Comparison of Alternative Marine Fuels

SEA\LNG Ltd

Report No.: 2019-0567, Rev. 3
Document No.: 11C8I1KZ-1
Date: 2019-07-05

Project name:	Alternative marine fuels study	
Report title:	Comparison of Alternative Marine Fuels	
Customer:	SEA\LNG Ltd	
Customer contact:	Steve Esau	
Date of issue:	2019-07-05	
Project No.:	1-1C8I1KZ	
Organisation unit:	Environment Advisory	
Report No.:	2019-0567 Rev. 3	
Document No.:	11C8I1KZ-1	

DNV GL AS Maritime
Environment Advisory
Veritasveien 1
1363 Høvik
Norway
Tel: +47 40223162

Objective:

To assess the commercial and operational viability of alternative marine fuels, based on existing academic and industry literature. The approach assesses how well selected alternative fuels perform compared to LNG fuel. The alternative fuels included are hydrogen, ammonia, methanol, LPG, advanced biodiesel (hydrotreated vegetable oil - HVO) and electricity (batteries).

Prepared by:	Verified by:	Approved by:
Jon Anders Ryste Senior Consultant	Martin Wold Senior Consultant	Terje Sverud Head of section

Martin Wold, Joakim Frimann-Dahl,
Christos Chryssakis, Magnus S. Eide,
Øyvind Endresen, Håkon Hustad

DNV GL Distribution:

☒ OPEN. Unrestricted distribution, internal and external.

☐ INTERNAL use only. Internal DNV GL document.

☐ CONFIDENTIAL. Distribution within DNV GL according to applicable contract.*

☐ SECRET. Authorized access only.

*Specify distribution: SEA\LNG

Keywords:
Alternative marine fuels
SEA\LNG

Rev. No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
0	2019-05-15	First draft to client	JAR	MAWOL	
1	2019-05-29	Second draft to client	JAR	MAWOL	
2	2019-06-28	Final draft	JAR	MAWOL	TSV
3	2019-07-05	Final report	JAR	MAWOL	TSV

Table of contents

ABBREVIATIONS

ICE – Internal Combustion Engine

FC – Fuel Cell

CH_3OH / MeOH – Methanol

NH_3 - Ammonia

H_2 - Hydrogen

NG – Natural Gas

LPG – Liquefied Petroleum Gas

HFO – Heavy Fuel Oil

HVO – Hydrotreated Vegetable Oil

MGO – Marine Gas Oil

BMS – Battery Management System

1 EXECUTIVE SUMMARY

The overall ambition of the study has been to assess the commercial and operational viability of alternative marine fuels, based on review existing academic and industry literature. The approach assesses how well six alternative fuels perform compared to LNG fuel on a set of 11 key parameters. Conventional fuels are not covered in this study, however 2020 compliant fuels (HFO+scrubber and low sulphur fuels are included in the conclusion for comparative purposes.

The methodology applied in this study is a five-step process. First, 16 pathways from energy source to fuel to on board energy converter ("engine") were established (step 1). Then, a comprehensive literature search was performed to assemble a wide range of literature relevant for the selected pathways and the 11 assessment parameters defined in the project scope (step 2). Through a categorization and evaluation process the most relevant references were selected (step 3). In the data extraction phase (step 4), values for the key assessment parameters were collected, converted to a common unit for comparison and visualized in graphs, illustrating minimum to maximum ranges and average values. Lastly, the results for each pathway were evaluated and compared (step 5). The result of step 1-5 was an assessment based on identifying, summarizing and presenting objective findings based on existing literature on the topic of alternative fuels.

Certain general conclusions can be drawn when looking at the parameters highlighted as "highest priority", namely fundamental features, barriers and other aspects which will have a significant impact on the future uptake. Such features can often be translated back to cost (the business case) or technical feasibility. Below key graphs comparing the performance of the assessed fuels and technologies are shown.

Energy density: The energy density of a fuel partly determines how applicable the fuel is for certain ship types and ship operations. Because of its low volumetric and gravimetric densities, employing batteries to propel deep-sea operation is challenging and for most cases simply not feasible/realistic. LNG has around 40 % lower volumetric energy density than diesel, roughly the same as LPG. When accounting for the storage system, LNG has roughly 1/3 the volumetric energy density as diesel. Liquid hydrogen, ammonia and methanol have even lower volumetric energy density – around 40-50 % of LNG. Biodiesel is the only fuel which is close to matching the energy density of diesel.

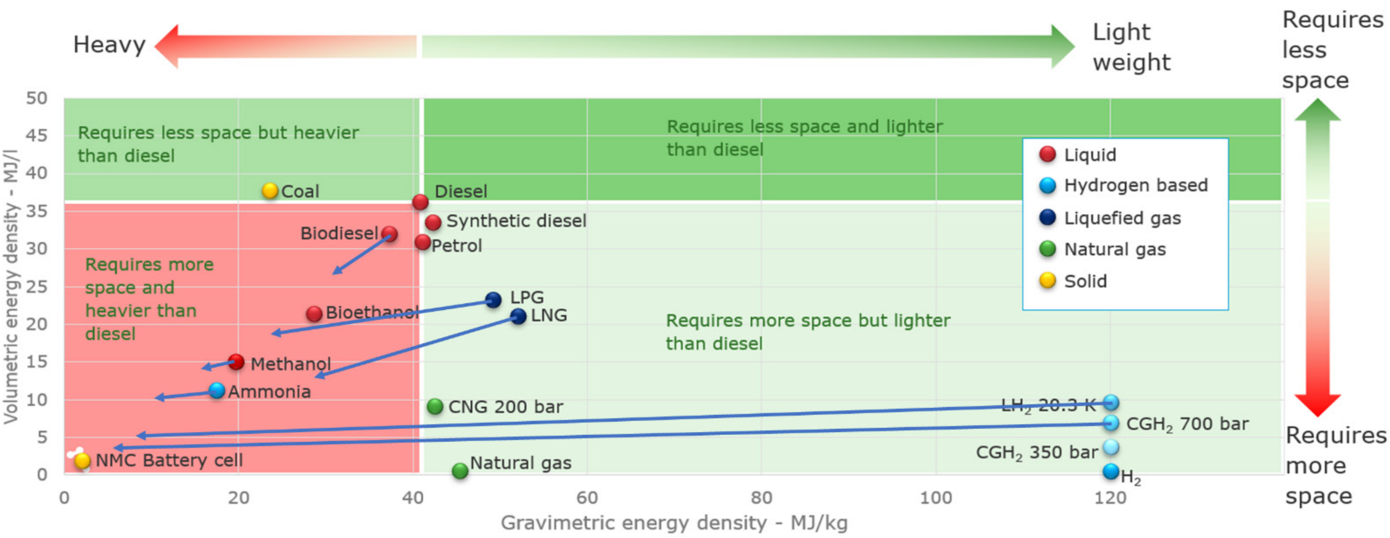

Figure 1-1: Energy densities for different energy carriers (inspired by /49/ /72/ and /73/). The arrows represent the impact on density when taking into account the storage systems for the different types of fuel (indicative values only)

Energy cost: It is clear that LNG, methanol and LPG are competitive in terms of energy costs, while HVO is significantly more expensive. Hydrogen and ammonia are also far more expensive, and the large cost range indicates a significant uncertainty in terms of pricing. In addition, the distribution cost and mark-up is not included for hydrogen, ammonia and HVO in the figure below.

