Fuels and engine technologies with focus on GHG and Energy utilization

Current greenhouse gas emissions (GHG) from maritime transport represent around 3% of global anthropogenic GHG emissions. These emissions will have to be cut in half by 2050 to be consistent with Paris agreement goals (UNFCCC, 2015; IMO, 2018). Assuming continuous annual sea transport growth of 3% and 1% annual energy efficiency improvements as seen from 1970 (Lindstad, 2013; Lindstad et. al., 2018), the GHG emissions must hence be reduced by 75 – 85% per ton-mile up to 2050, to achieve a 50% reduction of the total sea transport emissions. Basically, the required emissions reduction can be achieved through:

- Reducing fuel consumption per ton or unit transported.
- Switching to fuels with zero or lower carbon content.
- Combining both options.

Previous studies on fuels and engine technologies have tended to focus either on the emission impact of the fuels covering GHG and local pollution in a well-to-wake (WTW) perspective, or on alternative engine technologies in a tank-to-wake (TTW) perspective. In contrast, the motivation for the present study has been to investigate alternative engine technologies with focus on fuel flexibility, potential GHG reductions and energy utilization. This paper is intentionally kept short to ensure that both the authors and the readers keep focus and concentrates on the real differences among the options.

1 SHIP EMISSIONS AND CLIMATE IMPACT

The main source of emissions from a ship is the exhaust gas from its combustion engine, followed by the emissions from producing the ship fuel. Of these exhaust gases, carbon dioxide (CO_2) affects climate only, while carbon monoxide (CO), Sulphur oxides (SOx), nitrogen oxides (NOx), methane (CH_4) and particulate matters including Black Carbon (BC) have both global climate effects and regional and local impacts on human health and environment. Presently, NO_X and SO_X are regulated due to human health and local pollution, and CO_2 is regulated due to global warming through IMO's MARPOL convention. IMO is now under increased pressure to also regulate un-combusted methane (CH_4), which is a GHG gas trapping 85 times more heat than CO_2 over a 20-year period, and Black carbon (soot-particles) which attracts heat in the atmosphere and boosts melting when it lands on snow and ice.

Metrics that weight emitted (exhaust) gases according to their global warming potential (GWP), to report them in terms of "*CO_2 equivalents*" (CO_2eq), are used to communicate their contributions to climate change (Shine, 2009). GWP gives negative weights to 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. GWP20 measures the effect over 20 years and gives a relatively high weight on ‘short lived greenhouse gases’ like methane. In contrast GWP100 gives a larger weight to CO_2 that resides much longer in the atmosphere.

While all gases and aerosols emitted from both man-made activities and the nature influence the global climate, the main focus in the Fifth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC, 2014) was on CO_2, CH_4, N_2O and fluorinated gases. IPCC's First Assessment Report was completed in 1990, and since then there has been a continuous learning curve and advancement of the research front. As an example, the 100-year impact of methane (GWP100) has increased from 21 CO_2eq, used in the Kyoto protocol (1997), to 25 in the fourth IPCC 2007 report, and 30 CO_2eq in the fifth IPCC (2014) report. Recently ICCT (2020) even used 36 in their latest report on LNG as a marine fuel. In practice, increasing the GWP factors for methane implies that methane accounts for a larger share of the total GHG emissions and that the total annual GHG increases as illustrated by Figure 1.

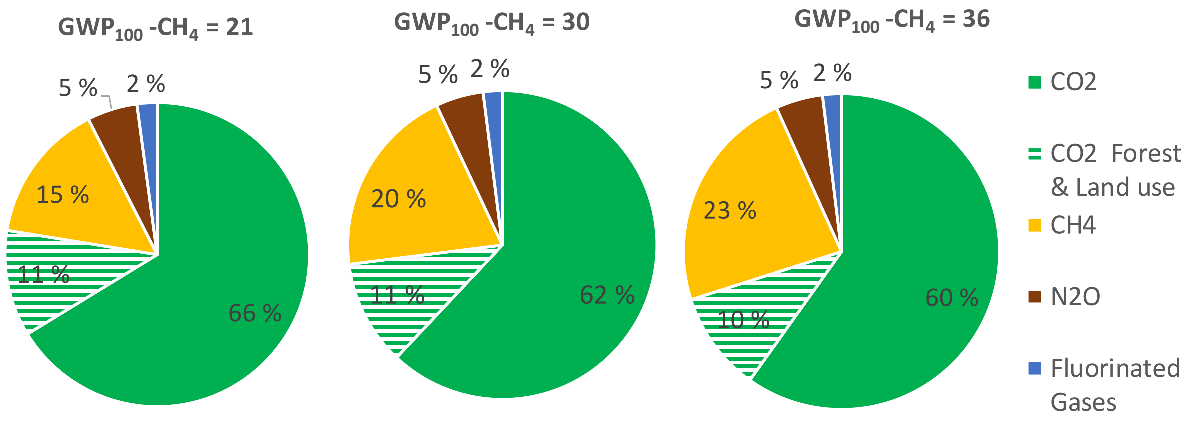

Figure 1: Illustration of the impact of the increased GWP factor for methane (GWP100) on its share of total GHG emissions, using 2010 as the reference year (IPPC, 2014) for the calculations.

2 MATERIALS AND METHODS

Previous studies of marine fuels have used both simplified and more advanced life-cycle assessment (LCA) methodology to assess environmental impacts from fuel extraction and processing to combustion in the ship’s engine. Life cycle assessment enables evaluation of a product environmental performance throughout its whole life cycle from raw materials extraction, through production, usage, end-of-life treatment and final disposal. Previous studies can be grouped into three main categories:

- The first are the well-to-tank (WTT) studies (upstream) that include all emissions from the production of the fuels and the transport needed to deliver them into the ship’s fuel tanks. JEC (2013), Exergia (2015), GREET (2018) and Alvarez (2018), are examples of studies with focus on the well-to-tank supply chains.

- The second group of studies are tank-to-wake studies (TTW), with focus on the combustion of marine fuels as a function of engine technology and fuel (Campling et al, 2013; Johansson et al., 2013; Brynolf et al., 2014; Jiang et al., 2014; Acciaro, 2014; Lindstad et al., 2015). Some of these TTW studies have focused primarily on understanding and optimizing the combustion processes to reduce pollution and un-combusted hydrocarbons (Stenersen and Nilsen, 2010; Hiltner et al., 2016; Stenersen and Thonstad, 2017; Hutter et al., 2017; Krivopolianskii et al., 2018; Ushakov et al., 2018; Ushakov et al., 2019).

- The third group of studies are well-to-wake (WTW) studies that assess the overall emissions from the fuel supply and the fuel combustion in the ship's engine. Compared to full LCA studies, the complexity is reduced by excluding the construction and decommissioning phase for the oil and gas chains. Comparing these initial studies (Bengtson et al., 2011; Verbeek et al., 2011; Chryssakis and Stahl, 2013; Bengtson et al., 2014; Brynolf et al., 2014; Brynolf et al., 2014a) with the newest studies within the field (Thinkstep, 2019; Lindstad, 2019; ICCT, 2020; Lindstad and Rialland, 2020), the initial studies generally assumed lower energy consumption for producing LNG than for producing diesel (MGO). Furthermore, the initial studies assumed low methane slip upstream, or did not took it into account. In the present study, the analysis is based on the most recent knowledge and publications. Figure 2 illustrates the well-to-wake emissions for conventional fuels, LNG, ammonia, hydrogen.

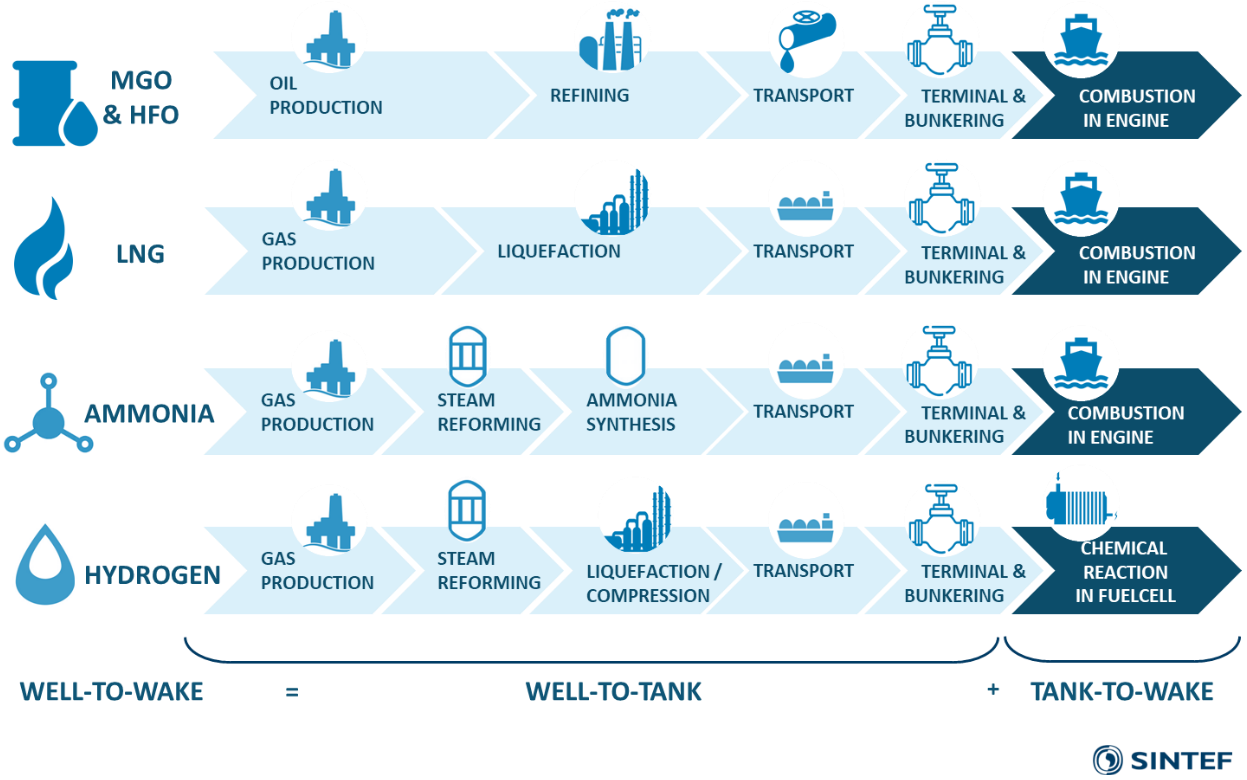

Figure 2: Well-to-Wake emissions for conventional fuels, LNG, ammonia, hydrogen.

