HYDROGEN THE NEXT MARITIME FUEL

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ABSTRACT

With stricter emission rules and more public focus on maritime transport, reducing emissions in a cost efficient way has become a necessity for maritime transport and marine operations. Current emissions from the sector accounts for 10–15% of global anthropogenic Sulphur oxide and Nitrogen oxide emissions, and around 3% of global carbon dioxide (CO_2) emissions (Smith et al., 2014). These emissions are assumed to increase by 150 – 250 % by 2050 if no actions are taken, i.e. business as usual (BAU) scenarios with a tripling of world trade. Fulfilling anticipated climate requirements could require the sector to reduce emissions per freight unit by a factor of five or six. The focus of this paper is therefor to investigate the environmental impact of traditional fuels and then compare them with the pros and cons of introducing Hydrogen as a marine fuel.

Keywords: Shipping and the Environment, Greenhouse gases, Abatement cost and options, Marine fuels, Low carbon fuels, Hydrogen.

1. INTRODUCTION

Ships emit both to air and sea, and the main source of these emissions are the exhaust gas from burning traditional fossil fuel in the ships 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 gas as a byproduct. Of these exhaust gases: Carbon dioxide (CO_2) affects climate only, while Carbon monoxide (CO), Sulphur oxides (SOx), nitrogen oxides (NOx), methane (CH_4), black carbon (BC) and organic carbon (OC) affect climate and also have adverse health impacts. The emitted carbon- dioxide (CO_2) is a function of the carbon content in the fuel. The emitted Sulphur oxide (SOx) is a function of the Sulphur content in the fuel. The emitted Nitrogen-oxide (NOx) 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 (Duran et al. 2012; Ehleskog 2012, Lindstad et al. 2015a). The emitted Black Carbon (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 methane (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).

Current emission regulations set limits for Sulphur oxide (SOx) and nitrogen oxide (NOx) for health and environmental reasons, and for carbon dioxide (CO_2), in order to mitigate global warming (Eide et al., 2013) through the Energy Efficiency Design Index (EEDI). Noteworthy emissions of NOx and the SOx mitigate global warming (Lauer et al., 2007; Eyring et al., 2010), whereas emissions of black carbon (BC) and methane (CH_4), which are unregulated, contribute to global warming (Jacobson, 2010; Bond et al., 2013; Myhre and Shindell, 2013; Fuglestvedt et al., 2014; Lindstad and Sandaas, 2014). Emission metrics such as Global Warming Potential (GWP), which express emission impacts in terms of "*CO_2 equivalents*", have become the standard 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 positive figures are used for those that have a warming effect. Some of the exhaust gases are short-lived climate forcers and impact climate over relatively short timescales. Others, such as CO_2, operate on 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 earlier short-lived forces (Borken-Kleefeld et al., 2013).

Previous studies has documented that it is possible to reduce emissions in a cost effective manner, i.e. emissions can be cut with net cost savings (Buhaug et. Al., 2009; DNV 2010; Lindstad, 2013). The main measures are slower speeds, larger vessels, more slender designs, hybrid power setups, and fuels with lower environmental impact.

First slower speeds, the core insight is straightforward, the power output required for propulsion is a function of the speed to the power of three. This means that when a ship reduces its speed, its fuel consumption per freight work unit is reduced (Corbett et al., 2009; Seas at Risk and CE Delft, 2010; Psaraftis and Kontovas, 2010, Lindstad et al., 2011; Psaraftis and Kontovas, 2013).

Second, larger ships – and shipments – tend to be more energy efficient per ton transported than smaller (Cullinane and Khanna, 2000; Sys et al., 2008; Notteboom and Vernimmen, 2009; Lindstad et al., 2012; Lindstad et. al. 2015b). The key observation is that when the ship's cargo-carrying capacity are doubled, the required power and fuel use typically increases by about two thirds, so fuel consumption per freight unit is reduced. The vessels building cost increases with about half of the increase in cargo capacity and costs of crew, maintenance and management rise less than proportionally with cargo capacity.

Third, the design focus of seagoing vessels such as bulkers and tankers has emphasized maximizing cargo-carrying capability for a given building cost, with less attention being paid to energy consumption per transported unit. Lindstad et al. (2013), Lindstad et al. (2014), Lindstad (2015) have challenged this approach and investigated cost and emissions as a function of alternative bulk and tank vessel designs with focus on a vessel's beam, length and hull slenderness expressed by the length/displacement ratio. The results show that when the block coefficient is reduced and the hull becomes more slender, fuel consumption and emissions per ton falls.