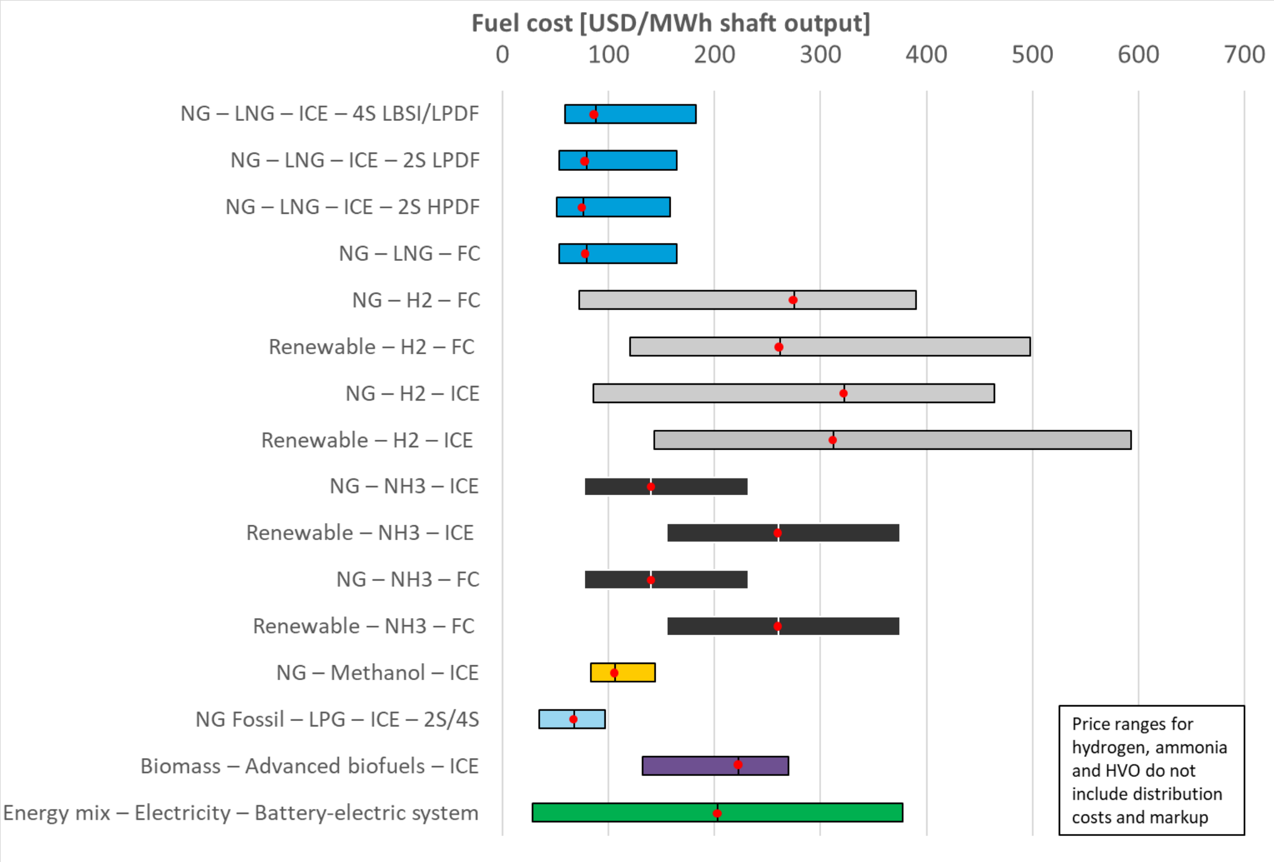

Figure 1-2: Energy cost for the fuel/technology pathways, taking into account the energy content and system efficiency [USD/MWh shaft output]

Capital cost: The additional capital costs for using alternative fuels primarily comprise of the converter cost, storage tank cost and any necessary processing systems. This report has focused on the converter and storage tank costs.

When assessing converter costs, it is evident that fuel cells are currently many times more expensive than internal combustion engines. Moreover, the big range in cost for fuels cells indicates a large degree of uncertainty. Fuel cells also have a significantly shorter life expectancy than internal combustion engines, and fuel cell stack replacement is expected several times during a vessel's lifetime, leading to additional capital costs.

When comparing storage tank costs the converter efficiency, tank storage utilization factor and storage lifetime have been considered. The cost for storage tanks for methanol and HVO are the lowest while LNG tank costs vary slightly depending on efficiency of converter. For hydrogen DNV GL have found tanks for liquefied hydrogen to be significantly more expensive due to lower storage temperatures, higher insulation quality and fewer maritime applications. For LPG, DNV GL have found the cost of installing LPG systems on board a vessel to be roughly half that of an LNG system if pressurized type C tanks are used in both cases. Although there is no available data for ammonia, the storage tank costs are expected to be at the same level as that of LPG, considering both fuels are stored under similar conditions. Even though battery-electric systems have close to double the efficiency of internal combustion engines and fuel cells, they have a significantly higher storage unit cost compared to the other alternative fuels. This is due to a high battery cost and limited battery lifetime which may be down to approximately 1/3 of that of systems for the other fuels.

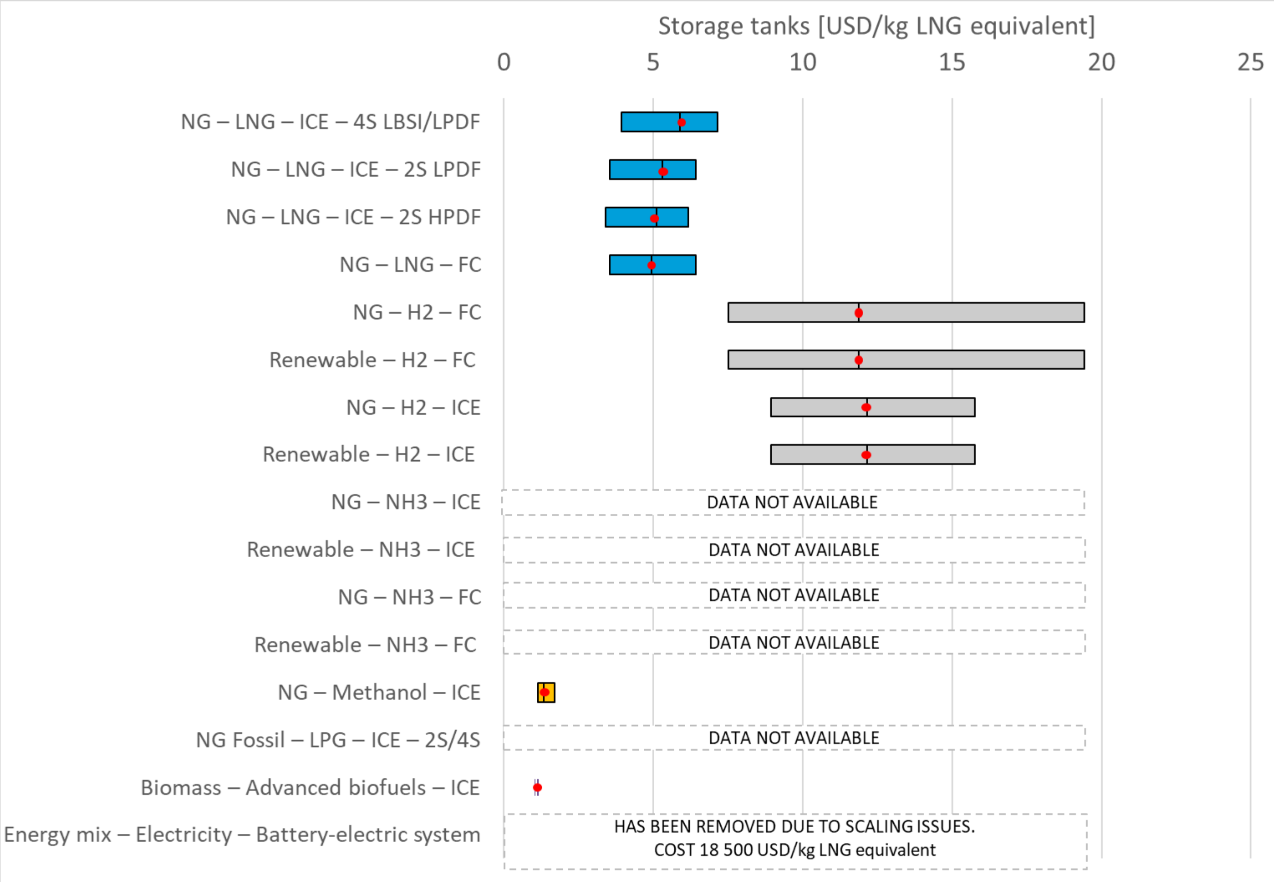

Figure 1-3: Capital costs of storage tanks for the different fuel/technology pathways, taking into account energy content, system efficiency, utilization of storage system and storage system lifetime [USD/kg LNG equivalent]

Well-to-wake GHG emissions: The well-to-wake GHG emissions includes emissions from production, transport and storage of each fuel, as well as combustion/conversion to mechanical energy onboard the vessels. The resulting comparative measure of well-to-wake emissions is the mass of CO2 equivalent emissions per unit of shaft output energy. The results show that the emission ranges are substantial for some of the pathways, illustrating variations in modes of production, transport and storage, or simply that there is significant uncertainty when modelling lifecycle fuel emissions. The production and storage of hydrogen requires a considerable amount of energy, so its competitiveness with regard to GHG emissions largely depends on low-emission energy production.

