8 600	11.7	14.8	164	6 100	8 800
Tanker 70' dwt	400	72 900	12 100	12.2	15.1	183	7 800	10 800
Tanker 120' dwt	900	109 300	15 000	11.6	15.3	186	9 000	15 000
Tanker 160' dwt	500	162 300	18 800	11.7	16.0	206	10 900	18 400
Tanker 300' dwt	600	313 400	25 000	12.5	16.0	233	17 500	30 000
Container 9' dwt	1 100	8 600	6 000	12.4	16.5	190	3 700	5 900
Container 20' dwt	1 300	20 400	12 600	13.9	19.5	200	7 500	13 300
Container 47' dwt	1 700	46 800	30 500	15.5	23.3	224	14 600	29 800
Container 90' dwt	900	87 300	59 500	16.3	25.3	250	25 600	55 700
Container 180' dwt	100	177 000	83 000	14.8	25.0	242	30 200	77 800
LNG & LPG 7' dwt	1 100	6 700	3 800	11.9	14.2	180	3 200	4 300
LNG 70' dwt	500	68 500	22 600	14.9	18.5	254	18 500	27 100
LNG 120' dwt	50	121 300	37 400	16.9	19.3	277	34 100	43 000
Cruise > 10' GT	250		42 600	15.5	21.3	261	42 000	71 600

There are three types of scrubbers.

- The first one is the open loop scrubber which can be delivered both with and without a cleaning system for the wash water, where the cleaning system separates out soot and other particles above a certain size. Without a water cleaning system everything is dumped in the sea together with the sulphur washed out of the exhaust gas.

- The second, the closed loop scrubber runs in closed loop enabled by wash water cleaning the chemicals. This solution delivers the wash water for processing when it arrives in ports.

- The third is a hybrid scrubber which combines the two modes and can release the wash-water in open mode at sea and run in closed mode in ports and sensitive areas. With increased use of scrubbers, there will be ports and coastal areas where open loop will be banned from being used, while hybrid scrubbers running in closed loop mode are assumed to be allowed. Running the scrubber increases energy consumption by around 2 % compared to using compliant low sulphur fuels or distillates.

Desulfurizing residual fuel oils implies cost and complexity similar to conversion from residual to distillate – this in comparison to sulphur removals from distillates which is common technology for all refineries. Shell, the major oil company, and Concawe, the association of oil refineries (Concawe, 2009; Concawe 2012; Shell 2016; Shell 2017; Silva 2017) have published figures stating that conversion or desulphurisation consumes energy equivalent to 10 % - 15% of the energy content in the residual fuel input.

HFO and diesel are used on traditional diesel engine while LNG is burnt on two types of alternative dual fuel engines, high pressure and low-pressure systems:

- Dual fuel means that the engine can run on traditional fuel such as LFO or MDO in addition to LNG. In the high- pressure dual fuel LNG concept the LNG is injected under high pressure, typically around 350-bar and ignited by a small amount of diesel. At high engine loads, this gives nearly a complete combustion of the gas and hence nearly zeros Global Warming effect due to no methane slip. At lower loads the percentage of diesel must be increased, and the methane slip might increase due to less efficient combustion. To meet IMO Tier 3 requirements, high-pressure LNG solution requires add on processes and equipment such as Exhaust Gas Recirculation (EGR) in combination with advanced process control of the engine.

- In the low-pressure system, the LNG is injected under low pressure comparable to the Otto cycle (petrol engine). The benefit of the low pressure is that it gives low NOx emissions and no additional treatment technologies are needed to meet IMO tier 3 requirements. The disadvantage with the low-pressure dual fuel LNG engines is that the methane slip (due to unburnt methane) is much higher than for the high-pressure dual fuel engine both at high and low loads.

- It should be noted that the high-pressure LNG dual fuel engines currently are only available as 2-stroke diesels. 2-stroke diesels have been and are the preferred engine type for tankers, dry bulkers and container vessels from 5000 – 10000 kW installed power and upwards. Its advantage is the slightly lower fuel consumption per kWh produced compared to the 4-strokes. The disadvantage is that a 2 -stroke engine requires a much larger height inside the ship, which generally is not available on Ro-Ro vessels due to the ramps or in Cruise vessels where that space has a much larger value for passengers.

The methane emission factors used in this memo are based on assuming 50 % of fuel is consumed at high power and 50 % at low power and are: 0.75gram CH_4 per kWh for the high-pressure dual fuel engine (currently only available on 2 -stroke engines); 5.3 gram CH_4 per kWh as an average for low pressure solution based on the average measured by Stenersen and Thonstad (2017) for the Norwegian NOx fund. Moreover, for the low-pressure options we also present a State of the Art (SoA) figure representing the most advanced engine control systems applied in combination with best engine design. Table 2 shows typical fuel consumption as a function of engine type and fuel for HFO, MDO and LNG. Moreover, it shows un-combusted methane CH_4 as a percentage of fuel combustion when these dual fuel engines run on LNG.