Fourth, traditionally seagoing vessels have operated at high power to achieve their designs speeds at open sea, i.e. 75 – 90 % of power to achieve 90 – 95 % of their maximum speeds. More recently higher fuel cost and poor freight market have changed this habit; it has become common practice to operate at 15 to 50% of the installed power in calm to moderate sea states. When engines operate at low power, fuel consumption per kWh produced increases slightly while exhaust gases such as nitrogen oxides and aerosols such as black carbon increase rapidly due to less favorable combustion conditions. Lindstad and Sandaas (2014) and Lindstad et al (2015c) has investigated potential emission reductions which can be achieved by introduction of hybrid engine setups, i.e. engines of different sizes, battery storage of energy to take peak power requirements, and advanced power management systems. The results indicate that hybrid technologies reduce both emissions and fuel consumption and that the climate impact of the emission reduction is much larger than the impact due to the reduction in fuel consumption alone.

Fifth emissions of CO_2 can be cut by switching to fuels with lower total emissions through fuel cycle including production, refining and distribution (Buhaug et al., 2009). Biofuels is one such option, which can be considered as an alternative to fossil fuels, and there are various studies that examine the feasibility. Bengtsson et al. (2012) derive a conclusion that the biofuels are one possible measure to decrease the global warming impact from shipping, but that it can be to the expense of greater environmental impact for other impact categories. Liquefied natural gas (LNG) have a higher hydrogen to carbon ratio, which results in lower CO_2 emissions compared to more traditional hydro carbon fuels such as marine diesel oil or heavy fuel oil (Buhaug et al., 2009). The disadvantage is that the exhaust gas contains un-combusted methane (CH_4) which for some engine technologies might offset the whole gain by the higher hydrogen to carbon ration than in traditional fuels. Hydrogen is another interesting fuel as its direct combustion has the lowest environmental impact. The basic chemical reaction is that hydrogen reacts with oxygen, which gives energy and water: $2H_2 + O_2 \rightarrow \text{Energy} + 2H_2O$. Compared to traditional combustion no nitrogen oxides, Sulphur oxides or particles are detectable. The Fuel cell technology in ships, (FCSHIP-project) has investigated the application of fuel cells on board ships for both main propulsion and auxiliary applications. The offshore supply vessel Viking Lady has a fuel cell installed and the objective is that the fuel cell can produce part of the energy that is produced by the auxiliary engines (Biello, 2009).

The current emissions from seagoing vessels accounts for 10–15% of global anthropogenic Sulphur oxide and Nitrogen oxide emissions, and around 3% of global carbon dioxide (CO_2) emissions (Smith et al., 2014). These emissions are assumed to increase by 150 – 250 % by 2050 if no actions are taken, i.e. business as usual (BAU) scenarios with a tripling of world trade (Buhaug et. al. 2009). Fulfilling anticipated climate requirements could require the sector to reduce emissions per freight unit by a factor of five or six. The focus of this paper is therefor to investigate the environmental impact of traditional fuels and then compare them with the pros and cons of introducing Hydrogen as a marine fuel. The employed model is described in the next section, followed by its application and data, and the obtained results are discussed in the final section.

2. MODEL DESCRIPTION

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

$$P_i = \frac{P_s + P_w + P_a}{\eta} + P_{aux} \quad (\text{Eq. } 1)$$

Equation 2 calculates voyage cost as a function of required power, voyage length, and vessel characteristics (see Lindstad et al., 2014; Lindstad et al., 2015).

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

The first term represents cost at sea, while the second determines costs in port. During a voyage, sea conditions will vary. This is dealt with by dividing each voyage into sailing sections, with a distance D_i for each sea condition that influences the vessel's speed v_i and the required power P_i. The hourly fuel cost per section is given by $\left(K_{fp} \cdot P_i \cdot C_{Fuel}\right)$, where K_{fp} is the fuel required per produced kWh, which is a function of engine load, and C_{Fuel} is the cost per unit of fuel. 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 costs in port, where D_{lwd} is the total number of hours spent in port.

Emissions, ε per pollutant per voyage are calculated as expressed by equation 3:

$$\varepsilon = \sum_{i=1}^{n} \frac{D_i \cdot P_i \cdot K_{ep}}{v_i} \quad (\text{Eq. } 3)$$

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 tonne transported is calculated by equation 4.

$$GWP_t = \sum_{i=1}^{n} \varepsilon_{\,e} \cdot GWP_{et} \quad (\text{Eq.} 4)$$

Here, $\varepsilon_{\,e}$ is emissions of pollutant *i* and GWP_{et} is the GWP factor for each pollutant within the given period.