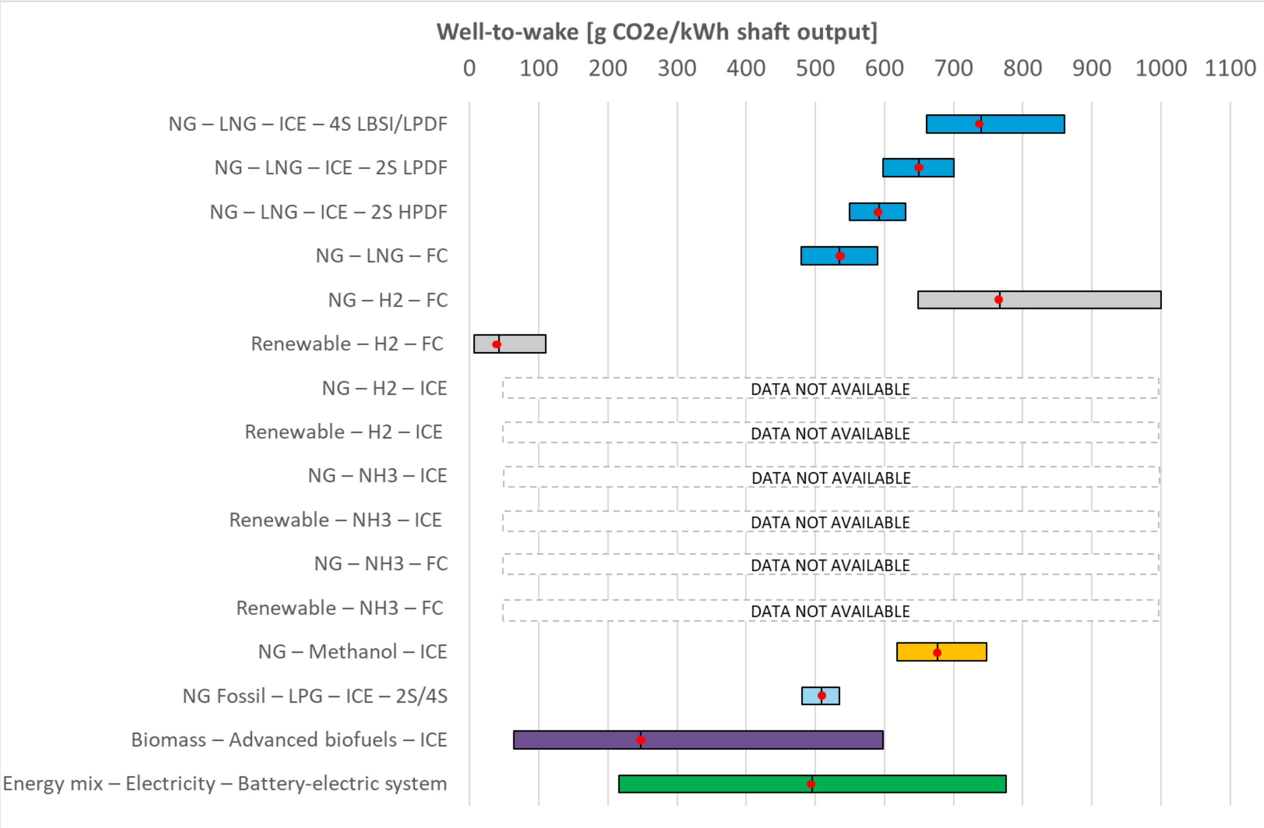

Figure 1-4: Well-to-wake emissions for fuel/technology pathways, taking into account energy content of fuel and system efficiency [g CO2e/kWh shaft output]

The figures presented above represent the results from data found in available literature, supplemented with assumptions by DNV GL to enable consistent comparison. Based on this and expertise on the subject matter, DNV GL has in the following given its interpretation and evaluation of the results for each parameter and per fuel. In addition, the 2020 sulphur cap compliance options HFO+scrubber and low sulphur fuel oil (LSFO)/MGO have been added to Figure 1-5 for comparison. These fuels have not been subject to an in-depth analysis on each parameter, and the given colour is based on a simplified assessment by DNV GL.

In the report both fossil and renewable pathways are assessed for the ammonia, hydrogen and fully electric options. However, in the following we address only the renewable pathways, as in the long term these energy carriers only make sense when produced from renewable sources. These represent long term solutions with potential for decarbonizing shipping. For LNG, methanol and LPG only production from fossil sources are considered in Figure 1-5. It is worth noting that these energy carriers can also be produced based on renewable sources, but in this report these pathways are not covered in detail. Synthetic LNG and bio-LNG is however commented on where relevant.

In Figure 1-5. a colour scheme using five colours has been applied. The colours represent performance on the key parameters for LNG and the different alternative fuels. We emphasise that this is a generic study and that when evaluating alternative fuels, the specifics for the case being evaluated have to be taken into consideration, such as ship specifications, local conditions, access to energy carriers and so on.

(1) Taking into account maturity and availability of technology and fuel.

(2) GHG benefits for LNG, methanol and LPG will increase proportionally with the fraction of corresponding bio- or synthetic energy carrier used as a drop-in fuel.

(3) Results for ammonia, hydrogen and fully-electric shown only from renewable energy sources since this represents long term solutions with potential for decarbonizing shipping. Production from fossil energy sources without CCS (mainly the case today) will have a significant adverse effect on the results.

(4) Large regional variations.

(5) Needs to be evaluated case-by-case. Not applicable for deep-sea shipping.

Figure 1-5: DNV GL's interpretation of results and evaluation of status of viability for different alternative fuels (internally rated), within selected assessment parameters (i.e. potential barriers). 2020 compliant conventional fuels have also been included for reference and for these the given colour is based on a simplified assessment by DNV GL.

Time to commercial availability of promising alternative fuels will depend largely on level of R&D efforts, and even more importantly on the level and speed of which environmental regulations are implemented and incentive schemes are developed. As shown in this report, several of the promising alternative marine fuels are far more expensive than current solutions, and adoption rate will be minor/at piloting stage until regulations or incentive schemes makes them more competitive.

HFO+scrubber/LSFO: The 2020 sulphur cap compliant conventional fuels perform well on most parameters, being well-known and widely used fuels. There are some concerns regarding availability of these fuels post 2020, but compared to the alternative fuels, the availability will still be significantly better. The major downside of using these fuels is the poor environmental performance. There will be investment costs and operational cost of using scrubbers but these are low compared to costs of the alternative fuels.

Hydrogen: The main advantage of hydrogen is the possibility of being a zero emissions fuel if produced from renewables. Furthermore, future hydrogen production capacity fits well with the anticipated energy transition to renewable power production on land. The most prominent challenges for hydrogen are the costs and the lack of bunkering infrastructure. Hydrogen will mainly be produced from natural gas without CCS (as is the case today), until the transition to renewable power production is well under way. However maritime projects opting for hydrogen may ensure use (and contribute to increased production) of hydrogen produced from renewables, at the expense of higher cost and likely slower uptake. Another key challenge for hydrogen is its applicability. This limits the ship segments for which hydrogen can be used significantly. With current technology, hydrogen seems limited to shortsea shipping when considering current costs of tanks and fuel cells and range limitations due to its low density. It should also be noted that costs for required safety systems and mitigating measures (considering the flammability of hydrogen) is not quantified explicitly in the literature and may represent additional costs compared to what is presented in this report. The extent of safety mitigating measures and the cost of these will first be clear once rules have been developed for the use of hydrogen as fuel.

Ammonia: With an energy transition to renewables, ammonia will have the potential to become a carbon free energy carrier with higher density than hydrogen, and in principal technically feasible for deep sea. However, the current maturity is low and green ammonia is expensive, limiting the feasibility for use as an alternative fuel. Moreover, the lack of a bunkering infrastructure represents a barrier for using ammonia as an alternative marine fuel and is likely to remain a barrier for a long time while the market matures. Similarly to hydrogen, GHG emissions from ammonia remain high with the current production from fossil energy sources without CCS, until the transition to renewable power production is well under way. However maritime projects opting for ammonia may ensure use (and contribute to increased production) of ammonia produced from renewables, at the expense of higher cost and likely slower uptake. It should also be noted that costs for required safety systems and mitigating measures (considering the toxicity of ammonia) is not quantified explicitly in the literature and may represent additional costs compared to what is presented in this report.

Methanol: The main upside for methanol is the relatively good performance on applicability, being able to utilize existing converter technology and low tank costs, which further translates into low capital costs. On the other side, a major downside to methanol as an alternative fuel is its environmental performance when produced from fossil sources as assumed in this report. Methanol is priced close to, or higher than MGO in today’s market. It is evident from Figure 7-1 that methanol performs very similarly to LPG, but with an expected somewhat slower maturing and uptake due to (presently) lower cost saving incentive. With continued pricing at this level, we expect to see a very limited uptake of methanol as an alternative fuel.

LPG: Low energy cost (close to LNG) and low capital costs make a compelling economic case for LPG. However, operational experience is very limited, thus the maturity level is medium. In addition the lack of bunkering infrastructure is a barrier for using LPG as an alternative marine fuel. Moreover, a major downside to LPG as an alternative fuel is its environmental performance when produced from fossil sources as assumed in this report.

HVO: The applicability of HVO fits well as an alternative fuel since it is considered a drop-in fuel, being a direct substitute for conventional petroleum-based fuels. On the other side, HVO is expensive and there is currently limited production capacity and bunkering availability of HVO, which raises the question of whether this is a scalable fuel for maritime use. In addition, the use of exhaust gas treatment systems to address the issue of NOx and PM emissions must be considered to meet current and future expected requirements.

Fully electric: Fully electric systems have the benefit of zero emissions when using electricity from renewable sources. However, the low energy density and significant storage costs means that fully electric systems are only feasible for a very limited number of vessel types and sizes with short sailing distance.

(Bio-LNG) and liquefied synthetic methane (from Power-To-Gas process) are fully compatible drop-in solutions which represents carbon neutral pathways for the gas engines and LNG distribution system. The material properties are very similar to LNG and for all practical means they can be considered identical. Both LBG and liquefied synthetic methane are promising fuels for shipping, but are not covered in detail in this study.