3 ENGINE TECHNOLOGY

In the old days, ocean-going ships were powered by sail and the duration of the voyage was totally dependent on the wind, weather and the currents. With the invention of the coal-fired steam engine, the first vessel powered by steam was introduced 200 hundred years ago (1820). Still, in many trades, the steamship never became competitive against sailing vessels; one reason was that on long voyages the amount of coal needed to power the ship would occupy most of its cargo carrying capacity, due to low thermal efficiency of the steam engines and the low energy content of the coal. In 1903 the first motorship was launched, with the diesel engine invented by Rudolf Diesel (1893, 1897). The high energy intensity of diesel combined with the high thermal energy efficiency of the diesel engine reduced the required space and weight of the fuel to be carried onboard to a tenth (1/10) compared to steamships. Due to this the motorships outcompeted both the coal-fired steamships and the sailing vessels over the next decades up to the 1930s.

Today, when the diesel engine is challenged by alternative power solutions, it is neither due to its high thermal energy efficiency of around 50%, the high energy density of the diesel, the price of the fuel, safety, nor the easiness of its operation. The main reason is the need to reduce GHG emissions, and secondary the need to reduce local pollution in areas with high air pollution.

In this study, we assessed the following fuels and their associated engine technologies with focus on GHG and energy utilization, both on a well-to-wake basis:

- HFO, VLSFO and MGO (Heavy Fuel Oil, Very Low Sulphur Fuel Oil, and Marine Gas Oil) are combusted in traditional diesel engines or in dual fuel engines. Dual fuel means that the engine can run on both liquid and gaseous fuels.
- Liquefied Natural Gas (LNG) is burnt in dual fuel engines, either in low-pressure dual-fuel-Otto-engines or high-pressure dual-fuel-diesel-engines.
- Liquefied Petroleum Gas (LPG), methanol and ammonia (coming soon) is burnt in high-pressure dual-fuel-diesel-engines.
- Hydrogen and ammonia can be used as fuel, for fuel cells to produce electricity for electric motors to power the vessel. A fuel cell is an electrochemical cell that converts the chemical energy of the fuel and an oxidizing agent (often oxygen) into electricity through a pair of redox reactions.
- Electricity stored in batteries on board for electric motors to power the vessel.
- Biofuels, either burnt in diesel engines if they are a biodiesel or in dual fuel engines if they come in any other form.

In the following sections we will focus on the most important issues regarding the engine technologies for the purpose of this assessment. In a high-pressure dual-fuel-diesel-engine, the fuel is injected at a pressure of 300 – 350 bar and ignited by a small amount of diesel. The resulting combustion is nearly complete. This implies nearly zero methane slip when the engine is powered by methane (LNG). Another benefit of the high-pressure dual-fuel-diesel-engine is that it can burn nearly any fuel currently known, i.e. conventional fuels, biofuels, LNG, LPG and ammonia, all with a high and consistent thermal energy efficiency. Some of these fuels will require modifications of the engine injection and control systems, but the engine is prepared for it, so the required modifications are moderate. The diesel process runs with high combustion temperatures, and after treatment of the exhaust gas through Selective Catalytic Reduction (SCR) or Exhaust gas Recirculation (EGR) are needed to meet IMO Tier 3 NOx requirements.

In a low-pressure engine, the LNG is injected under low pressure, comparable to the Otto cycle (petrol engine). A benefit of the low-pressure, is that it gives low NOx emissions, and hence fulfils IMO tier 3 NOx requirements without after treatment of the exhaust gas. Its disadvantage is that the methane slip (due to unburnt methane) is much higher than for the dual-fuel-diesel-engine, both at high and low engine loads. The methane slip at medium and high loads originates from the pre-mixing of air and fuel, allowing the air/fuel mix to enter regions of the cylinder where combustion will not occur, i.e. crevices, cylinder wall (Krivopolianskii et al., 2018). At low loads (25% or less), achieving complete combustion is even more challenging, due to bulk quenching in the coldest areas of the combustion chamber (Heywood, 2018) resulting in high methane slip and hence also higher fuel consumption (Stenersen and Thonstad, 2017). Adding it all up, also the thermal energy efficiency tends to be lower for the dual-fuel-Otto-engine when it run on LNG compared to the dual-fuel-diesel-engine. For more insight, see Ushakov et al. (2019). When a dual-fuel-Otto-engine runs on diesel, due to fuel prices or lack of LNG availability, the lower thermal efficiency also implies a higher fuel consumption compared to a conventional diesel engine. Assuming a higher thermal efficiency both for dual-fuel-diesel-engines and pure-diesel-engines compared to dual-fuel-Otto-engine is in line with ICCT (2020).

For fuel cells we have seen a rapid development since 2000 motivated by the need for reducing the transport sector's GHG emissions and its contribution to local pollution. Proton-exchange membrane fuel cells, also known as polymer electrolyte membrane fuel cells (PEMFC), are a type of fuel cell being developed for transport applications, as well as for stationary fuel-cell applications. Their distinguishing features include that they operate at temperature in the range from 50 to 100 °C and a low pressure. Regarding thermal energy efficiency, the PEMFC are at a comparable level to the combustion engines, i.e. around 50%.

Batteries and electric motors to power vessels is not a recent invention. It was used on smaller vessels from the 1880s until the 1920s, when the internal combustion engine became dominant. With increased focus on GHGs and local pollution, it has become attractive again, both in hybrid setups in combination with combustion engines and to enable fully electric vessels. There have been significant technical advances in battery technology in recent years, and more are to be expected in the future. When the batteries are charged from the onshore grid with Green electricity (from renewable energy source), a fully electric ship will emit no GHGs, nor any exhaust gases causing local pollution, with a very high-energy, i.e. around 80% including both battery and electric motors. The disadvantage is that batteries have a very low energy intensity both in weight and volume compared to conventional fuels as diesel (MGO). However, too show the full future potential of batteries we have included three possible future battery technologies in addition to the present one.

4 Well-to-tank GHG emissions

Well-to-tank emissions include all emissions from the production of the fuels and the transport needed to deliver them into the ships' fuel tanks. For a conventional fuel it includes oil production, processing and transport to the refinery, oil refining at the refinery, transport to the ship and bunkering operation. In the past, studies have shown:

- Very different greenhouse gas (GHG) impacts from the use of LNG, and few of these studies have compared their results with other studies.
- In comparison, previous studies have shown only small variations between published GHG impacts of MGO, VLSFO and Liquid Petroleum Gas (LPG).
- For Biofuels, there are large variations in WTT emissions, due to their different source of origins and all indirect effects. Biodiesel, biogas, bio-jet-fuel, ethanol, methanol – the type of biofuel does not matter much. It is the kind of plant or animal which the biofuel is made from that determines the well-to-tank emissions of using biofuels. Biofuels are not allocated any tank-to-wake emissions since the basic theory is that any carbon combusted from biofuels was first sequestered by plant growth, so there is no net change in atmospheric carbon.
- Both hydrogen and ammonia have well-to-tank emissions, with a magnitude that depends on their production process.

To provide a concise overview, the specific well-to-tank emissions of each fuel will be commented and displayed through tables and figures in the following well-to-wake chapter.

5 Well-to-wake GHG emissions

This section contains the following sub-sections focusing on well-to-wake emissions: fossil fuel; biofuels; zero-carbon fuels (hydrogen and ammonia). To enable traceability and easy comparisons, diesel (MGO) is kept as the reference fuel through all comparisons.