3. APPLICATION AND DATA

The vessel types in focus for this study are the worlds' cargo transport vessels. Table 1 shows key 2012 figures per vessel type and the totals (Lindstad et al., 2015d).

Table 1: Vessel types and Sea-freight in 2012

Vessel type	Number of vessels	Average vessel size	Freight work	Market share
	2012	Dwt	Billion ton nm	%
Dry Bulk	10 400	68 600	20 000	42%
General Cargo	16 500	5 300	2 300	5%
Container	5 100	41 600	9 000	19%
Reefer	1 100	5 700	225	0%
RoRo	2 600	7 600	550	1%
OilTanker-mainly crude > 80' dwt	2 000	183 500	10 000	21%
OilTankers-mainly product < 80'dwt	5 400	13 300	2 000	4%
Chemicals	4 900	18 000	2 300	5%
LNG & LPG	1 600	27 600	1 500	3%
RoPax	2 900	1 600	125	0%
Totals	52 500	30 800	48 000	100%

Cargo vessels are typically powered by four stroke medium speed engines connected via a gear and a clutch to the propeller or by two-stroke slow-speed engine connected directly to the propeller without any clutch or gear. The required power for auxiliary engines, cargo-handling gear, ‘hotel functions’ and any thrusters is produced by smaller combustion engines connected directly to electricity generators that supply power through the main switchboard. Excess heat from the cooling system on the main engine is utilized for bunkers, cargo and other heating purposes. Fig. 3 illustrates a typical example of a standard power plant setup for a setup with a two-stroke slow speed engine. It should be noted that thrusters are not usually installed on these types of vessels.

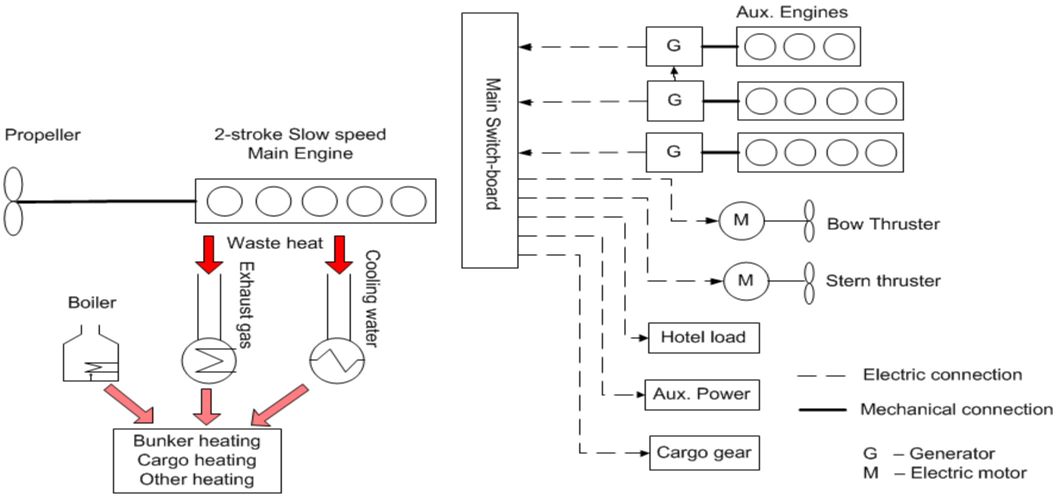

Fig 1: Power and propulsion installations in a standard power plant setup

There is no doubt that the power setup as shown in Fig. 1 was efficient when vessels operated at the high power levels allowed by low fuel prices. However, with higher fuel prices this engine setup will operate at low to medium power. This implies higher specific fuel consumption per kWh produced and, due to incomplete combustion, significantly higher emissions of exhaust gases such as NOx and black carbon (BC), as illustrated by Fig 2. Overall, for low power operation, the CO_2-equivalent emissions increase much faster than the CO_2-only emissions per produced kWh. This implies that low-power operation increases the environmental impact per produced kWh significantly compared to high-power operations.