The energy cost is a key driver/barrier for the uptake of any alternative fuel and based on existing literature it can be concluded that there is a high uncertainty in expected price/cost for the fuels with significant GHG reduction potential. We currently don't know which of the alternative fuels will become more competitive and available for shipping. This depends not at least on how global mega trends within energy production and GHG abatement develops. But it is not likely that any major uptake of expensive alternative fuels with significant GHG reduction potential can be expected until required by regulations or heavily incentivized. Given current plans and typical development speed of regulations and incentives, no significant move towards such fuels is likely to happen until between 2025-2030 – at the earliest. Towards 2030 will however be a key period for R&D, piloting, rule development, product development and early commercialization.

When assessing the different alternative fuels on the defined parameters, it became evident that there are several gaps in the available data. This pertains especially to ammonia, but also several of the other fuels have certain knowledge gaps. For some of the fuels and parameters, the available data shows a noteworthy span in values from minimum to maximum, meaning that the uncertainty for the specific parameter is significant. Some of these uncertainties most likely reflect solutions which are currently maturing. For these, ongoing research and development, testing and piloting will provide data that will give significantly increased knowledge in the coming years. Suggested further work is therefore to investigate whether such development is ongoing where data is missing, or uncertainty is significant, and potentially initiate further studies to provide high quality data for more complete and detailed comparison of the different alternative fuels. There are also highly relevant energy carriers such as liquified biogas and synthetic methane and diesel (and other electrofuels) which are not covered in this study. Including such fuels would give a more complete picture of the fossil and renewable alternatives of all energy carriers.

2 GOALS OF STUDY

The shipping industry faces the challenge making the right investment decisions now to enable it to comply both with short term local emissions regulations e.g. the IMO 2020 sulphur cap, and the long-term climate legislation under consideration by the IMO, while remaining economically competitive. Shipping companies and investors need to be sure that the long-lived assets in which they are investing will not require major additional investment to comply with future regulations, or in the worst case be rendered obsolete by them. A range of alternative fuels and technologies are available for ships to reduce emissions. The reduction potentials vary significantly, depending on the primary energy source, the fuel processing, the engine type/converter, and the supply chain. The various alternative fuels and their diverse characteristics make it difficult, and potentially irrelevant, to clearly identify 'winners and losers'.

The overall ambition of the project has been to carry out a comprehensive study, based on existing academic and industry literature, on the commercial and operational viability of alternative marine fuels. The approach of the study has been to assess how well a selection of alternative fuels perform compared to LNG on a set of parameters. In addition, the 2020 compliant fuels HFO+scrubber and low sulphur fuels are included in the conclusion for comparative purposes.

3 INTRODUCTION

Shipping activities impact on climate change, health and the environment. Introducing alternative fuels such as LNG could significantly reduce emissions and impacts, as well as environmental risk associated with spills of heavy fuel oil (HFO) and other marine oils.

Globally, alternative fuels are emerging as viable options to oil-based fuels. Among the fuel alternatives to marine bunker oil, LNG is the most prolific with around 300 ships in operation or in order (currently 165 ships in operation and 154 confirmed orders), and applications around the globe and in most ship segments (see **Figure 3-1**). For more than 50 years, LNG carriers have been capable of burning boil-off gas from their LNG cargoes. Steam turbines consuming natural boil-off-gas were the preferred propulsion system, until the dual-fuel engines were introduced in early 2000s, enabling large fuel savings over the traditional steam turbines. A new era started when LNG was used as a primary fuel by the Norwegian car & passenger ferry Glutra in 2000. Following Glutra, several Norwegian ferries and offshore service vessels adopted LNG as fuel. The 'first movers' was vessels operating in Norwegian waters, and within relatively fixed geographical areas. The past few years have seen the first icebreaker, bulk carriers, car carriers, container ships, roll-on, roll-off (ro-ro) cargo ships, and oil/chemical tankers, as well as dredgers and cruise ship using LNG. It took 13 years for LNG fuel to spread outside Norway. By end of 2016, 57% of the ships were based outside Norway, and as of May 2019 this figure has increased to 74%.

In addition to LNG, biofuels and methanol are available in certain ports, and fully electric/hybrid ships are emerging in the short-sea segment for offshore and passenger ships/ferries. Shore-side electricity/cold-ironing is also emerging in certain ports. An important development is the electrification of the Norwegian domestic ferry sector, accounting for approximately 70 battery-electric ferries over the next few years. Uptake is also reported outside Norway. A few LPG-fuelled vessels, as well as methanol- and ethane-fuelled ships, have also been introduced (**Figure 3-1**). The first commercial applications of hydrogen fuel cell-powered ferries/passenger ships are planned in Norway, Scotland and California the coming years.

Use of different fuels will require different propulsion systems (energy converters) and storage/supply systems. Alternative propulsion systems for shipping include pure gas, dual- and multi-fuel engines, marine fuel cells, battery-electric propulsion systems, and gas and steam turbines. Several types of dual-fuel engines have been introduced in the market which increases fuel flexibility significantly. Beyond LNG, fuels such as methanol, ethanol, LPG (liquid petroleum gas) and soon likely also ammonia can be burned in different types of dual fuel engines, in addition to HFO/MGO. Promising steam- and gas-turbine concepts are also being considered.

It is expected that a global energy transition towards greater use of renewable energy will lead to an abundance of affordable renewable power production on land. This energy can be used for production of several of the fuels covered in this report, making them low or zero emission fuels.

The shipping industry faces the challenging decisions of making the right investments *now* to enable ships to comply both with short term local emissions regulations (e.g. the IMO 2020 sulphur cap), and the long-term GHG emission regulations to be adopted by the IMO, and still remain economically competitive. In this report, DNV GL has collected information on how various alternative fuels perform compared to LNG (the basis for comparison). It was the ambition of the project to collect and present data for both 2020 and 2030. However, it became evident that data for 2030 is very limited, thus it was chosen only to focus on 2020. The overall ambition of the study has been to assess the commercial and operational viability of alternative marine fuels, based on existing academic and industry literature. The approach assesses how well an alternative fuel performs compared to LNG fuel. The alternative fuels included are:

- Hydrogen
- Ammonia
- Methanol
- LPG
- Advanced biodiesel, hydrotreated vegetable oil (HVO)
- Electricity (in batteries)

Each of these fuels were assigned with relevant converters, such as internal combustion engines, fuel cells and battery-electric systems. In total 11 parameters have been defined for assessment. These parameters are divided into four main categories: **applicability, economics, environment,** and **scalability**.

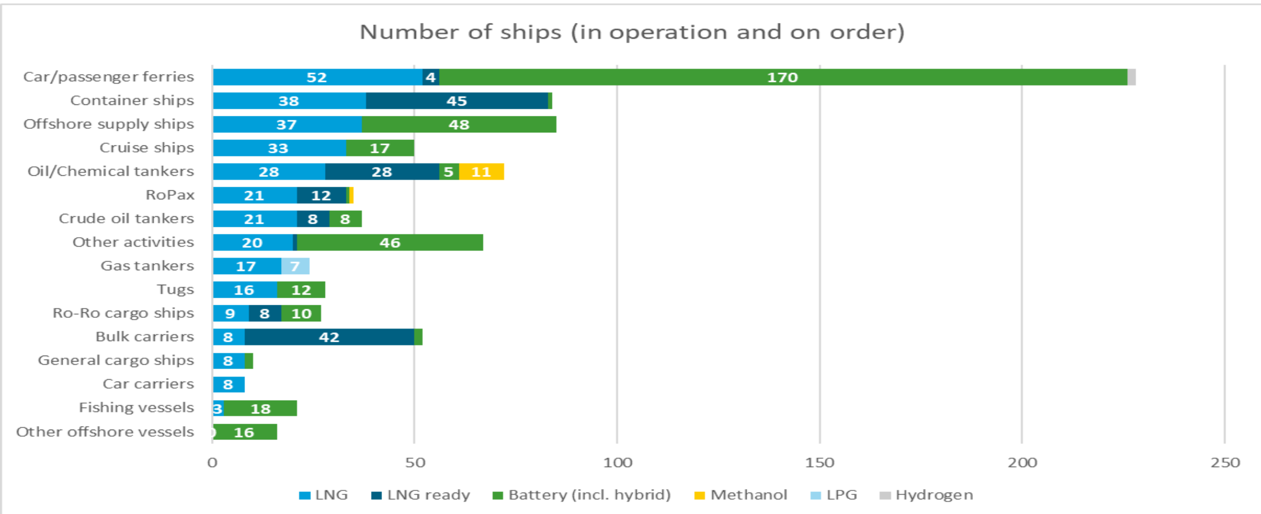

Figure 3-1: Uptake of alternative fuels in the world fleet, July 2019 (ships in operation and on order) (/24/)

4 METHODOLOGY

The methodology applied in this study is illustrated in Figure 4-1, and each step of the process is described in the following subchapters.

The project mandate was to evaluate key assessment parameters of various alternative fuels and compare them with LNG. First, the pathways from energy source to fuel to converter were established (step 1). Then, a comprehensive literature search was performed to assemble a wide range of literature relevant for the selected pathways and the 11 assessment parameters defined in the project scope (step 2). This phase was carried out through an extensive survey process including web searches, internal searches (DNV GL reports and academic papers) and input from SEA\LNG members.