5.1 Fossil fuels well-to-wake GHG emissions

The following fossil fuels have been included: MGO, VLSFO, HFO in combination with Scrubber, LNG, LPG and Methanol. The first three are made from crude oil while LNG, LPG and Methanol are made from natural gas. In principle, with modern technology and advanced chemistry, nearly any fossil feedstock can be used to produce nearly any fossil fuel, but that tends to come at a high cost and increased well-to-tank emissions compared to the standard pathways. ICCT (2020) and Lindstad and Rialland (2020) found that estimates of well-to-tank (WTT) emissions can vary widely across previous studies both for LNG and when LNG is compared with conventional fuels. In comparison, previous studies have shown only small variations between published GHG impacts of MGO, VLSFO and LPG. For more insight, see Lindstad and Rialland (2020). There are reasonable reasons for some of these variances. However, what is needed to make fair comparison between individual fuels are the relative differences between the fuels found in each of the main previous studies. Table 1 contains the WTT emissions values in CO_2 equivalents ($CO_{2e}q$) with GWP100 for LNG and conventional fuels applied by recent studies (Thinkstep, 2019; Lindstad, 2019; ICCT, 2020) and two studies performed 5 – 7 years back in time (JEC, 2013; Exergia, 2015). In this study MGO is kept as the reference fuel, i.e. 100%, so all relative differences are quoted versus MGO.

Table 1: WTT GHG emission estimates for alternative fuels

Previous studies (GWP100)	LNG	MGO	VLSFO	HFO	LPG	LNG/MGO
	Gram CO_2 eq per MJ					
JEC (2013) JRC-Concawe	19.4	15.4			8.2	126 %
Exergia (2015)	19.4	15.0				129 %
Thinkstep (2019) Middle East	18.2	13.5	11.7	11.9		135 %
Thinkstep (2019) Global average	18.5	14.4	13.2	13.5	8.2	128 %
Lindstad (2019)	18.5	14.4	13.2	9.6		128 %
ICCT (2020) North America	21.5	17.4	16.8	14.3		124 %

The main observations from Table 1 are: First, that the relative differences between the individual studies regarding LNG is smaller than the variance for MGO; Second, when we divide the LNG value on the MGO value for each study, the study results are quite close, i.e. that WTT emissions for LNG are 24 – 35% higher than for MGO. The Thinkstep (2019) report is well known and publicly available, and its figures for LNG, MGO and VLSFO are all within the main range of published values. Therefore, we use them for the WTT calculations in this study. For HFO there is a large variation in HFO estimates; First, due to differences in allocation principles; Second, the chemical composition of the crude in different region, i.e. light weighted easily refined North sea crude oil, versus heavy crude oil with a higher sulphur content from oil-sand; Third, transforming all the crude into distillates at modern highly advanced refineries tends to come at a high energy consumption compared to just leave a part of it, as heavy fuel oil to be burnt in ship engines or at power stations (Shell, 2016; Lindstad et al., 2017). One of the arguments for scrubbers is that they burn HFO (from 2020 onwards) coming from older and less advanced refineries, where the HFO are the bottom of the barrel (waste product). For these reasons, we use the values by Lindstad (2019) of 9.6 gram of CO_2eq per MJ for HFO to fully exploit the maximum GHG reduction potential of using HFO in combination with scrubbers.

For methane slip, when LNG is used as fuel, we investigate two scenarios for the dual-fuel Otto-engine. First, a low estimate based upon test bed measurements of methane (CH_4) slip and that thermal engine efficiency for a dual-fuel-Otto-engine can be nearly equal to diesel engines, apart from the methane slip, which in addition to its GHG effect increases the fuel consumption. The test bed values (Thinkstep, 2019) for the Otto-engine are 2.1 gram of un-combusted methane for the 2-stroke engine.

Second, an operational scenario based upon that real methane (CH_4) slip on ship in operations is higher than in test bed when the test cycle is performed on a ship at sea (Stenersen and Thonstad, 2017). However, even these values, might underestimate the real methane slip, since most of the global fleet today operates at around 50% power (Lindstad and Bø, 2018; Fairplay,

2018) and not at around 70% as assumed by the NOx test cycle. The explanation is that when power decreases below 50%, the methane slip in % of fuel consumption increases (Stenersen and Thonstad, 2017; Ushakov et al., 2018; Ushakov et al., 2019). Therefore, for the operational scenario 4 gram of un-combusted is applied. In comparison ICCT (2020) used 2.5 gram and Lindstad (2019) used 4 gram of un-combusted methane per kWh.

For the dual-fuel-diesel-engine, the testbed value (Thinkstep, 2019) and the operational values (Lindstad, 2019; ICCT, 2020; personal communication with MAN 2020) are all in the range of 0.14 – 0.3 gram per kWh. These variations make only very marginal impact of the assessment, so to make it simple, we will use 0.3 gram of un-combusted methane per kWh.

The main values for each of the fossil fuel and engine options assessed are shown line by line in Table 2. The numbers in the first column are used to show the origin of the values on that line, where 1 (one) is used for general consensus values such as lower calorific value of each fuel, 2 (two) is used for our input values and 3 (three) are the calculated values based on 1 and 2.

From Table 2 on next page we observe that:

- First, LNG combusted in a high-pressure dual-fuel-diesel-engine reduces GHG emissions with 9 – 15 % compared to MGO.
- Second, LNG combusted in a low-pressure dual-fuel-Otto-engine increases GHG emissions significantly in a short-term horizon (GWP20), i.e. 15 – 40% increase compared to MGO. And even with a long-term horizon it does not give any real reductions compared to MGO.
- Third, when the dual-fuel engines run purely on MGO, the GHG emissions increase by around 7% for the low-pressure dual-fuel-Otto-engine, compared to when the MGO is combusted in either a pure diesel-engine or in a dual-fuel-diesel-engine.
- Fourth, the potential GHG reduction with scrubbers are up to 3 – 4 % compared to MGO when combusted in a diesel engine when we assume that HFO is the bottom of the barrel from a traditional oil refinery.

Table 2: Well-to-wake (WTW) CO_2eq emissions per kWh for 2 -stroke engines

	2 - stroke engines		HFO & Scrubber Diesel engine	VLSFO Diesel engine	MGO Diesel engine	LNG DF Diesel engine	LNG DF Otto-engine (test bed)	LNG DF Otto-engine	MGO DF Diesel engine	MGO DF Otto engine	LPG DF Diesel engine	Methnol DF Diesel engine	Bio LNG DF Diesel engine	Bio LNG DF Otto engine
1	CO_2 emission factors		3.114	3.176	3.206	2.75	2.75	2.75	3.206	3.206	3.02	1.375	2.75	2.75
1	Low Caloric Value	MJ/kg	40.2	41.0	42.7	49.2	49.2	49.2	42.7	42.7	46.0	19.9	49.2	49.2
1	CH_4 - GWP100 CO_2 eq.					30	30	30					30	30
1	CH_4 - GWP20 CO_2 eq.					85	85	85					85	85
2	Thermal eng. efficiency	%	50 %	50 %	50 %	50 %	49.3 %	48.0 %	50 %	47 %	50 %	50 %	50 %	48 %
3	Compared to Diesel eng.	%				100 %	98.6 %	96.0 %	100 %	94 %	100 %	100 %	100 %	96 %
3	SFOC - Main fuel	Gram/kWh	180.0	176.4	169.4	146.0	147.8	151.7	169.4	180.2	151.0	348.9	146.0	151.7
2	SFOC - Pilot Fuel	Gram/kWh				1.5	1.5	1.5			6.0	6.0	1.5	1.5
2	Methane Slip	Gram/kWh				0.3	2.1	4.0					0.3	4.0
3	TTW - GWP100 CO_2eq.	Gram/kWh	560	560	543	415	474	542	543	580	475	499	9	120
3	TTW - GWP20 CO_2eq.	Gram/kWh	560	560	543	432	590	762	543	580			432	762
2	WTT - GWP100 CO_2eq.	Gram/MJ	9.6	13.2	14.4	18.5	18.5	18.5	14.4	14.4	8.3	31.3	19.5	19.5
3	WTT - GWP100 CO_2eq.	Gram/kWh	69	95	104	133	135	139	104	110	60	225	142	146
2	WTT - GWP 20 CO_2eq.	Gram/MJ	14.1	19.6	20.8	27.9	27.9	27.9	20.8	20.8				
3	WTT - GWP20 CO_2eq.	Gram/kWh	102	141	150	201	204	209	150	160				
3	WTW - GWP100 CO_2eq.	Gram/kWh	630	655	647	549	609	681	647	690	535	724	151	266
3	WTW - GWP20 CO_2eq.	Gram/kWh	662	702	693	633	794	971	693	740				
3	WTW - GWP100 in % of MGO		97 %	101 %	100 %	85 %	94 %	105 %	100 %	107 %	83 %	112 %	23 %	41 %
3	WTW - GWP20 in % of MGO		96 %	101 %	100 %	91 %	115 %	140 %	100 %	107 %				

These results are first visualised in Figure 3 for all the assessed fuels with GWP100. Thereafter, Figure 4 and 5 shows on one page the impact of using a 20 versus a 100-year time horizon when LNG and alternative LNG engine technologies are assessed on a WTW basis against conventional fuels (MGO, VLSFO, HFO & Scrubber). The figures show grams of CO_2eq per kWh for well-to-tank, tank-to-wake and methane slip for each of the investigated fuel and engine combinations. Moreover, the vertical dashed line shows the baseline value, i.e. the WTW of MGO, and the green number on its right side shows the value in % of the MGO-baseline.