Table 2: Fuel consumption and un-combusted methane

		Fuel type			Un-combusted CH_4 with LNG	
		HFO	MDO	LNG (CH_4)	Gram/kwh	%
Heating Value of fuel	MJ/kg	40.0	42.7	48.6		
Engine type						
2 stroke High Pressure	gram/kwh	190	175	155	0.75	0.5 %
4 stroke Low pressure	gram/kwh	205	190	170	5.30	3.1 %
4 stroke State of the Art	gram/kwh	200	185	165	3.00	1.8 %

Life Cycle GHG Assessment

Life cycle assessment (LCA) is a tool that enables the evaluation of a product environmental performance for example marine gas oil throughout its whole life cycle, i.e. from raw materials extraction, through production, usage, end-of-life treatment and final disposal (ISO 2006b). In this sense, as it presents a holistic overview of a product system; it allows identifying the most relevant environmental impacts as well as the contribution of the different life cycle phases to the total impacts. LCA can be employed to serve different applications, such as to compare different products or services that fulfil the same function, identify improvement opportunities in a production system, and as support for decision-making (Silva 2017).

Over the last years, a significant number of studies assessing the environmental impact of maritime fuels has been performed. The studies vary in goal and scope, the majority are tank-to-wake (TTW) studies, which only focus on assessing the impacts from the combustion of marine fuels. Only a few performed an impact assessment of marine fuels over a life cycle perspective, the so called well-to-wake (WTW) studies.

The fuel and abatement options assessed in this memo are:

- Heavy fuel oil (HFO) with a maximum Sulphur content up to 3.5%. In this study 2.7 % Sulphur content is used for calculations (Lindstad et al 2015).

- Heavy fuel oil where the Sulphur content has been reduced by desulphurization to 0.5% Sulphur (HFO-0.5 %). Marine diesel oil (MDO) with 0.5% Sulphur gives quite comparable emissions, but HFO 0.5 % is used since it will come at a price rebate compared to MDO 0.5 % S (Lindstad et al 2017) .

- HFO in combination with an exhaust gas scrubber to comply with the global Sulphur cap of 0.5% S from 2020 or 0.1 % S in ECA's. Here 0.5 % Sulphur has been used for calculations.

- Marine diesel oil (MDO), which is a diesel with a maximum Sulphur content of 0.1%.

- Liquid Natural Gas (LNG) in combination with diesel dual-fuel engines and High-pressure injection from MAN. Presently it's only MAN which delivers the high-pressure technology, while the other manufactures deliver the low-pressure technology. The MAN HP technology is currently only available on 2-stroke engines.

- Liquid Natural Gas (LNG) in combination with diesel dual-fuel engines and low-pressure injection.

Tank to wake (TTW) emissions

The tank to wake (TTW) emissions of a vessel depend on its energy use and the GHG emissions from combusting the fuel. Figure 1 shows the impact of the individual exhaust gases and the CO_2 equivalent with a 20-year time horizon (GWP20) for the assessed fossil fuels and abatement technologies. Moreover, Figure 2 shows more clearly the Global Warming Potential in the 20-year time horizon. Figure 3 is equivalent to Figure 1, but with a 100-year time horizon and here Figure 4 shows more clearly the Global Warming Potential in the 100-year time horizon. With the current need for rapid reductions of GHG emissions within the next decade and a 50% cut by 2050 (IPCC 2013), there are good arguments for giving larger weight to the results from using the 20 years horizon (Lenton, 2008). The main climate effects arise from:

- CO_2 including CO, which has a warming effect
- CH_4, which has a warming effect
- BC - Black Carbon, which has a warming effect
- N_2O, which has a warming effect
- NOx which has a cooling effect
- SOx (sulphate particles), which has a cooling effect
- OC – Organic Carbon, which has a cooling effect

Table 3 displays the applied emission factors per exhaust gas and their CO_2 equivalents based on their global warming potential (. The emission factors are showed in the table both for high power and low power operations per engine as a function of fuel type and engine technology. Converting from specific exhaust gas emission to CO_2 equivalents (GWP) implies that each gram of un-combusted CH_4 in the exhaust gas will be multiplied with 85 in a 20-year time perspective and 30 in a 100-year perspective. The GWP factors are negative for exhaust gases having a cooling effect and positive for the exhaust gases contributing to warming.

The two first lines in the table contain the GWP factors for a 20 and a 100-year time horizon. Line three in the table contains emissions per exhaust gas for HFO with a 2.7% Sulphur content before we got any NOx regulations (before 1999). Line four contains the emissions values we got for HFO 2.7% S when the global NOx regulations became stricter from 2011. The Net GWP per fuel type (and NOx regulation), representing the climate impact, is found by multiplying the emission for each exhaust gas with its corresponding GWP factor and then summing up these products for all the exhaust gases.

Mathematically the calculations can be expressed as:

$$NET\ GWP_{20} = \sum_{i=1}^{n} Emission_i * GWP\ factor_{20\ i}$$

$$NET\ GWP_{100} = \sum_{i=1}^{n} Emission_i * GWP\ factor_{100\ i}$$

The two last rows in the table shows the average emission values for the global fleet used in *The Second IMO GHG study* (Buhaug et al 2009) and in a study of *Future emissions from shipping and petroleum activities in the Arctic* (Peters et al 2011).

Table 3: Emission factors per exhaust gas in gram per kwh, GWP factors per exhaust gas and the aggregated climate impact per fuel type with a 20-year and a 100-year time horizon.