Through a categorization and evaluation process the most relevant references were selected (step 3). The aim of this step was to obtain a set of reliable sources with relevant information on investigated performance criteria for the pathways.

In the data extraction phase (step 4), values for the key assessment parameters were collected, converted to a common unit for comparison and visualized in graphs, illustrating minimum to maximum ranges and average values. Lastly, the results for each pathway were evaluated and compared (step 5).

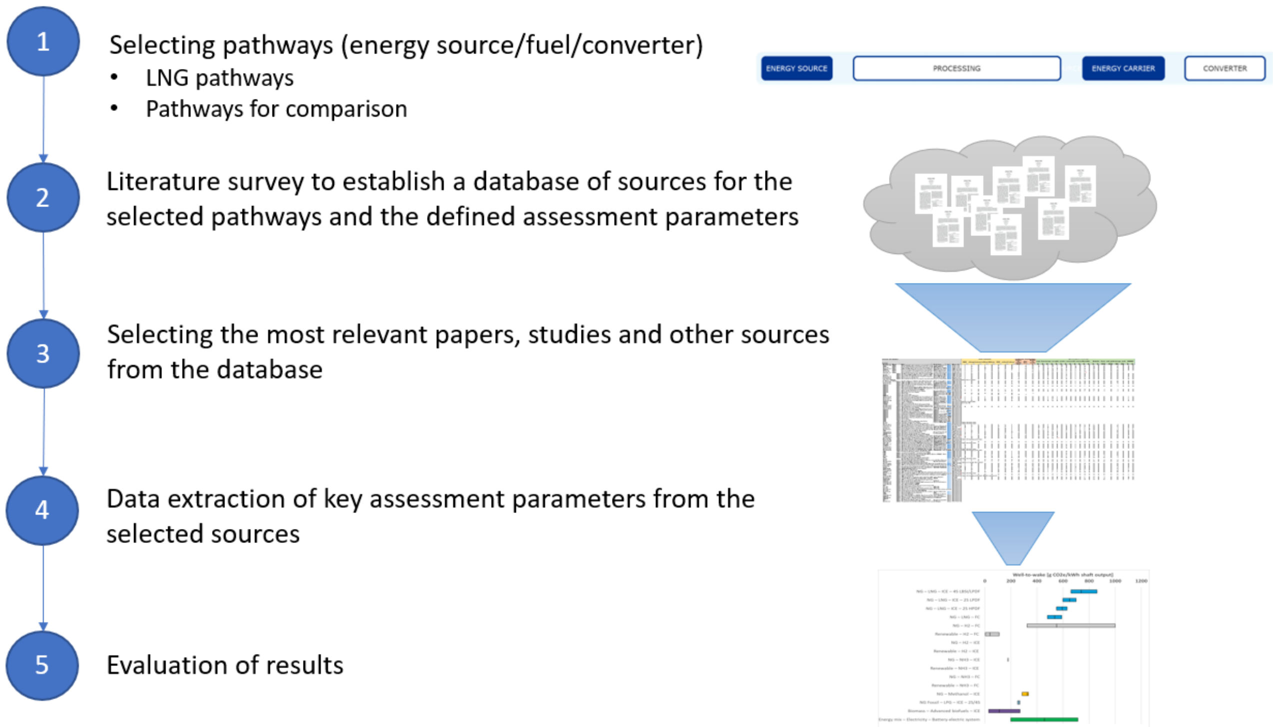

Figure 4-1: Study methodology

4.1 Step 1: Selecting pathways

A wide range of alternative fuels can contribute to reduced emissions of CO_2 and other pollutants (both GHG and local pollutants), though applicability, cost and availability currently restrict their use. The potential for alternative marine fuels will depend on factors related to physical and chemical characteristics, availability, costs, safety and ability to meet both global and local emission requirements. In most cases, selection will be based on a compromise between benefits and drawbacks of various fuel options. In this landscape, a distinction should be made between primary energy sources/feedstocks, energy carriers (fuels) and propulsion systems (energy converters) for use on board ships. The figure below represents the full picture of how a variety of energy sources can be exploited to create energy carriers for use on ships, and which energy converters can potentially be used on board.

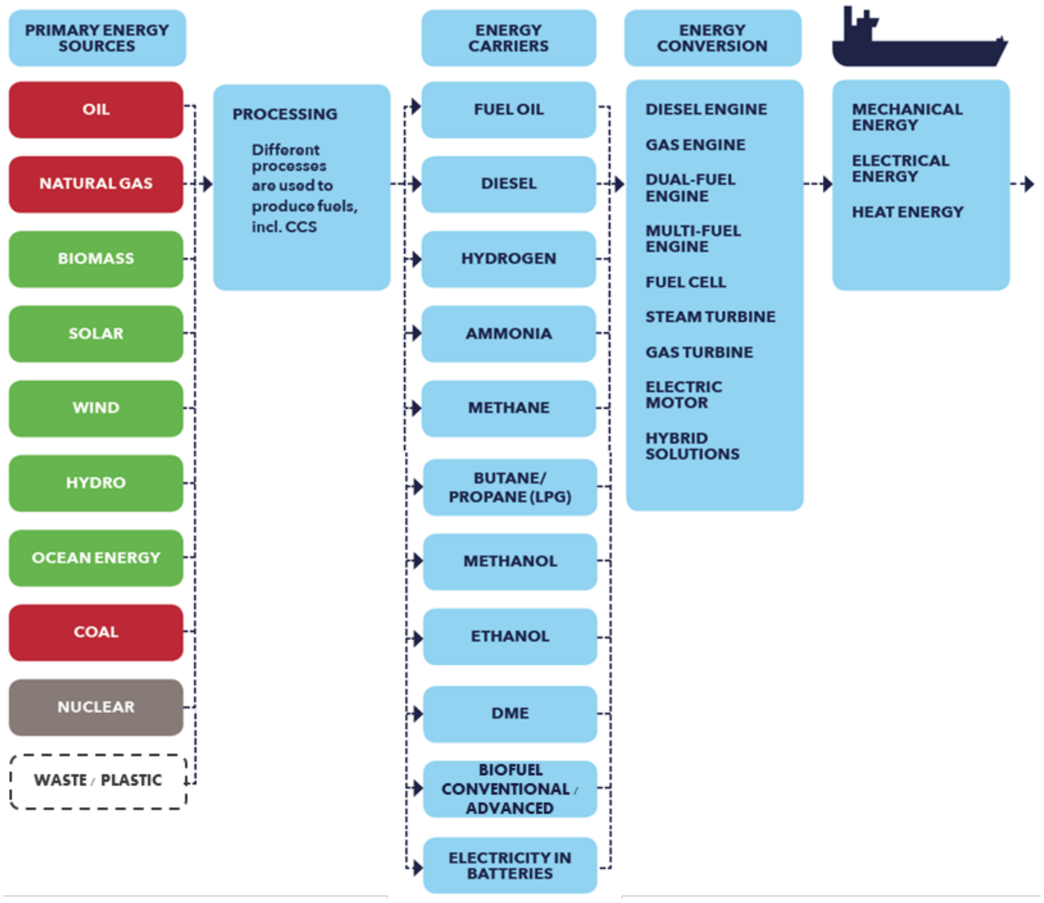

Figure 4-2: Simplified illustration of the chain from energy sources to mechanical energy for marine propulsion (/21/).

A number of combinations (technology pathways) of energy sources, energy carriers and converters can be made. In this report a total of 16 different alternative combinations are investigated, reflecting a span of existing and foreseeable promising technology pathways for shipping. Of these, three are ICE (Internal Combustion Engine) LNG pathways, differing on engine type. These are compared with 13 alternative pathways on pre-defined criteria (as outlined in chapter 3). Both fossil and renewable energy sources are considered, processed to different energy carriers (fuels). The marine converters included are ICE, fuel cell (FC) and battery-electric systems.

Note that not all potential technology pathways are included in this study. Those included are mature pathways, as well as pathways that DNV GL expect to mature during the next five to ten years. Time to commercial availability will however depend largely on level of R&D efforts, and even more importantly on the level and speed of which environmental regulations are implemented and incentive schemes are developed. As will be shown in this report, several of the promising fuel technologies identified (with respect to reduced GHG reductions) are far more expensive than current solutions, and adoption rate will be minor/at piloting stage until regulations or incentive schemes makes them more competitive. Only fuels and converters capable of propelling a ship are included.