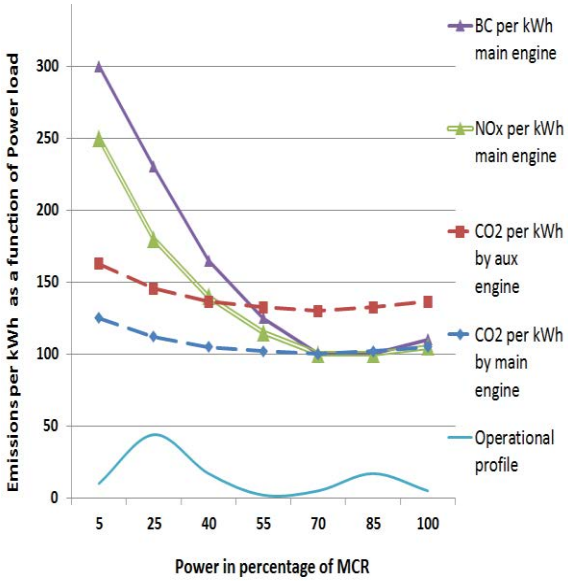

Fig 2: Fuel use and emissions per kWh as a percentage of power (MCR)

There is therefore a need for development of flexible power solutions on sea-going vessels, which can be more energy- and emission-efficient for the full operating range from low to high power loads. Fig. 3 shows three examples of more flexible options. The first of these, the Power Take-Off (PTO) uses the main engine to produce electricity for auxiliary machinery, such as hotel functions and cargo-handling gear, i.e. with lower specific fuel consumption per kWh produced The second, the Power Take Off & Power Take-in (PTO & PTI) also enables the propeller power to be increased by power from the auxiliary engines, and if the main engine stops the aux. engines can be used as the sole source of propulsion power. The third option, PTO & PTI and batteries, also allows power from batteries to be used to boost the available power in a survival condition, for peak shaving in heavy seas, and permits all machinery to be stopped when the vessel is idle at berth in port.