		IMO Tier	CO2	BC	CH_4	CO	N_2O	NOx	SO_2	OC	NET GWP_{20}	NET GWP_{100}
GWP_{20} factors			1	1200	85	5.4	264	-16	-141	-240		
GWP_{100} factors			1	345	30	1.8	265	-12	-38	-69		
High Power	HFO - 2.7% S	None	540	0.05	0.05	1	0.02	15.0	9.5	0.20	-1012	17
		Tier 2	570	0.05	0.05	1	0.02	12.0	10.0	0.20	-1005	62
	HFO - 0.5% S	Tier 2	570	0.05	0.05	1	0.02	12.0	2.0	0.20	123	367
		Tier 3	600	0.05	0.05	1	0.02	2.5	2.1	0.20	290	503
	HFO & Scrubber - 0.5% S	Tier 2	580	0.025	0.05	1	0.02	12.0	2.0	0.20	103	368
		Tier 3	610	0.025	0.05	1	0.02	2.5	2.1	0.20	270	504
	MDO - 0.1% S	Tier 2	570	0.05	0.05	1	0.02	12.0	0.4	0.20	349	427
		Tier 3	600	0.05	0.05	1	0.02	2.5	0.4	0.20	529	567
	LNG - Dual fuel HP	Tier 2	450	0.050	0.5	1	0.02	9.0	0.5	0.20	308	354
		Tier 3	450	0.050	0.5	1	0.02	2.5	0.1	0.20	457	441
	LNG - Dual fuel LP - Tier 3	AS IS	450	0.005	4.0	1	0.02	2.5	0.1	0.20	704	532
		SoA	450	0.005	2.5	1	0.02	2.5	0.1	0.20	576	486
Low Power	HFO - 2.7% S	None	600	0.2	0.1	2	0.02	22.5	10.5	0.22	-1028	5
		Tier 2	630	0.2	0.1	2	0.02	18.0	11.0	0.23	-997	68
	HFO - 0.5% S	Tier 2	630	0.2	0.1	2	0.02	18.0	2.2	0.22	244	403
		Tier 3	660	0.2	0.1	2	0.02	3.7	2.3	0.22	487	595
	HFO & Scrubber - 0.5% S	Tier 2	640	0.1	0.1	2	0.02	18.0	2.2	0.22	135	379
		Tier 3	670	0.1	0.1	2	0.02	3.7	2.3	0.22	378	571
	MDO - 0.1% S	Tier 2	630	0.2	0.1	2	0.02	18.0	0.5	0.22	484	468
		Tier 3	660	0.2	0.1	2	0.02	3.7	0.5	0.22	741	663
	LNG - Dual fuel HP	Tier 2	490	0.05	1.0	2	0.02	12.0	0.1	0.22	393	388
		Tier 3	490	0.05	1.0	2	0.02	3.7	0.1	0.22	525	484
	LNG - Dual fuel LP - Tier 3	AS IS	490	0.05	6.6	2	0.02	3.7	0.1	0.22	1001	652
		SoA	490	0.05	3.5	2	0.02	3.7	0.1	0.22	737	559
Previous Studies	Buhaug et al. 2009		595	0.07	0.06	1.4	0.02	14.8	10.3	0.2	-1042	51
	Peters et al. 2011		595	0.07	0.06	1.4	0.02	14.8	10.3	0.2	-1042	51

GWP factors based on: World average excluding Artic: , BC - Collins et al. 2013; CH4 - IPCC 2013; CO - Fry et al 2012; N2O - IPCC 2011; Nox - Fry et al 2012; SO2 - IPCC 2013; OC - IPCC 2013

Emission factors based on: Kasper et al 2007; Buhaug et al 2009, Hennie et al 2012; Peters et al 2011; Duran et al 2012; Ehleskog 2012; Lack and Corbett 2012; Lindstad et al 2015;

Lindstad and Sandaas 2016; Stenersen and Thonstad 2017; Lindstad 2018; In house knowledge.

Operation profile of vessels will vary both within a shipping company and between companies. However, to keep it simple, we have here assumed that 50% of emissions are related to high power and 50% to low power. For each of the fuel and engine options there are two vertical bars, showing the impact of stricter NOx regulations. For HFO 2.7% S we show Tier 0 (before regulation) and Tier 2 (from 2011). For the other options apart from LNG low pressure (LNG-LP) we show Tier 2 and Tier 3 (ECA areas from 2016 and 2021). For LNG LP which by nature is Tier 3 we show AS IS expressing todays typical engines and State of the Art (SoA) expressing performance if best technology is applied (comes at a higher cost).