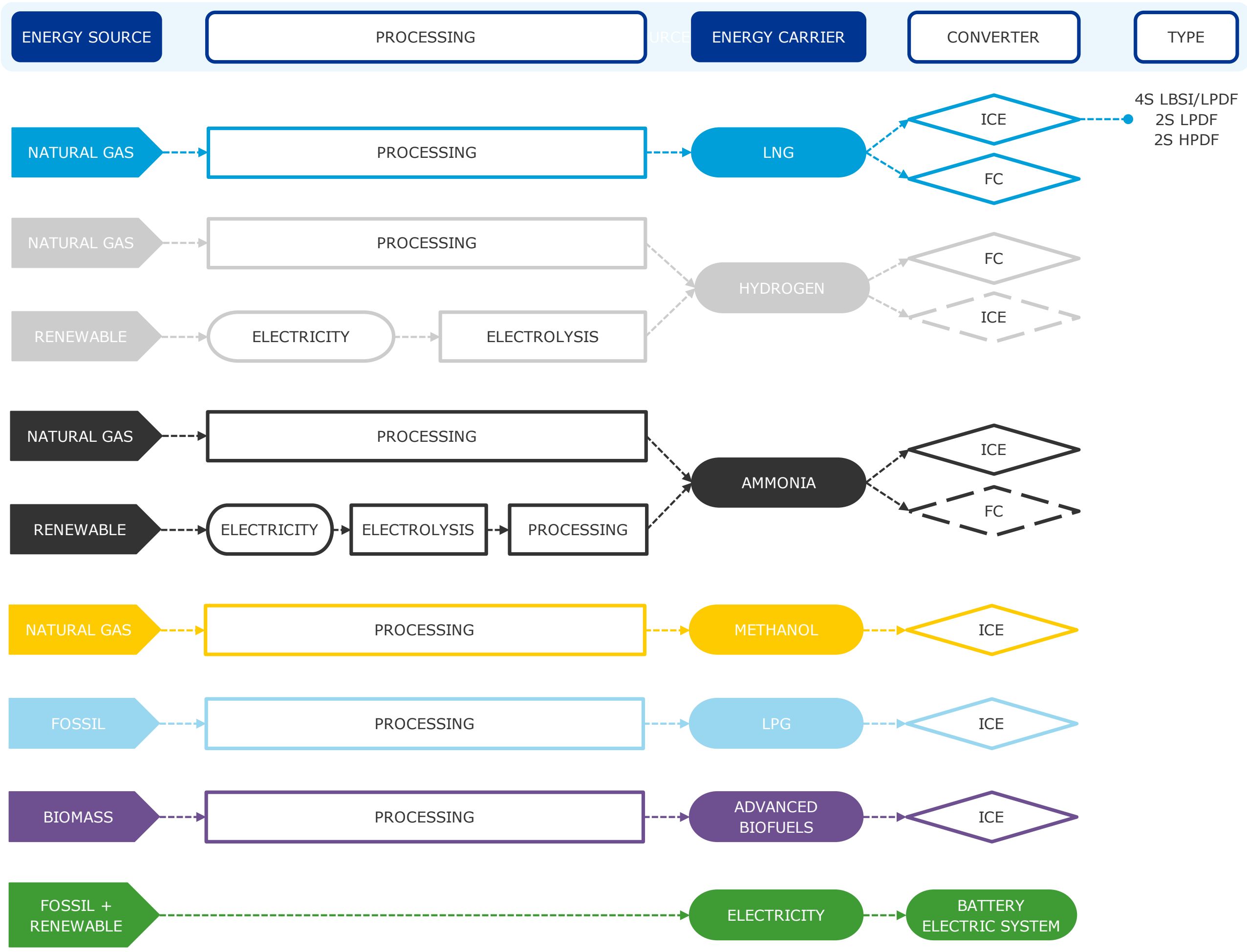

Figure 4-3: Pathways defined for assessment

BioLNG and synthetic LNG are not covered as separate pathways in this study but are included qualitatively where relevant. Regarding hydrogen as an energy carrier it is often not stated explicitly in the literature whether the information is valid for hydrogen in compressed or liquid form, but details of this has been given where available. Electrofuels, an umbrella term for synthetic fuels such as ammonia, diesel, methane, and methanol, which are produced from water, CO_2 or nitrogen using renewable electricity as the source of energy, are not covered in this study.

Of the 16 defined pathways shown above, the four leading to a converter with a dashed line will be covered more simplified and qualitatively than the rest.

Each pathway is described in more detail in section 5.

4.2 Step 2: Establishing a literature database

A literature database was established through a wide-ranging literature study to make available an extensive range of information sources to be used in the evaluation of the defined assessment parameters for each of the selected pathways described in section 4.1. The longlist of sources was assembled through web searches, internal searches (DNV GL reports and academic papers) and input from SEA\LNG members. This resulted in a list of more than 100 sources, spanning most of the assessment parameters and pathways within the scope of this project.

The assessment parameters were defined in the project scope and are described in the following subchapter.

4.2.1 Assessment parameters

In total, 11 parameters have been defined for assessment. These parameters are divided into the main categories **applicability, economics, environment and scalability**. The applied categorization is inspired by the work of /7/, /14/, /21/, /23/, /33/ and /54/. A comparison of fuel technology pathways will be conducted on each of the defined parameters.

Applicability

- Energy density
- Technological maturity
- Flammability and toxicity
- Regulations and guidelines (including existence of bunkering/fuel loading guidelines and regulations)

Economics

- Energy costs
- Capital costs

Environment

- GHG emissions - well-to-wake
- Local emissions - SOx, NOx and PM

Scalability

- Main current usages
- Availability
- Global production capacity and locations

4.3 Step 3: Categorizing database and selecting the most relevant papers and studies

A significant number of sources were collected in step 2. These were categorized on main topic and parameters covered to give an overview of assessment criteria and pathways covered by available literature, and to ease the selection process. For each assessment parameter, recent and high-quality papers and studies were selected. A paper or study often covered several parameters.

4.4 Step 4: Data extraction

For each chosen paper or study, the extracted data was indexed in ranges from low to high value and with a calculated average. For studies giving only one value for a certain parameter, this was used as both the low, high and average value. From this, the data was aggregated to show low to high values for all sources, in addition to calculating the average of the averages from each source. Statistics on the number of papers and studies constituting the basis for the ranges, have been provided in separate tables for GHG and local emissions, as well as energy and capital costs (see sections 6.2.1 and 6.2.2).

Once extracted data had been indexed, an additional targeted literature search was conducted in attempt to close any gaps of missing data or a low number of sources. Moreover, DNV GL has, where possible, applied domain expertise to assign realistic values where data was missing. For some parameters on certain fuels, the literature search did not uncover any reliable available data. In such cases, the assessment contains a gap, either because this data is not available or does not exist, or because it was not discovered in the literature study.

For certain parameters and input data, conversions have been necessary to ensure like-for-like comparison. Input data has been converted for energy cost, capital cost, GHG and local emissions. The end units for capital costs are USD/kW shaft output for *the converter* and USD/kg LNG-equivalent for the *storage tanks*. For energy cost and GHG emissions, the end units are USD/MWh shaft output and g CO_2e/kWh shaft output, respectively.

4.5 Step 5: Results and conclusions

Based on the results from step 4, the various alternative fuel pathways were compared to the LNG pathways. The results and conclusions are available in sections 6 and 7. The scope of this work has been to identify and summarize existing literature on the topic of alternative fuels and how they perform on selected assessment parameters. In section 6 the findings from the literature review are summarized. In the conclusions section, however, DNV GL's interpretation of the results can be found.

5 PATHWAY DESCRIPTIONS

In this report a total of 16 different fuel pathways are investigated, reflecting a span of existing and promising technology pathways for shipping. Each pathway consists of an energy source, a processing step, an energy carrier and a converter.

Of the 16 pathways, three are ICE LNG pathways, differing on converter (engine) type. These are compared with 13 alternative pathways. Both fossil and renewable energy sources are considered. The marine converters included are ICE, fuel cell (FC) and battery-electric systems.

A general description of energy converters that are relevant for several of the pathways (i.e. combustion engines and fuel cells) is given separately, followed by a short description of the pathways, including technical prerequisites.

5.1 Converters for multiple fuel pathways – fuel cells and combustion engines

5.1.1 Fuel cells

Fuel cells were previously used mainly for special purposes, such as in aerospace and submarines. The technology has matured and is in commercial use in applications such as forklifts, standby generators/uninterruptible power supply, and combined heat and power systems. Fuel cells have advanced to near commercial use for cars, buses, trucks and rail applications. Fuel cells can efficiently reduce and even eliminate emissions and noise, while fuel efficiency can be increased, compared to combustion engines. Depending on fuel-cell type, electrical efficiency of 50–60% is expected, which is slightly higher than marine diesel generators (/17/). With heat recovery, the efficiency can increase to 80%. Noise and vibrations are insignificant, and fuel cells are also expected to require less maintenance than conventional combustion engines and turbines, but cell lifetime has been an issue.

The cell converts the chemical energy of the fuel to electrical power through electrochemical reactions. Put simply, the energy conversion can be considered as being similar to that in batteries, but with continuous fuel and air supplies. Different fuel-cell types are available, and their names reflect the materials used in the electrolyte membrane. The properties of the membrane affect the permissible operating temperature, the nature of electrochemical reactions, and fuel requirements. DNV GL have previously evaluated seven fuel-cell technologies and concluded that the solid-oxide fuel cell, the proton-exchange membrane (PEM) fuel cell, and the high-temperature PEM, are the most promising for marine use (/17/). Depending on fuel-cell type, they can also be powered by carbon fuels such as natural gas – an option that, in particular, reduces NOx, SOx, and PM emissions.