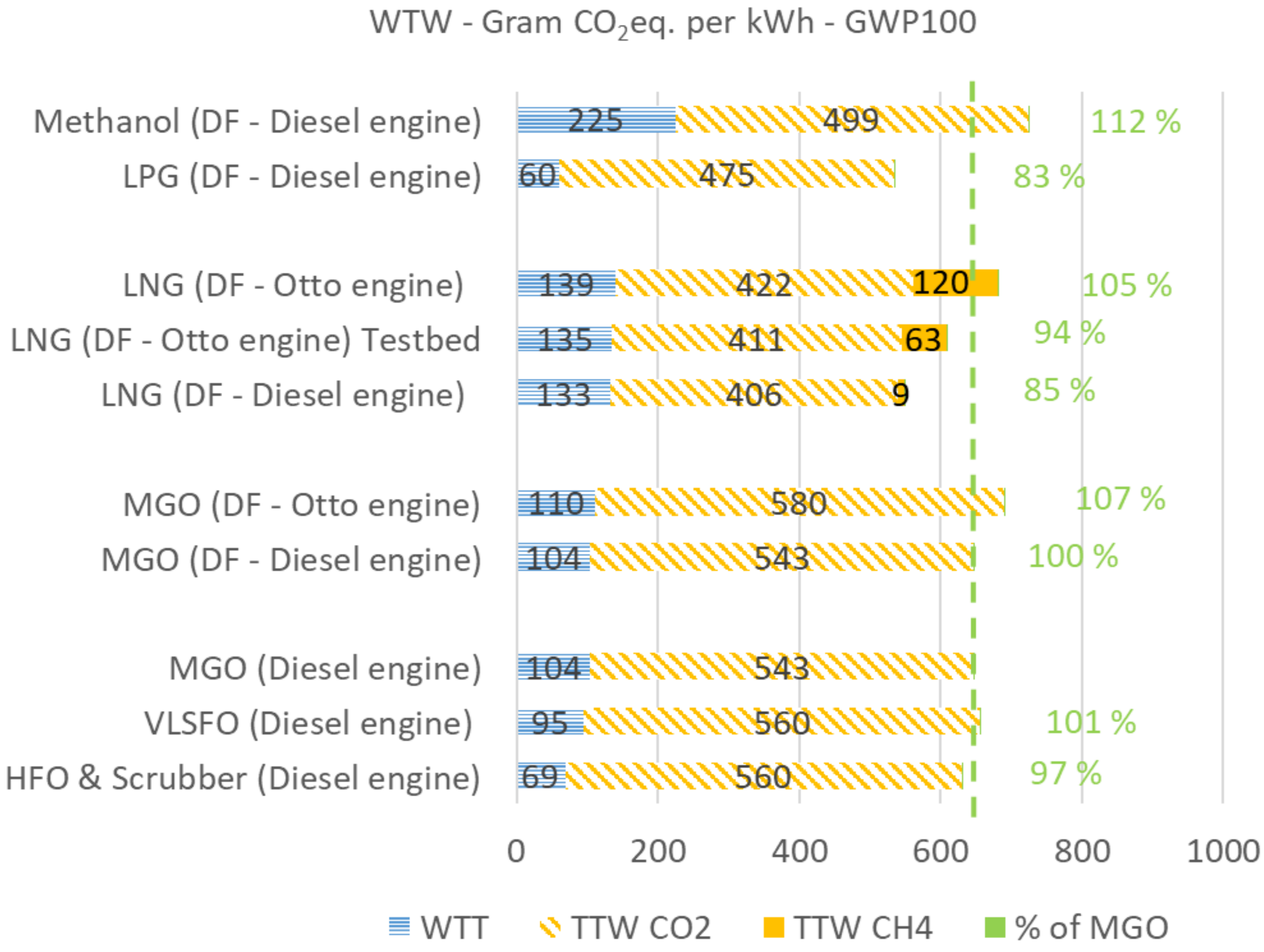

Figure 3: WTW CO_2eq emissions per kWh (GWP100) for fossil fuels and 2-stroke engines

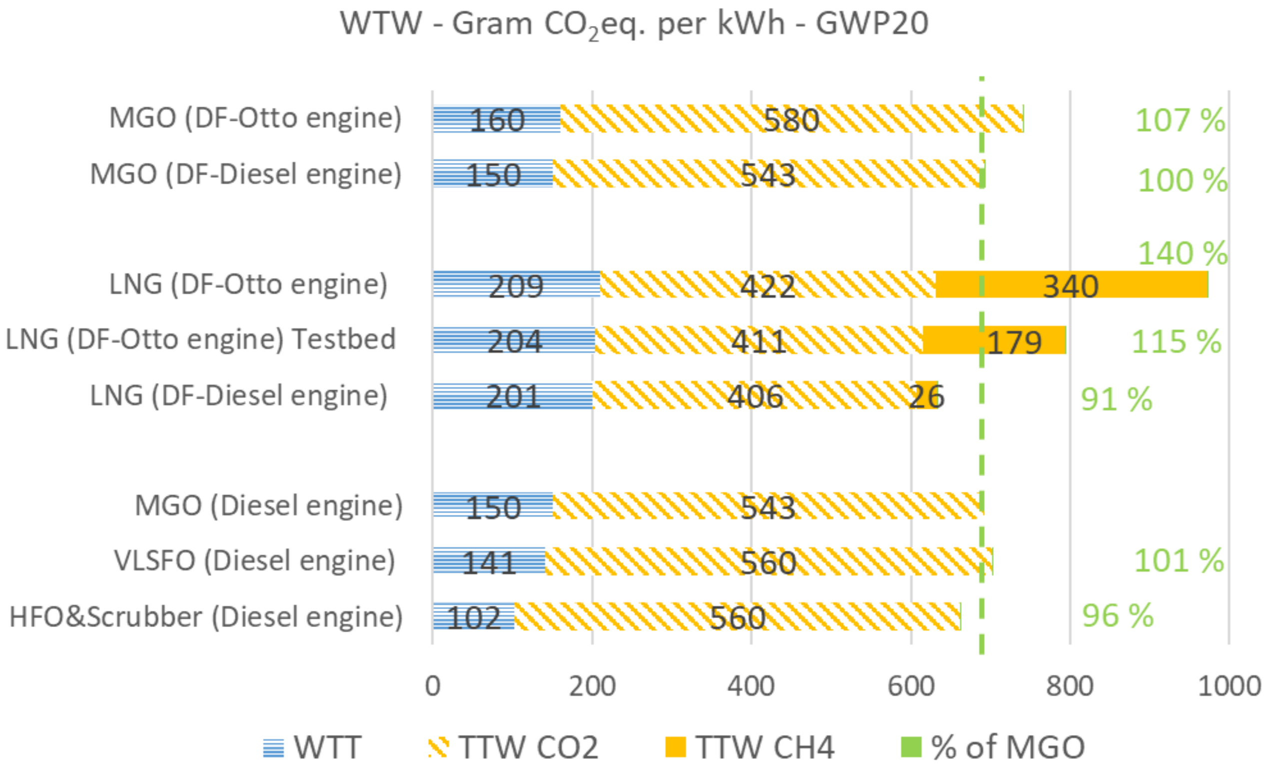

Figure 4: WTW CO_2eq emissions per kWh (GWP20) as a function of fuel and 2-stroke engine

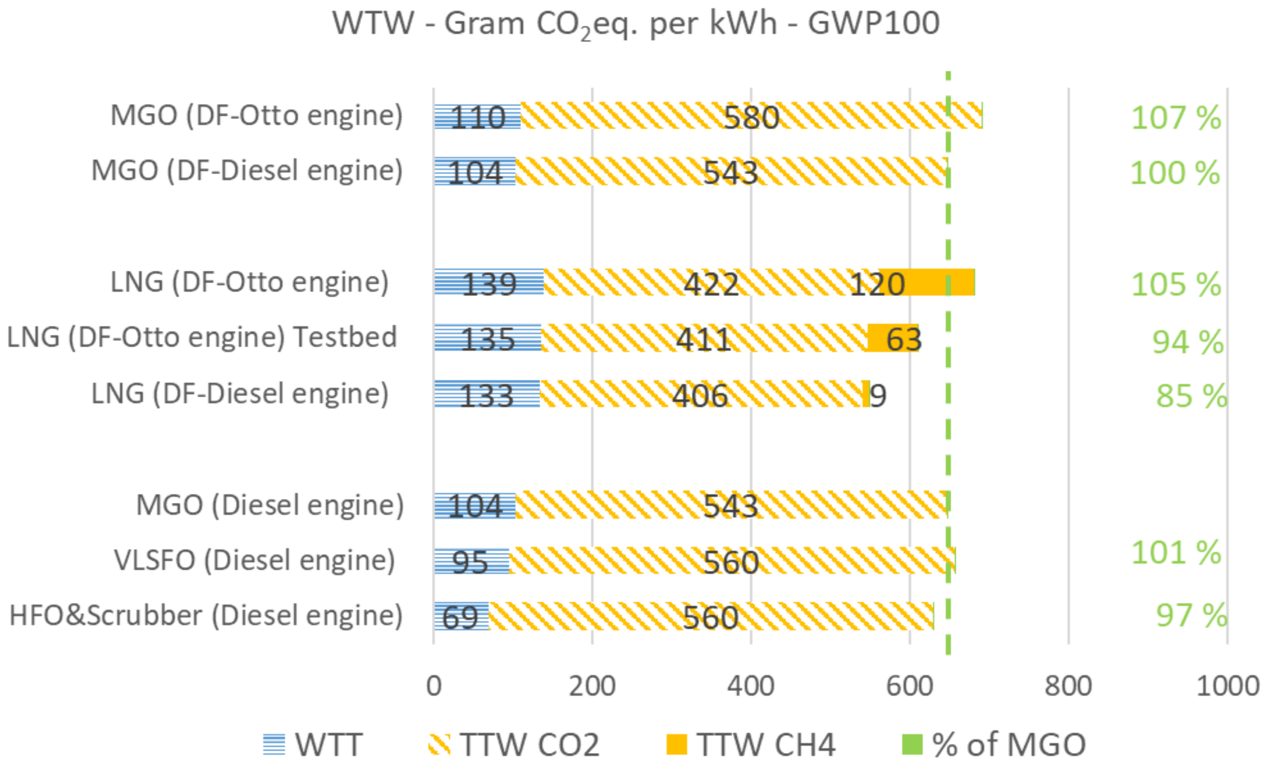

Figure 5: WTW CO_2eq emissions per kWh (GWP100) as a function of fuel and 2-stroke engine