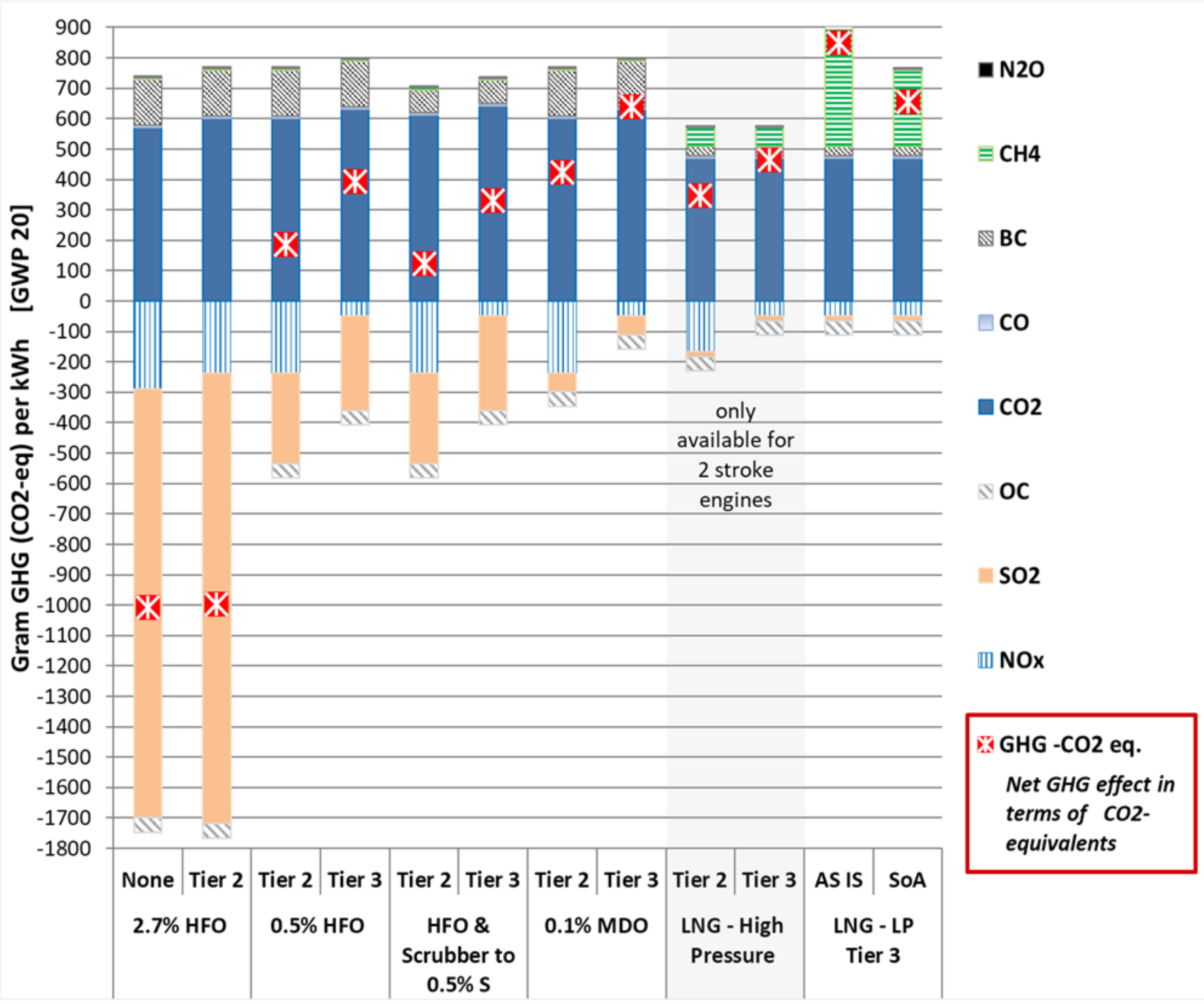

Figure 1: Global warming impact over 20-year horizon in gram CO_2-equivalents per kWh produced as a function of fuel, abatement technology and NOx regulation