5.1.2 Internal combustion engines

Internal combustion engines (ICE) is well-known technology, used in automotive, off-road and marine applications for more than 100 years. Marine engines are typically categorized in

a) slow speed engines, operating at maximum 300 RPM, but typically 80-140 RPM. These are 2-stroke engines, used for propulsion in large vessels

b) medium speed engines, operating in the range of 300-900 RPM. They are normally 4-stroke engines and can be used both for propulsion and auxiliary power generation on board a variety of ship types.

c) high speed engines, operating at speed higher than 900 RPM. They are 4-stroke engines, used for propulsion in smaller vessels (incl. high speed vessels), and for auxiliary purposes.

Marine diesel engines power most of the commercial shipping fleet today, the main exception being LNG carriers equipped with steam turbines. Shortly after the first dual fuel engine was introduced on LNG carriers in 2006, the ICE became the preferred solution also for LNG carriers. Already since 2000, dual fuel and pure gas ICE have been introduced for propulsion and auxiliary power also for other ships than LNG-carriers – ships of various sizes and operating profiles, ranging from small ferries and offshore supply vessels to large cruise ships, oil tankers and container vessels. The 2-stroke engines are offered in Diesel cycle (high pressure) or Otto cycle (low pressure), with the Diesel cycle offering higher efficiency and the Otto cycle having the advantage of lower capital costs and compliance with NOx Tier III standards without use of EGR or SCR in gas mode. The 4-stroke gas engines are Otto cycle and compliant with NOx Tier III. The use of LNG as a fuel in ICEs also offers elimination of SOx emissions, and significant reduction of particulate matter.

5.2 LNG pathways

The main component of liquefied natural gas (LNG) is methane (CH_4), the hydrocarbon fuel with the lowest carbon content and therefore with the highest potential to reduce CO_2 emissions. However, methane is a potent greenhouse gas, and methane slip must be kept under control in order to ensure reductions in GHG emissions when using LNG. LBG (Bio-LNG) and liquefied synthetic methane (from Power-To-Gas process) are fully compatible drop-in solutions which represents carbon neutral pathways for the gas engines and LNG distribution system. The material properties are very similar to LNG and for all practical means they can be considered identical. Both LBG and liquefied synthetic methane are promising fuels for shipping, but are not covered in detail in this study.

The technology required for employing LNG as ship fuel is readily available. Piston engines include low- and high-pressure 2-stroke engines, and low-pressure 4-stroke engines. Several LNG storage tank types, as well as process equipment, are also commercially available. The boiling point of LNG is approximately −163°C at 1 bar absolute pressure. Therefore, LNG must be stored in insulated tanks for cryogenic application, which are associated with high cost relative to conventional petroleum-based fuel storage and supply systems.

Use of LNG in fuel cells is also feasible.

Table 5-1: LNG technology options and properties

Converter	ICE 4-stroke Lean Burn Spark Ignition / Dual Fuel Low Pressure (4S LBSI/LPDF)	ICE 2-stroke Dual Fuel Low Pressure (2S LPDF)	ICE 2-stroke Dual Fuel High Pressure (2S HPDF)	FC
Components	Engine Storage tanks Process system	Engine Storage tanks Process system	Engine Storage tanks Process system NOx reduction system (EGR/SCR)	Fuel cell Storage tanks Process system Electric propulsion system Reformer Battery
Key challenges	Methane slip for some of the ICE's Cryogenic materials needed Fuel storage tank 2-3 times larger than for petroleum-based fuels			

Pathways

The four pathways covered for LNG in this study all encompass LNG produced from natural gas. The paths differ on the converter used; three alternative internal combustion engine types and a fuel cell.

Pathway 1: NG – LNG – ICE – 4S LBSI/LPDF Pathway 2: NG – LNG – ICE – 2S LPDF Pathway 3: NG – LNG – ICE – 2S HPDF Pathway 4: NG – LNG – FC	LNG

Out of scope

- Production from other energy sources than natural gas, for example bio-methane to liquid bio gas (LBG)
- Gas turbines as converter

5.3 Hydrogen pathways

Hydrogen (H_2) is an energy carrier and a widely used chemical commodity. It can be produced employing various energy sources, such as by electrolysis of renewables, or by reforming natural gas. Today, nearly all hydrogen is produced from natural gas. If the gas is produced from renewable energy sources, or from natural gas with carbon capture and storage (CCS), zero-emission value chains can be created. Even though its lifecycle emissions may be close to zero, it is important to note that producing H_2 for use as a fuel requires considerable energy.

Hydrogen is most efficiently utilized in fuel cells (efficiency typically 50-60 %, potentially higher for certain types with waste heat recovery), but it is also possible to apply it in adapted combustion engines (efficiency typically 40-50%). Some initiatives consider blending H_2 with other fuels to improve combustion and emission properties, as well as potentially reducing GHG emissions.

Finding volume-efficient ways to store hydrogen is challenging. Most commonly, it is stored either as compressed gaseous hydrogen (CGH) or cryogenic liquid hydrogen (LH2). Hydrogen molecules are small and can diffuse through many materials including metals. This is mainly an issue for compressed hydrogen (which is typically 250-700 bar) where the molecules are "pushed" into the storage material. There are two safety concerns with this behaviour; metal embrittlement (and eventually fracture) and gas "leakage". Material selection is therefore key to ensure the safety and integrity of the fuel tank and fuel supply system. Storage and bunkering of H_2 for use on ships will however require specially-designed storage tanks and bunkering systems, and there is currently limited experience with marine storage and use of H_2. Storage technologies are available from land-based applications.

Table 5-2: Hydrogen technology options and properties

Converter	FC	ICE
Components	Fuel cell Storage tanks Process system Electric propulsion system Reformer Battery	Engine Storage tanks Process system
Key challenges	Fuel storage is more massive and requires more space than petroleum-based fuels Cryogenic materials needed for LH2	

Pathways

The four pathways covered for hydrogen in this study encompass production of hydrogen from natural gas or from renewable energy, both for use in a fuel cell or an internal combustion engine. The two pathways (natural gas and renewable) covering the use of hydrogen in internal combustion engines will only be discussed qualitatively. In the shorter term, adapted combustion engines might be preferred, but we consider it likely that fuel cells will be the primary converter for use with hydrogen when the technology is sufficiently mature. Fuel cells exhibit zero NOx, SOx and PM emissions and higher efficiencies compared to internal combustion engines.

Pathway 5: NG – H_2 – FC Pathway 6: Renewable – H_2 – FC Pathway 7: NG – H_2 – ICE Pathway 8: Renewable – H_2 – ICE	Hydrogen

Out of scope

- Production from natural gas using CCS (the use of CCS reduces the CO_2 emissions when producing hydrogen from natural gas). The available data from this production method is very limited, and it is therefore not covered in this study. It is likely that the NG (CCS) pathway would lie between the NG (no CCS) and renewables pathways, both in terms of emissions and costs.

5.4 Ammonia pathways

Safety and regulatory challenges and space/weight considerations related to storing large quantities of hydrogen on ships have generated interest in exploring alternative hydrogen-based energy carriers. Several studies have pointed to ammonia (NH_3) as a potential fuel for shipping (/51/, /61/). Ammonia, sometimes called 'the other hydrogen', is carbon-free and liquefies at a higher temperature than hydrogen (-33^{o}C versus -253^{o}C). In addition, ammonia is over 50% more energy-dense per unit volume than liquid hydrogen (/51/). This simplifies storage and distribution compared to hydrogen. Ammonia is transported by multi-cargo gas carriers which can also transport LPG, hence equipment and costs for transporting ammonia can be estimated from this. The lower energy density of ammonia compared with LPG must be considered when calculating cost per energy unit however.

The first utilization of liquid anhydrous ammonia as a fuel was reportedly in buses in the 1940s. The bus fleet in question recorded thousands of kilometers without propulsion-related difficulties.[1] Combustion of ammonia is reported to have enhanced power output compared to traditional fuels and hydrogen (/51/). Ammonia has disadvantages as a fuel in combustion engines, such as very high auto-ignition temperature, low flame speed, high heat of vaporization, narrow flammability limits, and toxicity (/6/, /30/, /64/). Kong also reports that ammonia is corrosive to copper, copper alloys, nickel and plastics, so these materials must be avoided in an ammonia-fueled engine. In addition to the use in combustion engines, ammonia can also be used in hydrogen fuel cells or in fuel cells specifically designed for ammonia (/51/). However, for the use of ammonia in fuel cells to become commercially viable on a large scale, the technology must mature. This option has significant potential in the long term, but the paths are only covered qualitatively in this study.

[1] https://www.agmrc.org/renewable-energy/renewable-energy/ammonia-as-a-transportation-fuel/

As for other energy carriers, the GHG emissions from production of ammonia depends on the production method. Most of the ammonia produced today derives from natural gas, using the Haber–Bosch process (/1/, /6/). Ammonia can also be produced from naphtha, heavy fuel oil or coal, but this will generate larger CO_2 emissions per energy unit. By utilizing electrolysis, ammonia can also be produced from renewable sources, such as wind energy or solar power. A carbon-free production method would enable a carbon-free fuel since the tank-to-propeller phase does not emit any carbon.