5.2 Bio-fuels Well-to-Wake GHG emissions

Biofuels have no tank-to-wake emissions since the basic theory is that any carbon combusted from biofuels was first absorbed by plant growth, so there is no net change in atmospheric carbon. Compared to fossil fuels, the difference in biofuels well-to-tank emissions are of much larger scale due to their different source of origins and the indirect effects of alternative biofuels. Basically, it is the kind of animal, plant or waste which the biofuel is made from that determines its well-to-wake emissions, plus other GHGs than CO_2 emitted when combusted, i.e. mainly CH_4.

Figure 6 shows these differences and the large variations in values published by previous studies. Number 1 is the *State-of-the-Art technologies, measures, and potential for reducing GHG emissions from shipping* study (Bouman et al., 2017); Number 2 is used for *The Role of Sustainable Biofuels in Decarbonising Shipping* (SSI, 2019) presented at Cop 25 in December 2019. Number 3 shows that the impact of un-combusted methane is the same as for fossil fuels (Thinkstep, 2019; Lindstad, 2019).

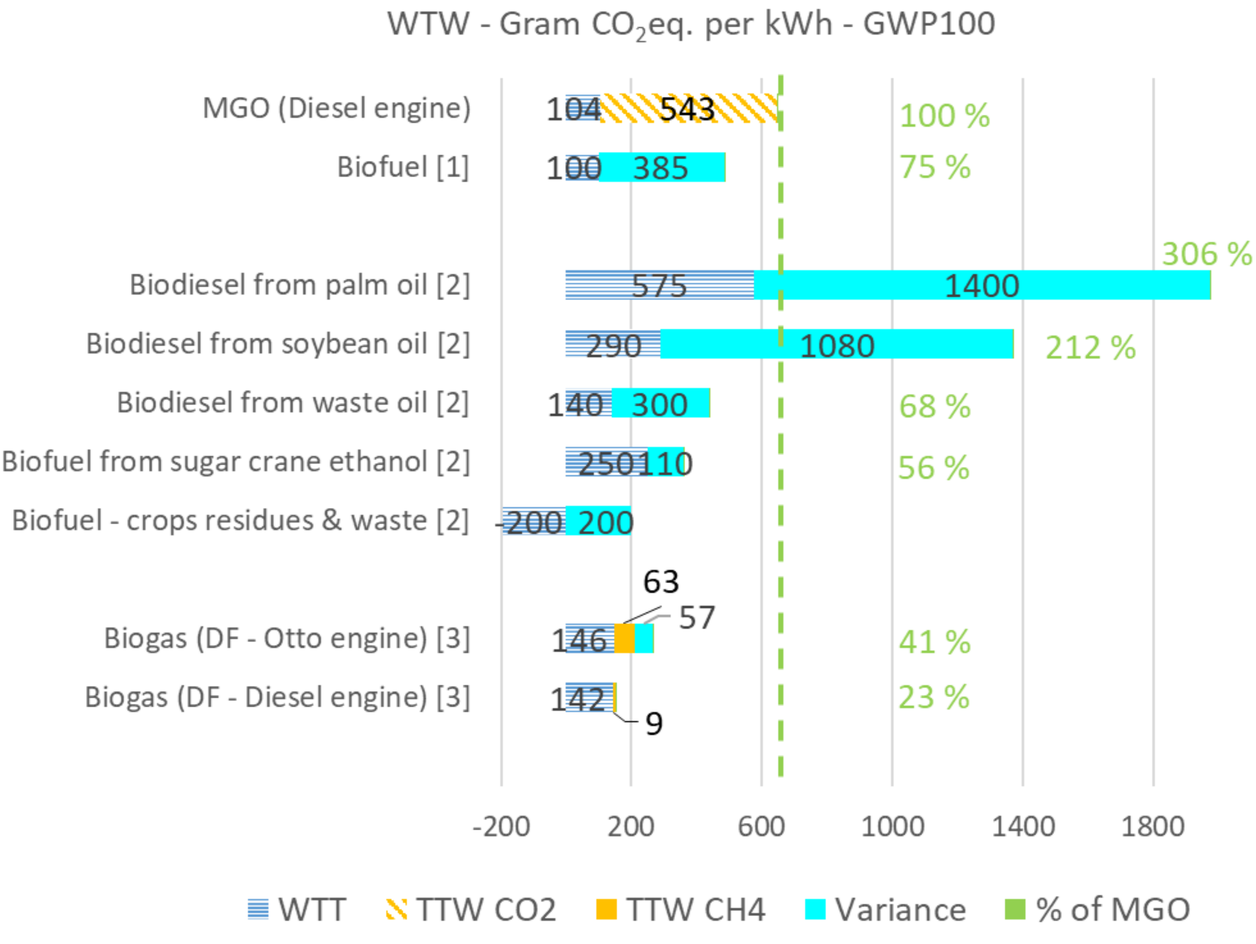

Figure 6: WTW CO2eq emissions per kWh (GWP100) for distinct biofuels

The observations are that some of the biofuels give only marginal reductions and in worst case, significant increases compared to fossil fuels. In contrast, other biofuels such as waste (including animal manure), might even give net GHG reductions. The big question which will be answered through the project Bio4-7Seas (NTNU Industrial Ecology and SINTEF Ocean) is: *What is the climate change mitigation potential of biofuels in the maritime sector*. Bio4-7Seas will start in the autumn of 2020.

If we turn the focus to alternative engine technologies, we can independently of the outcome of the Bio4-7Seas conclude that the dual-fuel-diesel-engines have the same advantages compared to the dual-fuel-Otto-engines as it has for fossil fuels, i.e. significantly lower methane slip when it run on biogas (methane) and overall, higher thermal energy efficiency. In addition, the dual fuel diesel engine can burn nearly any biofuel, while a pure diesel engine needs the biofuel in the form of biodiesel.

5.3 Hydrogen and ammonia well-to-wake GHG emissions

Hydrogen and ammonia are both fuels with zero carbon content, i.e. H_2 and NH_3 and hence no carbon are emitted when they are converted to propulsion energy in the fuel cell or in the dual-fuel-diesel-engine (ammonia only). It will hence be their WTT emissions that will make up their total WTW emissions. Hydrogen and ammonia are either made through steam reforming of natural gas or from electrolysis of water. Both processes are energy demanding, where around a third of the input energy is lost through the conversion process, i.e. to get One (1) ton of oil equivalent (TOE) of hydrogen we need around 1.5 TOE of natural gas as input. Compared to cooling down the natural gas to LNG and burn it in a dual-fuel diesel engine, the hydrogen or ammonia options will therefore come at around 50% higher cost and 50% higher CO_2eq. emissions per energy unit (TOE).

In reality this performance gap might be even larger: First, because additional energy are needed to pressurize or liquefy the hydrogen to a volume that makes it possible to carry it at sea; Second present fuel cells (PEMFC) in combination with the electric setup gives a lower thermal energy efficiency then the diesel engine and hence a higher fuel consumption; Third, while ammonia can be burnt in a dual-fuel-diesel-engine with nearly the same thermal efficiency as MGO or LNG, it is made from hydrogen in a conversion process using additional energy. The Sankey diagrams in Appendix 1 show the production pathways for the hydrogen and ammonia option assessed in this study, the energy input, the loses and what is delivered for propulsion. These Sankey diagrams have been made by Dr. Jørgen Bremnes Nilsen and Dr. Torstein Aarseth Bø, both Researchers at SINTEF Ocean.

The variance for each of the fuels in the Figure 7 expresses the difference between the steam reforming and the electrolysis. Here using the present EU-el mix, electrolysis comes at a higher emission level than steam reforming. At the top of the figure (after MGO and LNG) we find the WTW levels for hydrogen and ammonia produced with green fully renewable electricity used for the electrolysis process.