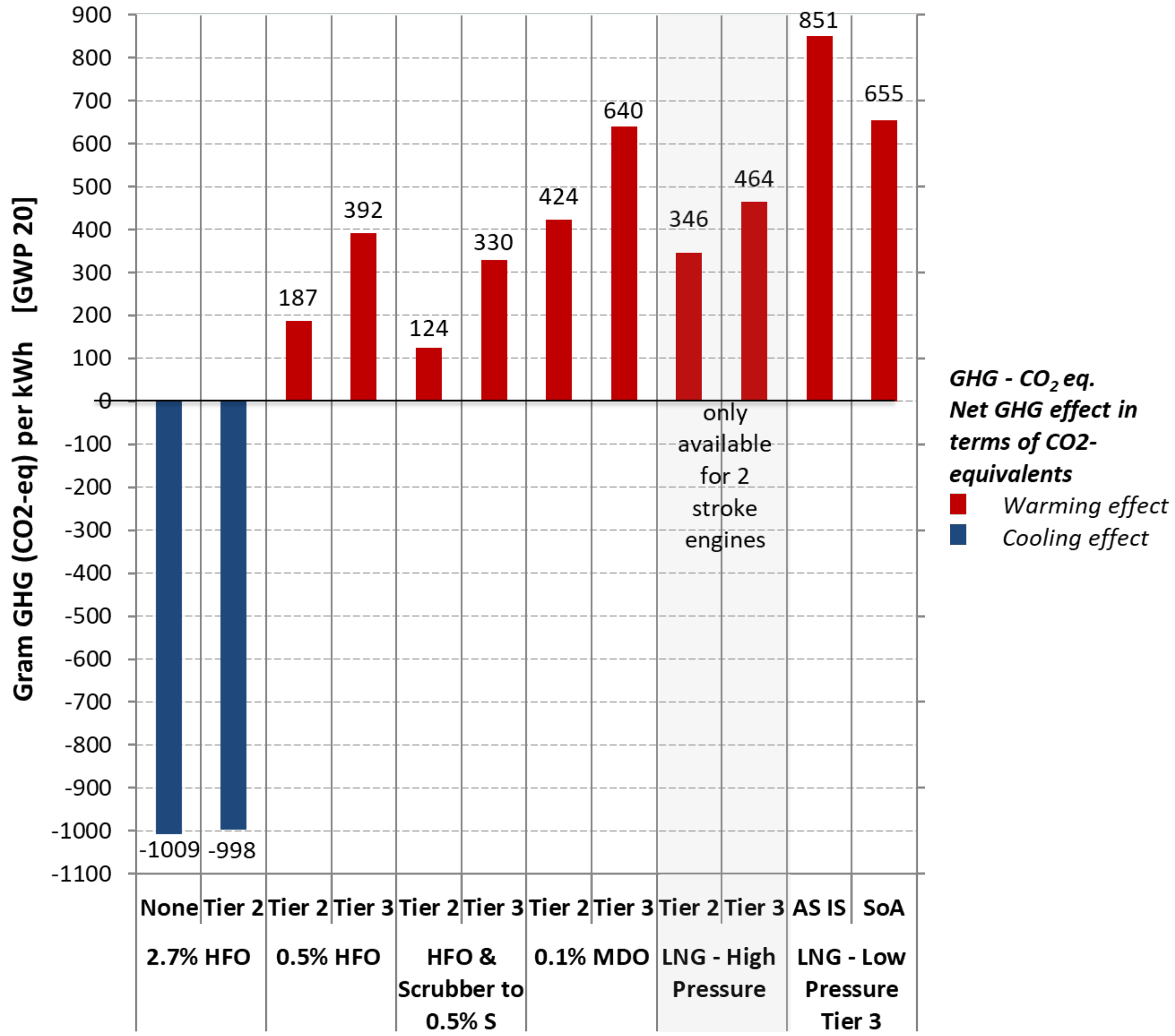

Figure 2: Net global warming and cooling impact over 20-year horizon in gram CO_2-equivalents per kWh produced as a function of fuel, abatement technology and NOx regulation

The main observations from figure 1 and 2 are:

- First, the global Sulphur cap from 2020 reducing maximum content from 3.5% S to 0.5% S changes shipping emissions from contributing to climate cooling to contribute to global warming (first two bars versus the next ten).
- Second, with stricter NOx rules, the global warming effect expressed through CO_2 equivalents increases further. The explanation is reduced cooling due to less NOx emitted and higher fuel consumption when engines are adjusted to minimize NOx instead of minimizing fuel per kWh produced.
- Third, the HFO & Scrubbers options give lower GHG emissions, than using a fuel oil with a maximum Sulphur content of 0.5% Sulphur. The explanation is that despite using around 2% more fuel to run the scrubber, the scrubber wash-out more than half of the soot (BC). In ECA areas with 0.1 Sulphur (not shown here) the difference will

be smaller due to more energy required to wash out the Sulphur, still the scrubber option will give lower GHG emissions.

- Fourth, in ECA areas the high-pressure LNG option (LNG-HP) will give the lowest GHG emissions and the overall best performance with the lowest total emissions (total high of the bars).
- Fifth the low-pressure LNG option (LNG-LP) gives the highest GHG emissions, i.e. the largest contribution to global warming. Moreover, even when applying best technology, it does not perform better than diesel (MDO).
- Sixth, in areas with snow and ice the impact of BC is roughly 5 times higher than globally (GWP_{20} Arctic factor of 6200 compared to 1200 per gram of BC globally). Arctic is hence the only area where LNG-LP options will outperform the traditional diesel and HFO options. But not necessarily versus the scrubber option, since 50% or more of the soot is washed out in the scrubber.

The ranking of options to mitigate global warming will then be (1 is best):

1. Continued use of HFO at high seas and cleaner fuels with low Sulphur content, i.e. less than 0.1% Sulphur close to coast and in ports (see Lindstad et al 2015a; and IBIA submission to MEPC autumn 2016 suggestion World-wide ECA close to coast and in ports)
2. LNG dual fuel gas engines with high pressure injection (only available on 2 – strokes)
3. HFO & Scrubbers (Hybrid or Closed Loop)
4. Cleaner fuels such as HFO<0.5% S or MDO<0.1%S
5. LNG dual fuel low pressure injection

If we change time horizon from 20 year to 100 years, which is relevant when judging pros and cons of the alternative technologies over the next centuries we get results as shown in figure 3 and 4. The main observation is that with a longer time horizon the impact of other exhaust gases becomes smaller than the impact of CO_2, and apart from the HFO 2.7% Sulphur options, all Global Warming Potentials come in at a comparable level.