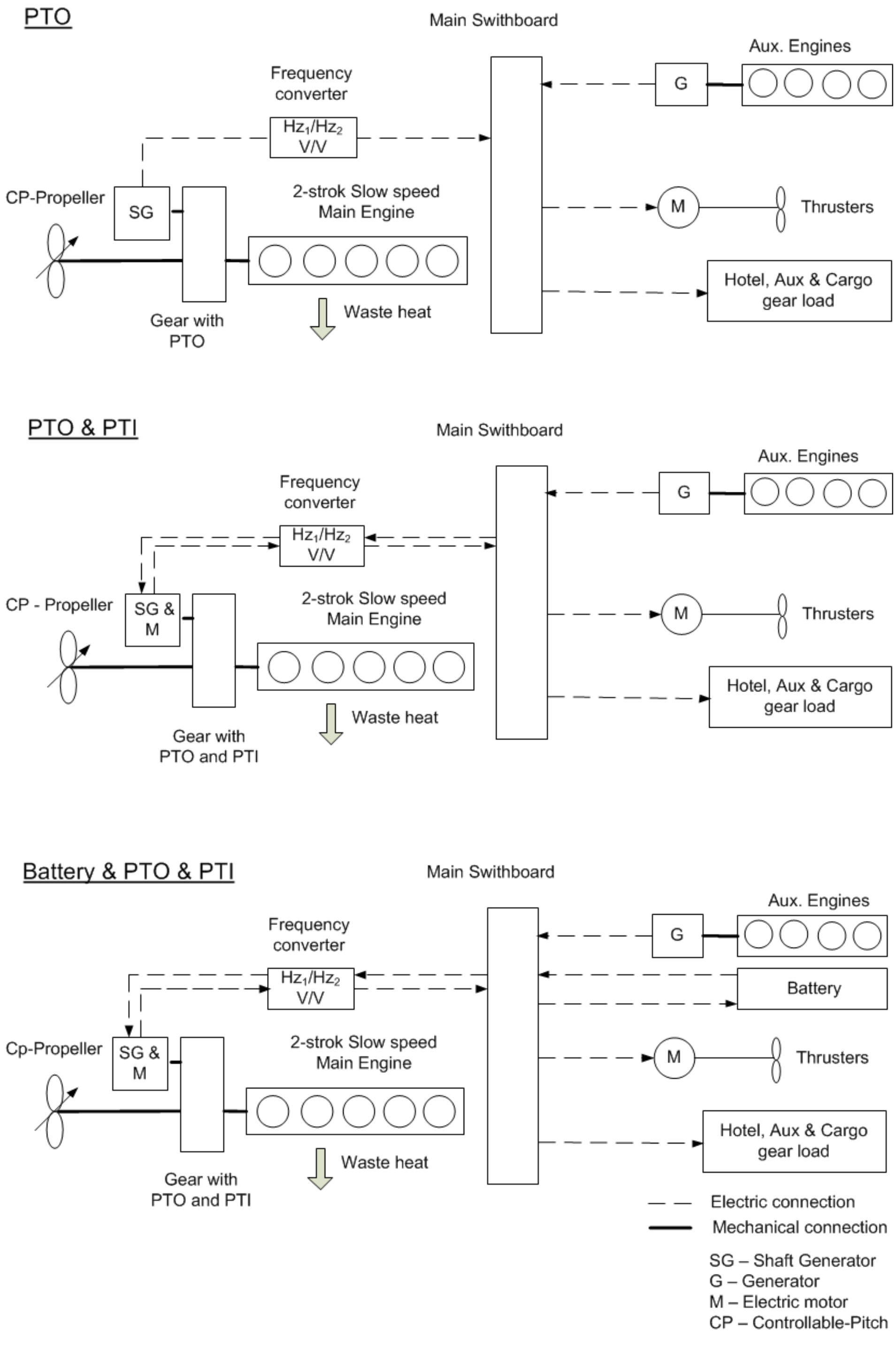

Fig. 3: Power and propulsion machinery setup for alternative hybrid setups

4. ANALYSIS AND RESULTS

We first investigates the climate impact of traditional fuels as a function of the chosen time horizon and the applicable NOx regulation, followed by impact as a function of operational area and impact as a function of power outtake. Table 2 shows the applied GWP factors and average emissions per kWh for

2 – strokes engines which satisfies the Tier 2 NOx regulations with an operational yearly profile containing both slow steaming and speeds close to the design speed (a mix of high and low power outtakes). For engines which shall meet Tier 3 regulation the fuel penalty is around 5 % , while an engine which does not even meet Tier 1 will have approximately 5 % lower fuel consumption.

Table 2: GWP factors and emissions in gram per kWh

Emission type	**CO_2**	**BC**	**CH_4**	**CO**	**N_2O**	**NOx**	**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
HFO 2.7% S - diesel engine average gram per kWh	602	0.13	0.08	1.4	0.02	15	10	0.2
MDO 0.5% - diesel engine average gram per kWh	602	0.09	0.08	1.4	0.02	15	2	0.2
MGO 0.5% - diesel engine average gram per kWh	602	0.09	0.08	1.4	0.02	15	0.4	0.2
LNG - high pressure dual fuel engine average gram per kWh	454	0.03	0.60	1.4	0.02	4.5	0.2	0.2

Exhaust gases which contributes to cooling, are plotted below zero and the warming ones are plotted above zero, and the net effect expressed as CO_2 equivalents are plotted as a red line (Net). Fig. 4 shows that heavy fuel oil (HFO) gives a large cooling effect the first 20 years after the exhaust gases have been emitted, while the low Sulphur alternative marine diesel oil and marine gas oil gives a net warming effect and that this warming effect increases with the stricter NOx regulations from 2016 onwards in US and Canadian water. Fig 5 shows what happens if we increase the time horizon to 100 years. Then the cooling effect from burning HFO is reduced to zero while the warming effect of the low Sulphur MDO and MGO increases further.