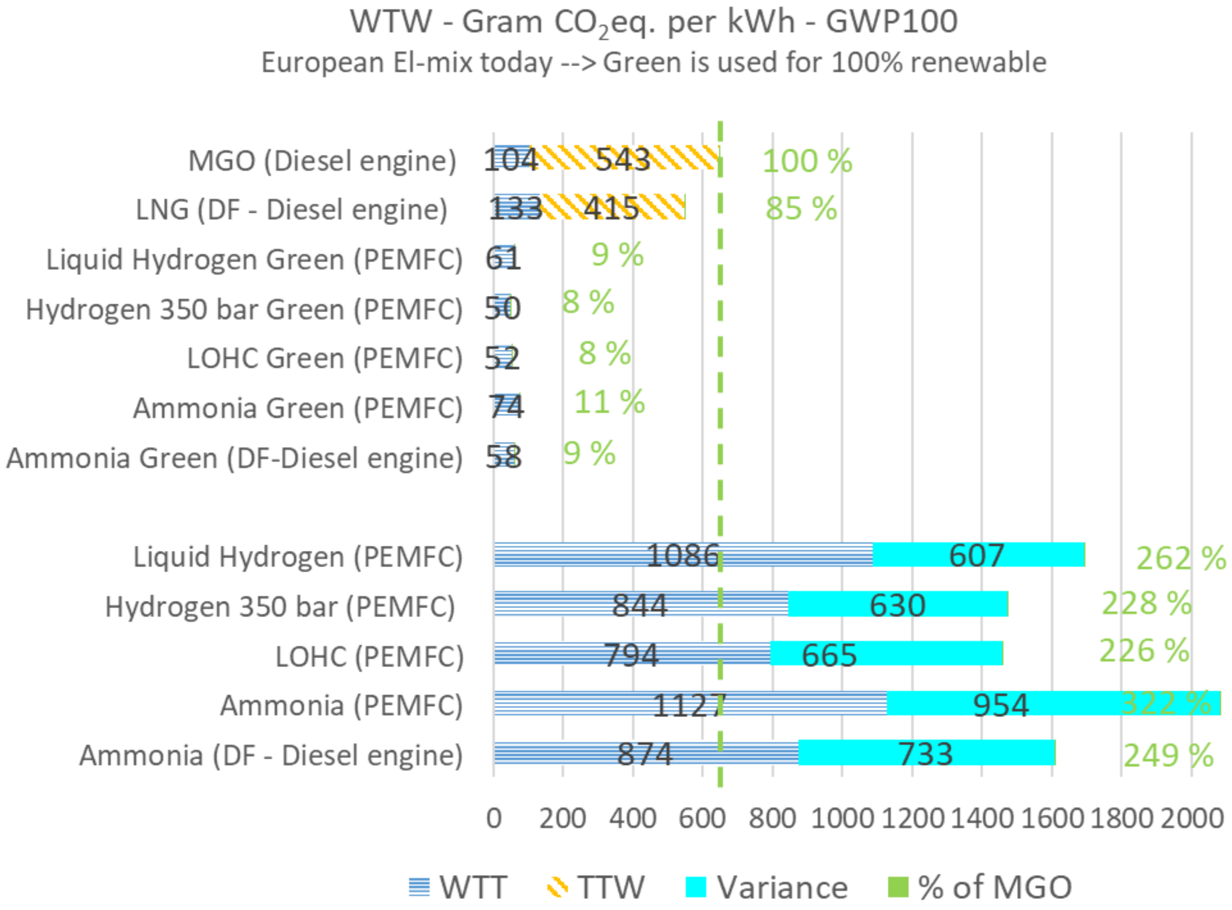

Figure 7: WTW CO2eq emissions per kWh (GWP100)

The main observation from Figure 7 is that if Hydrogen is produced from natural gas or through steam reforming or electrolysis based on EU-el mix, the well-to-tank emissions on their own exceeds the total WTW emissions of the conventional fuels. In contrast if the electricity is green, using ammonia or hydrogen reduces the WTW emissions with around 90% compared to MGO. This conclusion is fully in line with (Hoegh-Guldberg et al., 2019), which points out that decarbonizing of shipping through low carbon fuels requires that the land-based electricity becomes fully renewable and not as today, heavily dependent on fossil fuel.

6 Weight and Volumes and Energy Utilization

When the diesel engine today is challenged by alternative power solutions, it is not due to its high thermal energy efficiency of around 50%, the high energy density of the diesel, the price of the fuel, safety or the easiness of its operation. It is for the need to reduce GHG emissions and local pollution. Table 3 displays the fuel characteristics and their real weight and volume including their storage unit and engine units onboard a sea going vessels where all comparisons are made versus MGO (MGO = 1).

The main observations from Table 3 are:

- That volume and weight is a main argument for continued use of conventional fuels such as MGO, HFO, and VLSFO (not shown here) as illustrated in Figure 8.
- The last column shows energy utilization expressed as total energy input for the WTW divided on energy delivered for propulsion. The calculation methodology using MGO as an example, 1 MJ delivered on the tank + 0.2 MJ required for the WTT process gives 1.2MJ / 50% thermal energy utilization = 2.4.
- The energy utilization goes from 1.2 when the batteries on an electric ship is charged with Green renewable energy from the land-based grid, to 2.3 - 2.5 for fossil fuels with the exception of methanol at 3.3, which is the same as for batteries charged from the grid with the current EU-el. mix.
- Using Hydrogen or Ammonia roughly doubles energy consumption compared to fossil fuels, even when made from Green electricity, i.e. 3.6 – 5.5 compared to 2.2 – 2.4 for traditional fossil fuels (LPG, LNG, MGO).
- Comparing steam reforming of natural gas to electrolysis of water with Green electricity the energy consumption is similar, i.e. 3.6 – 5.7 versus 3.6 to 5.5.
- Electrolysis of water to hydrogen or ammonia based on the present EU-el-mix more than doubles energy consumption compared to Green electricity or steam reforming of natural gas.

After Table 3 follows Figure 8 which visualizes these bullets points and Figure 9 which shows energy utilization for the assesses fuels and their WTW pathways. In Figure 9 the green color on the bars are here used for renewable energy, while the yellow is used for fossil energy.

Table 3: Fuel characteristics and real weight and volume compared to WTW

Fuel and engine options	Density [kg/m3]	LHV (MJ/kg)	Energy conversion at ship	System volume factor	Real volume per TOE compared to MGO	Real weight per TOE compared to MGO	WTW energy / Propulsion energy (MJ/MJ)
MGO (Diesel engine)	850	42.7	0.50	1.1	1.0	1.0	2.4
HFO & Scrubber (Diesel engine)	990	40.0	0.50	1.2	1.0	1.1	2.3
LPG (DF - Diesel engine)	508	46.1	0.50	1.8	2.5	1.3	2.2
LNG (DF - Diesel engine)	470	49.2	0.50	2.0	2.9	1.5	2.4
Methanol (DF - Diesel engine)	791	19.7	0.50	1.1	2.3	2.2	3.3
Ammonia (DF - Diesel engine)	638	18.6	0.45	1.8	5.0	3.1	4.0 - 10.6
Ammonia (PEMFC)	638	18.6	0.35	1.8	6.4	4.0	5.1 - 13.6
Hydrogen 350 bar (PEMFC)	28	120	0.45	2.0	19.6	6.9	3.6 - 9.1
Hydrogen Liquid (PEMFC)	70	120	0.45	2.0	7.9	3.5	4.5 - 10.2
Hydrogen LOHC ((PEMFC)	941	7.5	0.41	1.1	5.3	7.0	3.6 - 9.6
Future Li-ion air battery (El - motor)		3.77	0.90	1.5	3.9	6.9	1.2 - 3.3
Future Li & Sillisium battery (El - motor)		1.46	0.90	1.5	8.6	17.8	1.2 - 3.3
Future Li-ion battery (El - motor)		0.98	0.90	1.5	27.5	26.7	1.2 - 3.3
NMC battery (El -motor)		0.61	0.90	1.5	68.7	42.8	1.2 - 3.3
LNG made from natrural gas: 18.5 gram CO_2 eq. per MJ							1.2
Natural gas to Hydrogen and ammonia: 10 gram CO_2 eq. per MJ							1.1
Green Electricity: 15 gram CO_2 eq. per MJ							1.1
Electricity EU-mix (GABI 2018 LCI-DATABASE): 418 gram CO_2 eq. per kWh							2.75