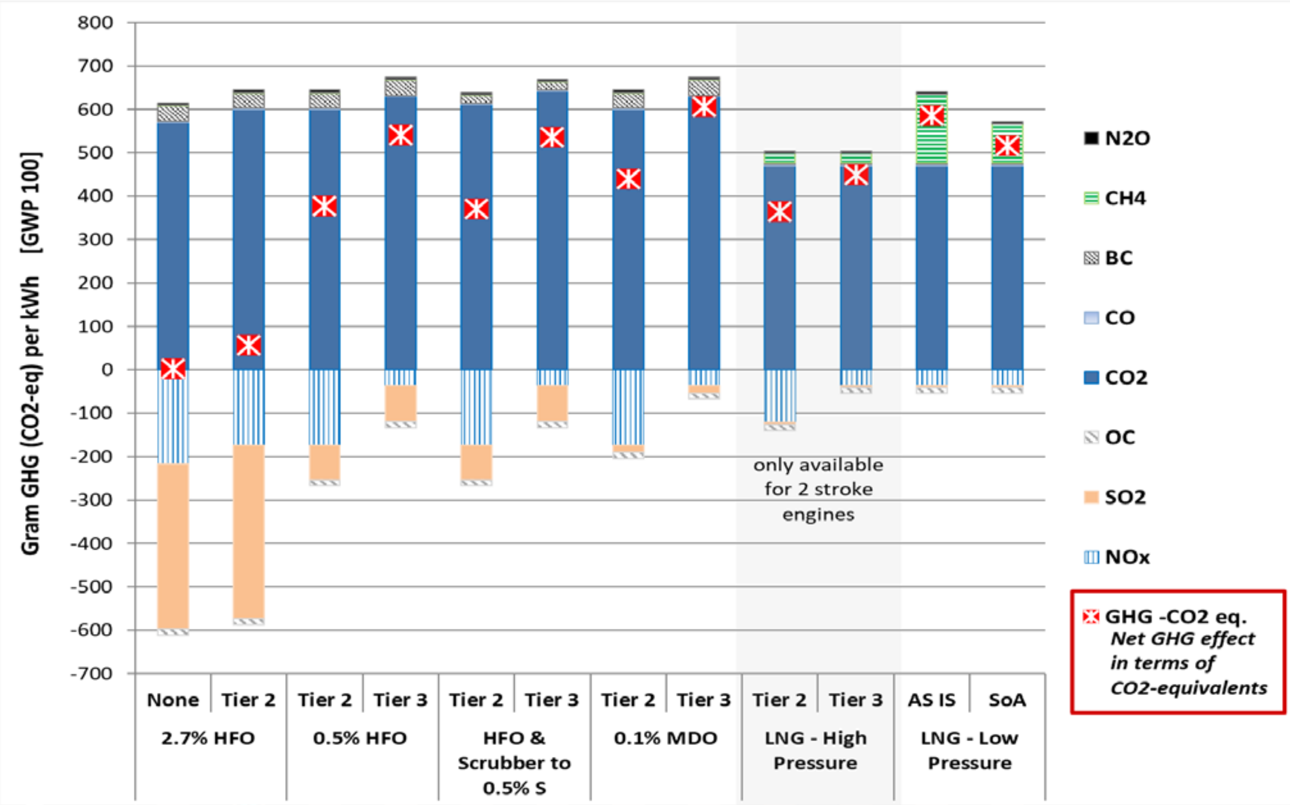

Figure 3: Global warming impact over 100- year horizon in gram CO_2-equivalents per kWh produced as a function of fuel, abatement technology and NOx regulation