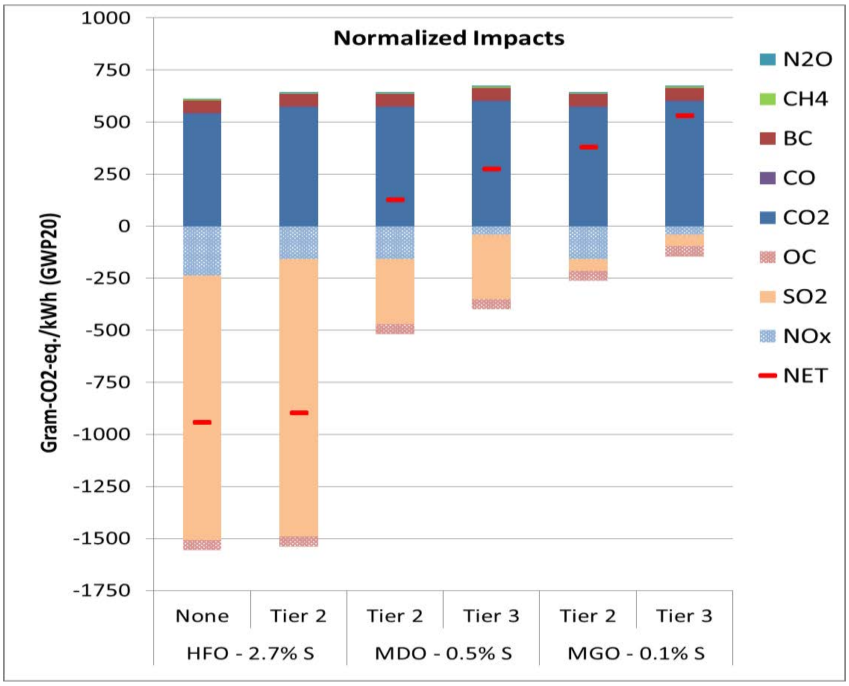

Fig 4: Gram Co2 eq. impact per kWh with a 20 year time horizon (GWP20) as a function of fuel and NOx regulation – Atlantic (Northern hemisphere)

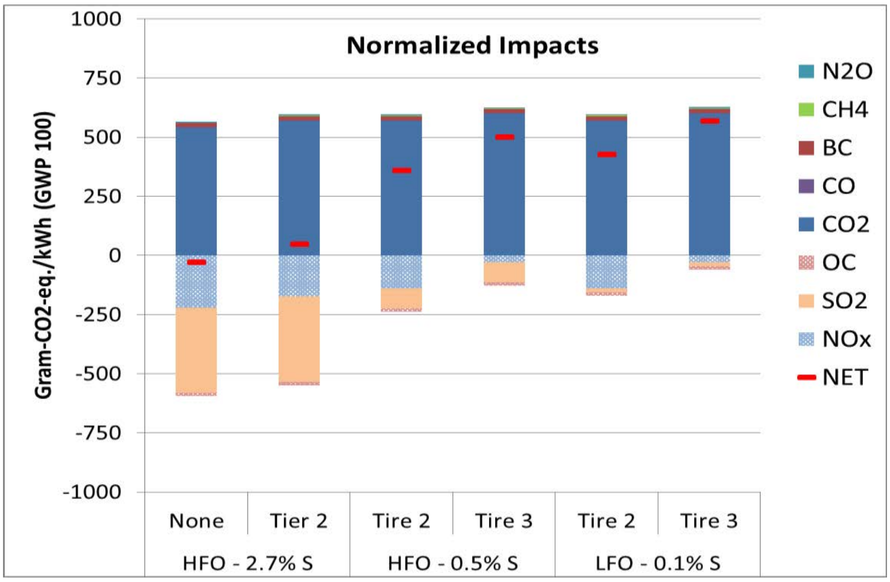

Fig 5: Gram Co2 eq. impact per kWh with a 100 year time horizon (GWP100) as a function of fuel and NOx regulation – Atlantic (Northern hemisphere)

Fig. 6 shows that while HFO gives a large cooling effect when burnt in the Atlantic compared to distillates, it does not give any significant climate benefits compared to distillates or LNG when burnt in the Artic. Fig 7 shows that the climate impact in the Artic can be significantly reduced by hybrid power setup containing PTO & PTI and batteries both such as those (as illustrated by figure 3) compared to traditional engine setups. It should here be noted that the this example is based on 4 stroke engines which has slightly higher fuel consumption than the two stroke ones, and that the LNG slip for the low pressure dual fuel LNG engine is 4 gram per kWh when operated at high power and 6 gram per kWh at low power.