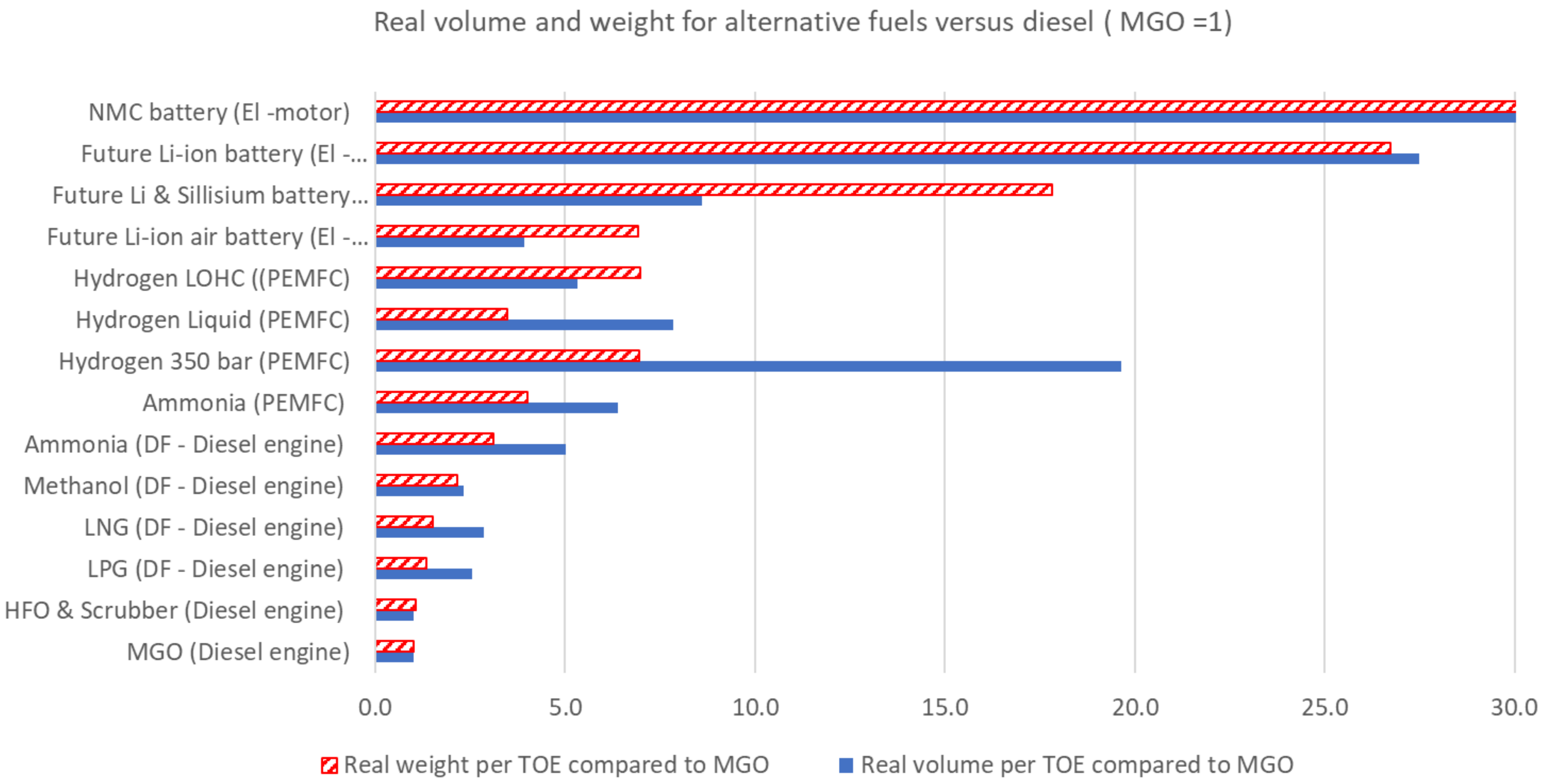

Figure 8: Real volume and weight for alternative fuels versus diesel (MGO=1)

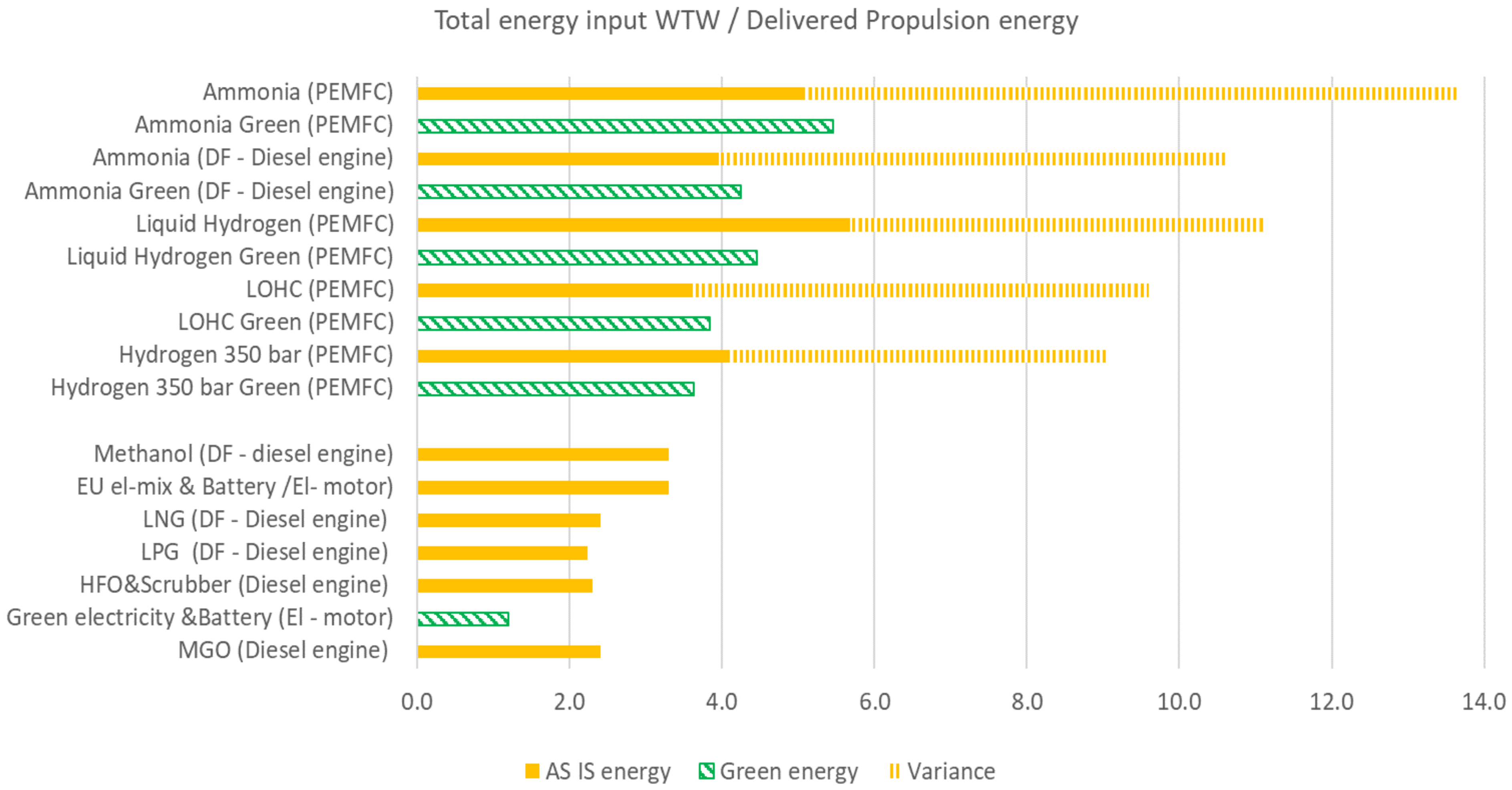

Figure 9: Total energy input versus delivered Propulsion energy (MJ/MJ). Here 2.4 for MGO implies that for each kWh delivered from the engine for propulsion and auxiliary, 1.4 kWh in total, are used for producing the fuel and lost through the exhaust gas and the cooling water

7 Conclusions

The motivation for the present study has been to investigate alternative engine technologies with focus on fuel flexibility, potential GHG reductions and energy utilization. When diesel out-competed coal on ships 100 years ago, it was simply because it reduced the weight and the volume of the fuel to a tenth, it was easier to handle and required less manpower on-board. Today, none of the new alternative fuels have any advantages regarding volume, weight or handling. In best case they increase volume 2 to 3 times and weight with 30% – 50% (LNG and LPG). While in worst case weight and volume increase from just 3 to 5 times MGO (ammonia) up to 7 to 20 times (pressurized hydrogen at 350 bar).

Both hydrogen and ammonia roughly doubles the energy consumption on a well-to-wake basis compared to conventional fuels, even when made from Green electricity, which makes them more costly if we simply assumes that there is a link between energy usage to produce the fuel delivered on the ship's fuel tank and its price.

Based on this study and its findings the following recommendations can be given:

1. Reducing fuel consumption per ton transported, will be a key requirement to:
   - Reduce the carbon intensity of the vessel, even without a fuel switch.
   - Enable use of fuels which will come at a higher cost per TOE than conventional fuels such as ammonia and hydrogen.
   - Avoid that the fuel occupies to much of a vessel available volumes and weight capacity, i.e. enable use of ammonia, hydrogen or electricity stored in batteries.
2. Replacing conventional fuels with fossil-based hydrogen or ammonia (as produced today) will increase the annual well-to-wake GHG emissions of a ship.
3. Hydrogen and ammonia can only reduce a ships well-to-wake GHG emissions if they are produced with Green renewable electricity or alternatively with steam reforming of natural gas and carbon capture technology.
4. Batteries charged with Green renewable electricity from the land-based grid gives the best energy utilization and is a technology under rapid development. In addition, batteries also give fuel and GHG savings in hybrid setups with combustion engines, even when charged by the engine(s) on boards (Lindstad et al, 2017; Lindstad and Bø, 2018).
5. With a dual-fuel Diesel-engine, the ship can burn nearly any fossil and biofuel with a high thermal energy efficiency and the lowest GHG (CO_2eq.) emissions per kWh (Lindstad, Eskeland and Valland, 2020). Moreover, if Green renewable ammonia becomes available within the first part of the ship's lifetime, it can be converted to run on ammonia.
6. If sustainable biodiesel becomes available for shipping, it will be a good GHG reduction option, especially for smaller ships with their standard diesel engine.
7. For existing medium and larger ships, HFO in combination with scrubbers and buying CO_2 quotas to offset the ships GHG emission, might be the best option both to reduce global GHG emissions and cost-wise for the operator.