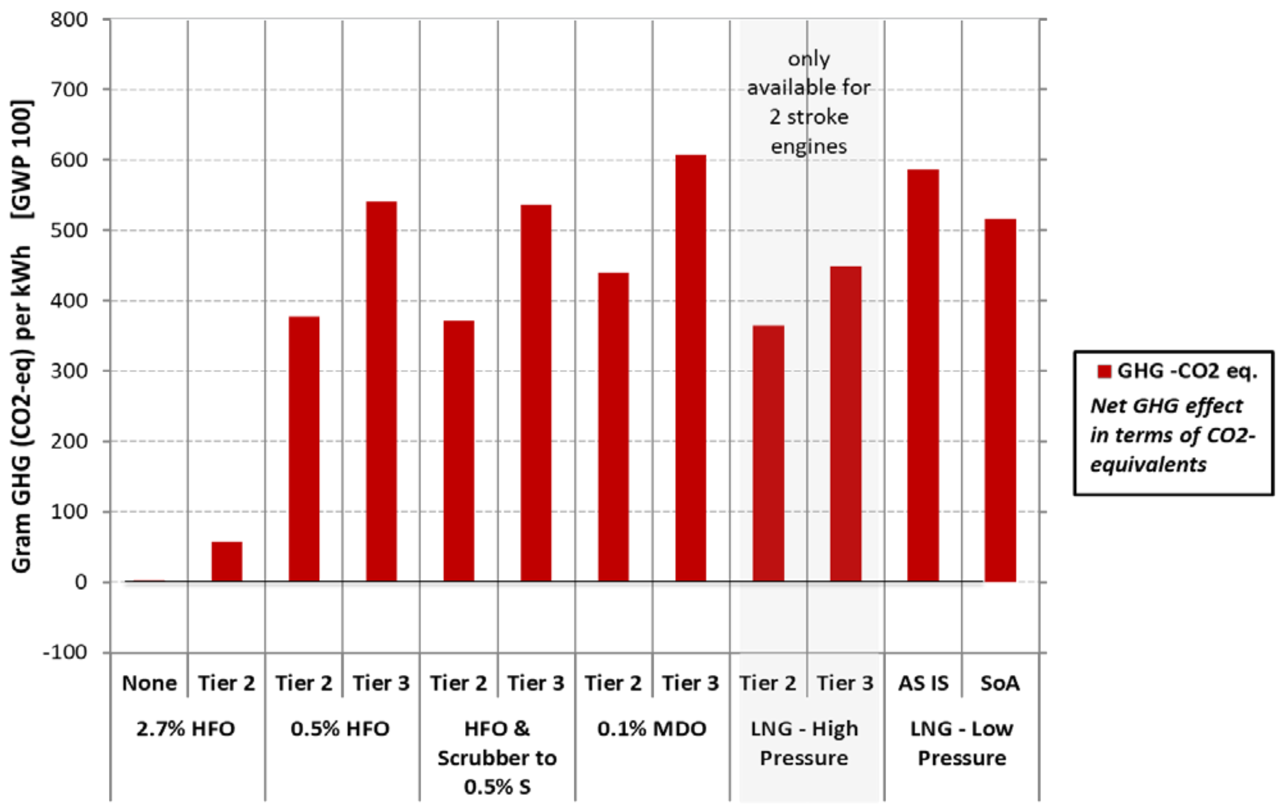

Figure 4: Net GHG effect over 100-year horizon in gram CO_2-equivalents per kWh

IMO POLICIES AND LEGISLATION IMPACT ON GLOBAL WARMING

For the period 2007–2012, on average, shipping according to the third IMO GHG study (Smith et al, 2014), accounted for approximately 3.1% of annual global CO_2 and approximately 2.8% of annual GHGs on a CO_2e basis u. A multi-year average estimate for all shipping using bottom-up totals for 2007–2012 is 1,015 million tonnes CO_2. International shipping accounts for approximately 2.6% of CO_2. For NOx and SOx the third IMO GHG study (Smith et al 2014) finds average annual totals of 20.9 million of NOx and 1.3 million tonnes of SO_x. Annually, international shipping is estimated to emit 18.6 million of NOx (as NO_2) and SO_x (as SO_2), respectively; this converts to totals of 5.6 million and 5.3 million tonnes of NO_x and SO_x (as elemental nitrogen and sulphur, respectively).

With stricter regulation policies coming into force for SOx and NOx after the reference years of the Third IMO GHG study the climate impact of shipping is changing as shown by Table 4. Line two in the table shows the current impact of shipping where the CO2 figure quotes the HLPOCC (2019) report with CO_2eq., GWP_{20} and GWP_{100} figures are calculated in line with the principles and methodology described in previous sections. The short version is that the CO_2 column includes only CO_2, while CH_4 and N_2O are included in addition in the GHG column. Moreover, the Climate columns includes also the impact of all the other exhaust gases in addition to the GHG's. Which means that the emissions from shipping in 2018 over the next 20 years contributes with a cooling effect of -3.5%, i.e. basically it offsets 3.5% of other GHG emissions. Line three shows the impact of shipping emissions if HFO 2.7% Sulphur was used worldwide. In that case the cooling effect would be 5% over the next 20 years and even in a 100-year perspective shipping would be climate neutral. With 2020 and the Global Sulphur cap all of this changes and shipping will no longer contribute too cooling. Line 4 shows the climate impact if all ships operates with scrubbers and compliant with 0.5% Sulphur Globally and 0.1% Sulphur in the ECA's, i.e. a 1.3% contribution to global warming compared to a 3.5% cooling effect in 2018, representing a net increase of nearly 5%. With LNG it becomes even worse, i.e. a 3% contribution to global warming over the next 20 years, representing a net increase of 6% compared to 2018. In Table 5 figures are displayed in million tons of CO2 eq.

Table 4: IMO policies and legislation impact on Global warming (percentage of Global totals)

	CO_2	GHG	Climate Impact - GWP_{20}	Climate impact - GWP_{100}
Third IMO GHG Study (2007- 2012)	3.1%	2.8%		
Current based on fuel mix, trade and ECA's (2018)	3.0%	2.7%	-3.5%	0.5%
Current if all ships on HFO 2.7%	3.0%	2.7%	-5.0%	0 %
Global 2020 Sulphur cap if all ships have scrubbers	3.0%	2.7%	1.3%	2.1%
Global 2020 Sulphur cap if all ships on LNG and 50/50 mix between High and low pressure (Diesel and Otto)	2.4%	2.6%	3.0%	2.4%

Table 5: IMO policies and legislation, impact on Global warming in million ton of CO_2 eq.

	CO_2	Climate Impact GWP_{20}	Climate impact GWP_{100}
Third IMO GHG Study (2007- 2012)	1 015		
Current based on fuel mix, trade and ECA's (2018)	1 050	-1 225	175
Current if all ships on HFO 2.7%	1 050	-1 750	0
Global 2020 Sulphur cap with all ships on scrubbers	1 050	450	735
Global 2020 Sulphur cap if all ships on LNG and 50/50 mix between High and low pressure (Diesel and Otto)	1 050	1 050	840

EMISSIONS TO WATER

At high seas, emissions to air of Sulphur and Nitrogen will mostly deposit in oceans, while in coastal areas much will deposit on land. On land, Sulphur in too high quantities has acidifying and damaging effects in ecosystems, human health and infrastructure. NOx exhaust gas emissions are undesirable too, at too high levels (health damages and over-fertilization). While the acidifying changes in the sea due to nitrogen and sulphur compounds are only a fraction of the effects from carbon dioxide (CO_2), the effects compounded in coastal areas are likely more damaging and undesirable in general. Research by Doney et al. (2011) has shown that acidification from shipping in coastal areas during the summer months can be as great as that from carbon dioxide. Moreover, even if acidification effect on the oceans from the Sulphur at high seas is small, the need for climate change mitigation might change how we assess this in the future.

- Closed loop scrubbers do not discharge the wash water at sea, instead the wash water is delivered it in port to certified handlers.

- With open loop scrubbers, acidification effect in coastal areas will increase since the Sulphur will be washed out directly in the sea, rather than spread out through winds and precipitation in a larger region (Lindstad and Eskeland 2016). To avoid this effect, the vessels with open loop scrubbers will have to run on distillates in coastal areas.

- With a hybrid scrubber acidification effect in coastal areas will be reduced, however the chemicals required to run in closed loop might have undesired effects when the wash water is dumped at high seas. This can totally be avoided, if also the wash water from the closed loop running mode instead is delivered in ports for after treatments together with the sludge (landed in port to certified waste disposal companies for treatment -Haz waste).