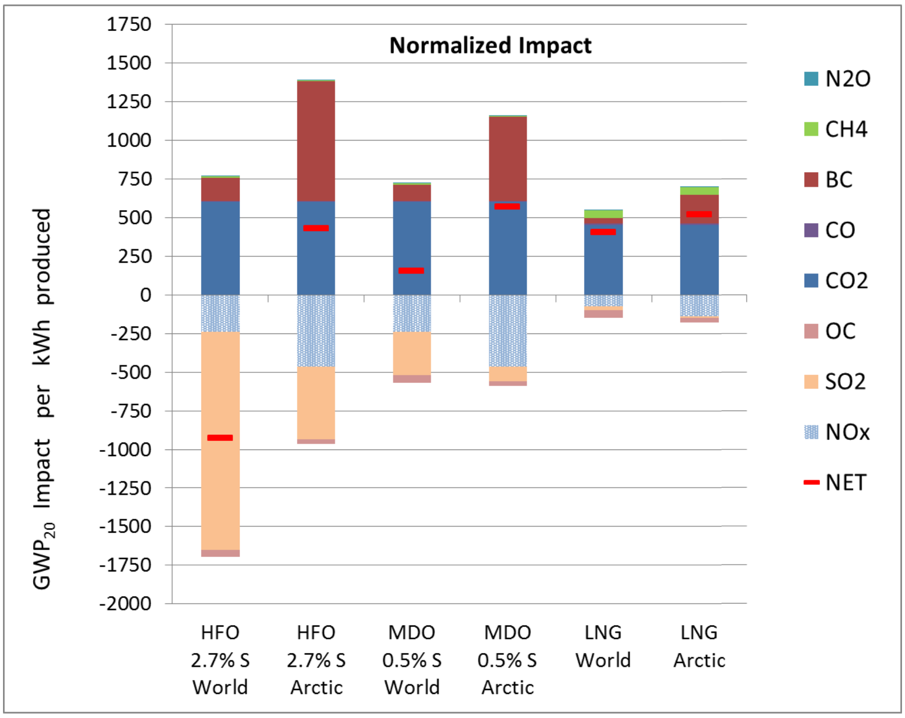

Fig 6: Gram CO2 eq. impact per kWh with a 20 year time horizon (GWP20) as a function of fuel and operational area – Atlantic (Northern Hemisphere) versus Arctic operations

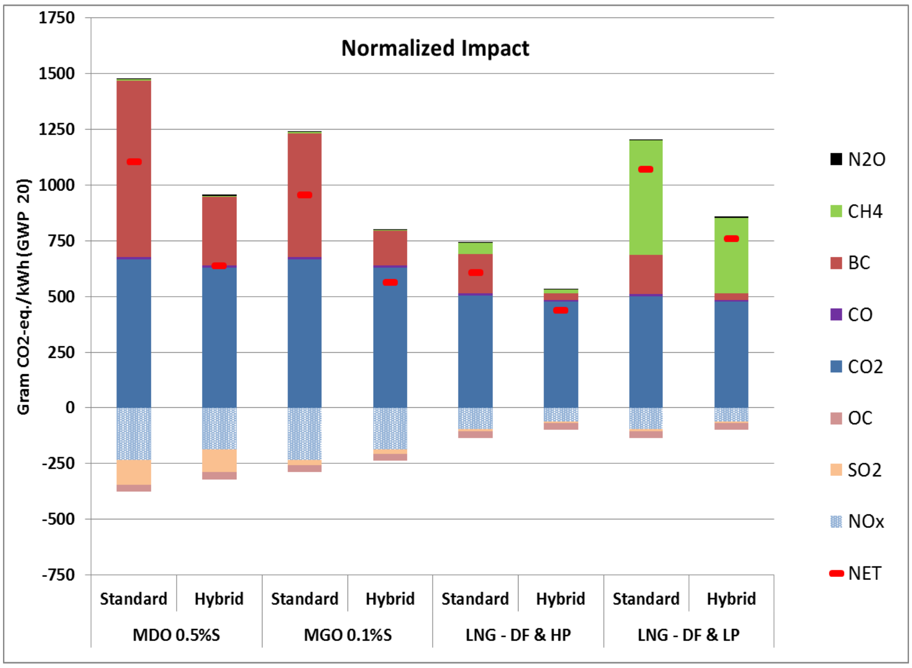

Fig 7: Gram CO2 eq. impact per kWh with a 20 year time horizon (GWP20) as a function of engine technology in the Artic

Based on these figures it can be concluded that apart from Heavy Fuel Oil which gives a cooling (except in the Artic) all distillates and LNG gives a large warming effect and there are no climate mitigation benefits of using LNG compared to conventional distillates (Marine diesel oil or Marine gas oil).

From a climate change mitigation perspective, it is therefore attractive to investigate if other alternative fuels such as Hydrogen could give climate benefits. Hydrogen is best known for being used as a fuel in fuel cells, but it can also be mixed with conventional diesel fuels in a combustion engine. The fuel cell technology utilizes direct electrochemical conversion of fuel energy to electricity and has the potential to operate with nearly zero emission. The key research and development issues that should be addressed for successful utilization of fuel cells on-board ships should be related to the fuel cell capabilities, power system integration, fuel flexibility, endurance and reliability. Specific issues related to power system integration are: hybrid power plant system design and architectures, power inverters and conditioners, operation and maintenance, and total power system energy management and control. Hydrogen storage can be performed in various ways either as compressed gas (CGH2), liquefied hydrogen (LH2) at cryogenic temperature, Cryo-Compressed Hydrogen Storage (CcH2), liquid organic hydrogen storage, chemical hydrogen storage, or absorbed in other materials e.g. metal hydride, glass microspheres and carbon nano-structures. With fuel cells in a hybrid power system, it will be of interest to use hydrogen also in the combustion engines to reduce emissions from piston engines. The mixture of hydrogen with conventional or bio-fuels or simply using hydrogen as an ignition or combustion enhancer are interesting solutions.