8. Lower prices of natural gas, in combination with the EEDI benefits of LNG, might become a strong driver for increased use of dual-fuel engines in general, especially if the LNG price in some regional areas stays bellow the HFO price.

This paper is based on the best intentions of contributing to sound analysis and decision making. In case anything has been misinterpreted or misunderstood please challenge the analysis.

Acknowledgement

This paper has been written by Chief Scientist, Dr. Elizabeth Lindstad. Valuable contributions and input have been received from: Per Magne Einang, Agathe Rialland, Dag Stenersen and Anders Valland regarding the fossil fuels, the biofuels and engine technology. The Sankey diagrams in Appendix 1 for alternative production roots for hydrogen and ammonia production is made by Dr. Jørgen Bremnes Nilsen and Dr. Torstein Aarseth Bø. In addition, they have contributed with valuable contributions and input to the analysis of hydrogen and ammonia versus conventional fuels in this report. All contributors work for SINTEF Ocean AS.

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Appendix 1 Sankey diagram for producing Ammonia and Hydrogen

The Sankey diagrams in Appendix 1 for alternative production roots for hydrogen and ammonia production is made by Dr. Jørgen Bremnes Nilsen and Dr. Torstein Aarseth Bø.

In addition to inhouse knowledge the Sanky diagrams is based on the following sources listed in the reference list (Sankintuna et al 2007; Mazloomi and Gomes 2012; Zhao et al 2012; JEC 2013; Najjar 2013; Verhelst 2014; Choi et al 2016; De-Troya 2016; Peters et al 2016; Van Biert 2016; Barthelemy 2017; Nikolaidis and Poullikkas 2017; Preuster et al 2018; Nidermann et al 2019; Zohuri, B. 2019).

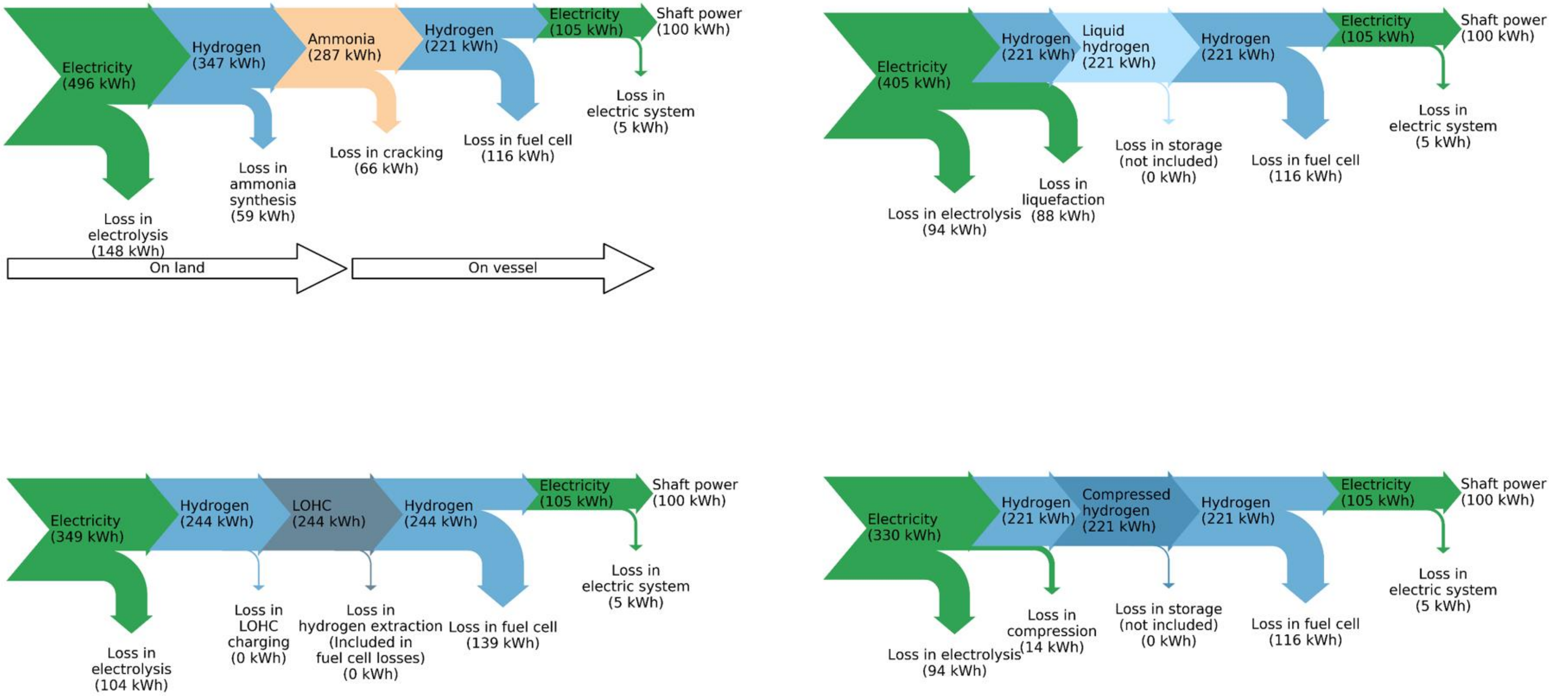

Figure 10: Sankey diagram of energy losses when making hydrogen and ammonia from electricity

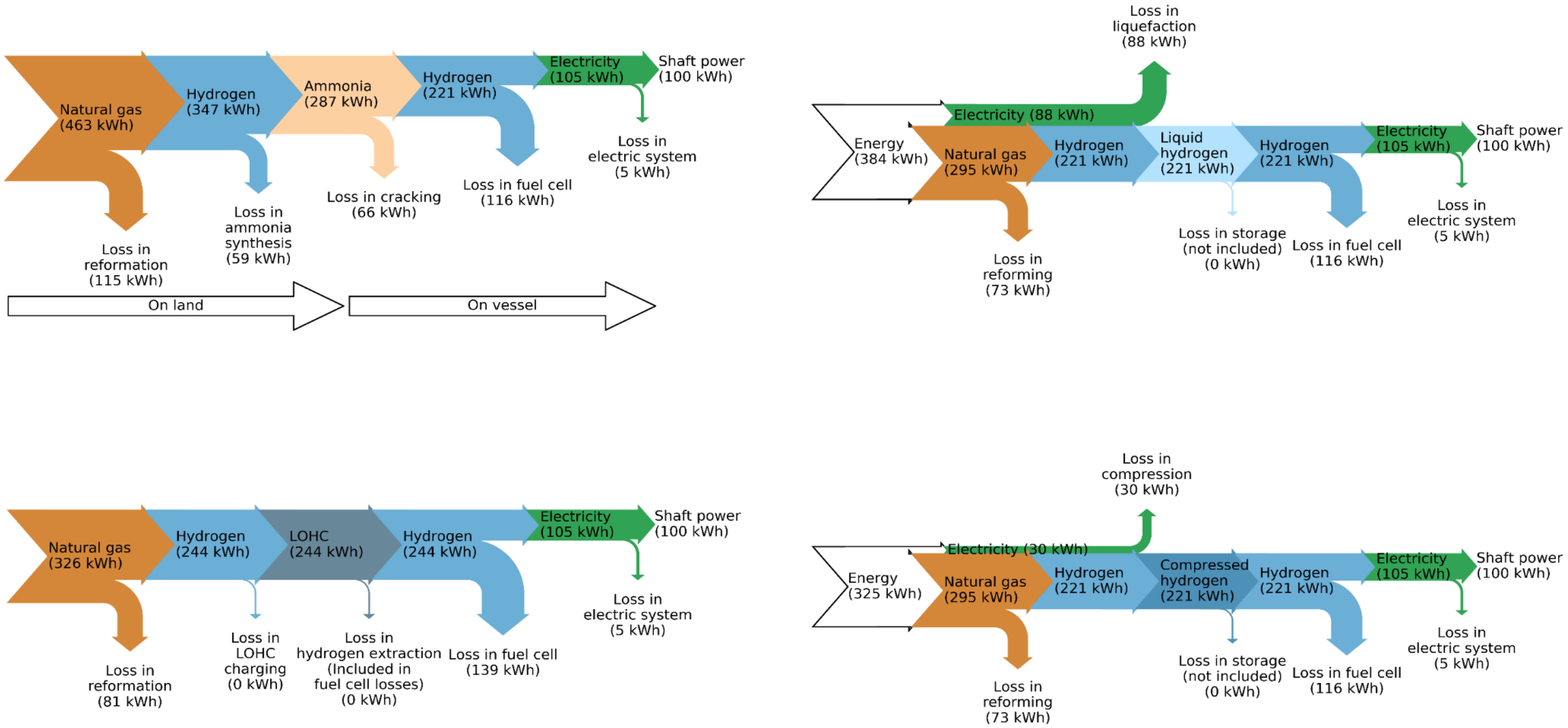

Figure 11: Sankey diagram of energy losses when making hydrogen and ammonia from natural gas