- Even for open loop scrubbers, a cleaning system for the wash water which separates soot and other particles should be included in the setup. When included, it reduces the amount of soot (BC) and particles (PM) which ends up in the ocean, maybe even compared to the clean fuel option (distillates). On the contrary, without a water cleaning system everything is dumped in the sea together with the washed-out Sulphur.

- With increased use of scrubbers, there will be ports and coastal areas where open loop will be banned from being used, while hybrid scrubbers running in closed loop mode to a larger degree is assumed to be allowed.

VESSEL TYPES FOR WHICH SCRUBBERS AND HFO IS AN ALTERNATIVE TO LOW SULPHUR FUELS

Figure 5 shows installed power and percentage of total maritime fuel consumed as a function of engine size. The vessels with the smallest engines, i.e. up to 1800 kW adds up to more than 40 % of the fleet, but they consume less than 15% of the fuel. Contrary only 3% of the vessels has more than 30 000 KW installed, and they consume more than 20% of the maritime fuel. Installing a scrubber comes at a high fixed start cost while the additional cost per 1000KW just increases marginally. Moreover, since it's the price differential between HFO and low sulphur fuels which gives the payback on the investment, scrubber investments give the highest payback on vessels with large engines and high annual fuel consumption. Table 6 shows examples of average annual fuel consumption for some vessel types if they are operated as they were in 2012 (Reduced speeds) and if they instead are operated at their design speeds. It also shows cost per ton of fuel in addition to the HFO price when scrubber is the selected abatement option.

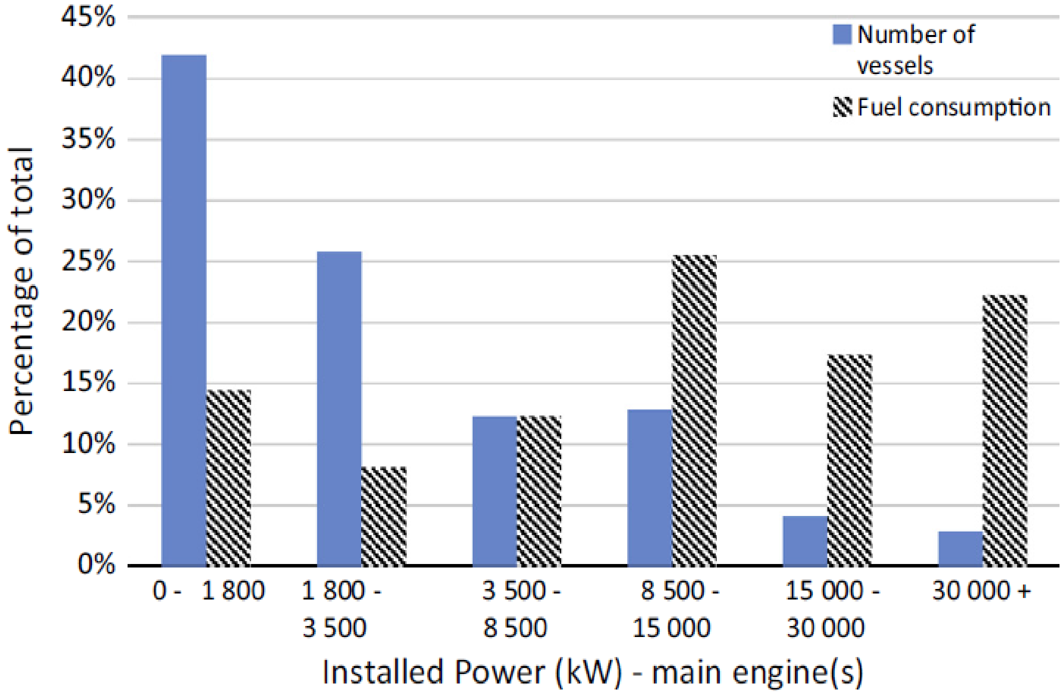

Figure 5: Installed Power and consumption for the world fleet

Table 6: Annual fuel consumption & scrubber cost in USD per ton of fuel for some vessel types

Ship type and size-group - dwt indicates average vessel size	Installed Power (kW)	Average 2012 speed	Days at sea 2012	Cost of Hybrid Scrubber (MUSD)	Annual fuel with 2012 speed (ton)	Scrubber cost in USD per ton of fuel	Annual fuel with Design speed (ton)	Scrubber cost in USD per ton of fuel
General Cargo 7' dwt	3 300	10.1	166	2.6	1 800	289	2 900	179
Tanker 9' dwt	3 200	8.8	148	2.6	2 400	217	4 600	113
LNG & LPG 7' dwt	3 800	11.9	180	2.6	3 200	163	4 300	121
Chemical Tanker 15' dwt	5 000	11.7	182	2.6	3 500	149	5 000	104
Dry Bulk 75' dwt	10 000	11.9	191	3	6 000	98	10 000	59
Tanker 120' dwt	15 000	11.6	186	3.3	9 000	73	15 000	44
Tanker 300' dwt	25 000	12.5	233	4	17 500	46	30 000	27
Container 90' dwt	59 500	16.3	250	6.4	25 600	50	55 700	23
Container 180' dwt	83 000	14.8	242	8.1	30 200	53	77 800	21
LNG 120' dwt	37 400	16.9	277	4.9	34 100	29	43 000	23
Cruise > 10' GT	42 600	15.5	261	5.2	42 000	25	71 600	15

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