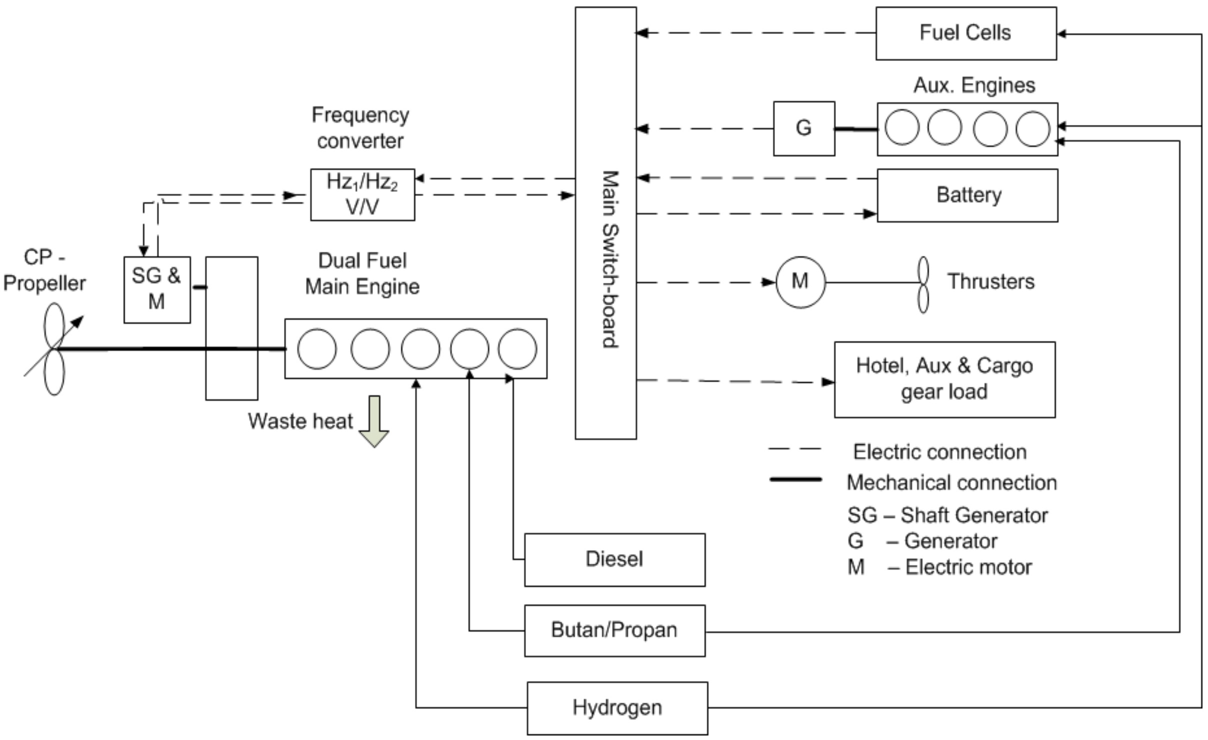

Fig 8: Power and propulsion machinery setup for an advanced hybrid power including hydrogen usage in fuel cells and in the main combustion engine

5. CONCLUSIONS

However, no standardized fuelling solution for hydrogen driven vessels exists. The development of safe, efficient and flexible/universal hydrogen bunkering systems for maritime operation will be complex and depend on factors e.g. upstream and downstream state of hydrogen, requirements for bunkering rate, HSE aspects, and footprint constraints.

Process component requirements and respective duty specifications for the bunkering system will depend heavily on the state of hydrogen in the supply (e.g. decentralized on-site electrolysis or centrally produced liquid hydrogen stored on site) as well as the storage mode on ships (e.g. liquid hydrogen, pressurized gaseous hydrogen or metal hydrides). The two typical extremes in this regard will be liquid-to-liquid transfer, requiring a highly insulated system with hydrogen at near-atmospheric pressure level and extremely low temperature: gas-to-gas transfer, requiring very high-pressure tolerance. Combinations of these two extremes may be highly relevant, such as quayside liquid storage combined with high-pressure storage on the vessel, which will require improved solutions relative to state of the art.

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