The most common use of ammonia is for synthesis of fertilizers or for house-cleaning products. Since there is already widespread demand for ammonia in land-based industries, infrastructure for transport and handling is in place. However, the development of a bunkering infrastructure remains a barrier for marine application. Ammonia as a ship fuel has quickly gained interest among many stakeholders over the last years, provided that carbon-free production, necessary infrastructure and promising on-board converters are realised.

Table 5-3: Ammonia technology options and properties

Converter	FC	ICE
Components	Fuel cell Storage tanks Process system Electric propulsion system Reformer Battery	Engine Storage tanks Process system NOx reduction system (EGR/SCR)
Key challenges	Fuel storage is more massive and requires more space than petroleum-based fuels	

Pathways

The four pathways covered for ammonia in this study encompass production of ammonia from natural gas or from renewable energy, for use in an internal combustion engine or a fuel cell. Internal combustion engines running on ammonia are likely to be available for order within 5-10 years, but uptake will be slow until regulations make ammonia competitive. DNV GL expect that fuel cells, in particular for ammonia, will mainly be used in pilot and early applications and for subsidized projects in the next 5-10 years. How long until the technology is sufficiently mature and commercially competitive remains to be seen, but it will likely only happen under a significantly stricter GHG regime. Due to this, the two pathways (natural gas and renewable) covering the use of ammonia in fuel cells will be discussed qualitatively in this report.

Pathway 9: NG – NH_3 – ICE Pathway 10: Renewable – NH_3 – ICE Pathway 11: NG – NH_3 – FC Pathway 12: Renewable – NH_3 – FC	Ammonia

Out of scope

- Production from other energy sources than natural gas and renewable energy
- Production from natural gas using CCS

5.5 Methanol pathway

Methanol, with the chemical structure CH_3OH, is the simplest alcohol with the lowest carbon content and highest hydrogen content of any liquid fuel. Methanol is a liquid between 176 and 338 K (−93°C to +65°C) at atmospheric pressure – making storage less expensive compared to LNG, H2 and NH3. Due to its density and lower heating value (19.5 MJ/kg), methanol requires approximately 2.5 times larger fuel tanks than MGO per energy unit, and similar or smaller fuel tanks than LNG – in particular if factoring in volume inefficiencies of C-type LNG tanks.

Methanol can be produced from several different feedstock resources, mainly natural gas or coal, but also renewable resources like black liquor from pulp and paper mills, forest thinning or agricultural waste, and even directly from CO_2 captured in power plants or from air.

When produced from natural gas, a combination of steam reforming and partial oxidation is typically applied, with an energy efficiency up to around 70% (defined as energy stored in the methanol versus energy provided by natural gas). Methanol produced from gasification of coal relies on a cheap, widely available resource, but the greenhouse gas (GHG) emissions are about twice as high as from natural gas.

There are two main options for using methanol as fuel in conventional ship engines: in a two-stroke diesel-cycle engine or in a four-stroke, lean-burn Otto-cycle engine. Only one single two-stroke diesel engine type is currently commercially available, the MAN ME-LGI series, which is now in operation on methanol tankers. Wärtsilä four-stroke engines are in operation on board the passenger ferry Stena Germanica.

It is also feasible to use methanol in fuel cells. A test installation has been running on the Viking Line ferry MS Mariella since 2017.

Table 5-4: Methanol technology options and properties

Converter	FC	ICE 2-stroke Dual Fuel High Pressure	ICE 4-stroke
Components	Fuel cell Storage tanks Electric motor Reformer Battery	Engine Storage tanks Process system NOx reduction system (EGR/SCR)	Engine Storage tanks Process system
Key challenges	Fuel tank 2-3 times larger than for petroleum-based fuels		

Pathways

Production from natural gas has been chosen as the energy source for the methanol pathway, as it is the conventional production method for methanol. Moreover, only internal combustion engines are considered a viable solution for methanol in the short to medium term. Thus, ICE is the converter of choice for the methanol path. Whether the engine is a 2-stroke or 4-stroke has not been specified, but there are mainly 2-stroke engines in operation, so data used primarily pertains to this engine type.

Pathway 13: NG – Methanol – ICE	Methanol

Out of scope

- Production from other energy sources than natural gas
- Production processes including CO_2 recovery
- Fuel cell as converter

5.6 LPG pathway

Liquefied petroleum gas (LPG) is, by definition, any mixture of propane and butane in liquid form. Specific mixtures of butane and propane are used to achieve desired saturation, pressure and temperature characteristics.

Propane is gaseous under ambient conditions, with a boiling point of −42°C. It can be handled as a liquid by applying moderate pressure (8.4 bar at 20°C). Butane can be found in two forms: n-butane or iso-butane, which have boiling points at −0.5°C and −12°C, respectively. Since both isomers have higher boiling points than propane, they can be liquefied at lower pressure. For land-based storage, propane tanks are equipped with safety valves to keep the pressure below 25 bar. LPG fuel tanks are 2-3 times larger than oil tanks due to the lower volumetric energy density of LPG and volume inefficiencies for C-type tanks (similar as for LNG).

There are two main sources of LPG: a by-product of oil and gas production or a by-product of oil refinery. It is also possible to produce LPG from renewable sources, for example as a by-product of renewable diesel production.

There are three main options for using LPG as ship fuel: in a two-stroke diesel-cycle engine; in a four-stroke, lean-burn Otto-cycle engine; or in a gas turbine. Currently, only one single two-stroke diesel engine type is commercially available, the MAN ME-LGI series. In 2017, a Wärtsilä four-stroke engine was commissioned for stationary power generation (34SG series). This engine had to be derated to maintain a safe knock margin. An alternative technology offered by Wärtsilä requires installation of a gas reformer to turn LPG and steam into methane by mixing them with CO_2 and hydrogen. This mixture can then be used in a regular gas or dual-fuel engine without derating.

Table 5-5: LPG technology options and properties

Converter	ICE
Components	Engine Storage tanks Process system NOx reduction system (EGR/SCR)
Key challenges	Fuel tank 2-3 times larger than for petroleum-based fuels

Pathways

Since production as a by-product of oil and gas production or as a by-product of oil refinery are the most common production methods for LPG, these have been combined and defined as a fossil energy source for production of LPG, in this study. The selected engine has not been specified as either a 2-stroke or 4-stroke engine, but since only 2-stroke engines are currently available, data will pertain to this engine type.

Pathway 14: Fossil – LPG – ICE	LPG

Out of scope

- Production from other than fossil energy sources
- Gas turbine as converter

5.7 Advanced biodiesel pathway

The overall GHG emissions from a given biofuel will depend on the feedstock and production process (/25/, /59/). Lifecycle GHG reductions in the range 20-90% are typically reported for different biofuels (/59/, /34/) but there is debate about the extent to which biofuels lead to GHG reductions, and there is a need for systems classifying different biofuels for use in shipping. The highest reduction potential is reported for advanced biofuels.

Biofuels can be blended with conventional fuels or used as 'drop-in' fuels fully substituting for conventional fossil fuels. A 'drop-in' fuel can directly be used in existing installations without major technical modifications. Biofuels are well suited to substitute oil-based fuels in the existing fleet. The most promising biofuels for ships are hydrotreated vegetable oil (HVO), fatty acid methyl ester (FAME) and liquefied biogas (LBG) [2]. HVO is a high-quality fuel in which the oxygen has been removed using hydrogen, which results in long-term stability. The fuel has characteristics that makes it suitable as a 'drop-in' fuel, substituting fossil fuels. In general, HVO is compatible with existing infrastructure and engine systems, subject to approval by the manufacturer, but minor modifications may sometimes be required. Overall, there is limited operational experience with the use of HVO as a fuel in the shipping industry. HVO is currently used onboard several ferries[3,4] operating in Norway without reported negative effects.

Table 5-6: Advanced biofuels technology options and properties

Converter	ICE
Components	Engine Storage tanks Process system NOx reduction system (EGR/SCR)
Key challenges	Currently limited availability of sustainably produced biofuels Fuel cost

Pathways

Advanced biofuels include a vast range of alternatives, but this study focuses on sustainably produced HVO as drop-in fuel employed as a direct substitute for conventional petroleum-based fuels.

Pathway 15: Biomass – Advanced biodiesel (HVO) – ICE	Advanced biodiesel

Out of scope

- Other biofuels than HVO

5.8 Fully electric pathway

On a *fully electric* ship, the power system (for both propulsion and auxiliaries) is entirely based on batteries which are charged through an on-shore connection to the electric grid while at berth. A *plug-in hybrid* ship, like a plug-in hybrid car (PHEV), can charge its batteries using shore power, but has a conventional engine in addition. The ship can operate on batteries alone on specific parts of the route, e.g. when manoeuvring in port or during stand-by operations. It can also operate 100% electric for normal operation, with engines only for back-up or in use for special operational circumstances. A

[2] https://lloydslist.maritimeintelligence.informa.com/LL1125334/Norden-successfully-runs-product-tanker-on-biofuel

[3] Ruter: https://ruter.no/om-ruter/miljo/gassdrevne-passasjerferger/

[4] TU: http://www.tu.no/artikler/de-blir-verdens-tre-forste-ferger-pa-kun-biodrivstoff/275609

conventional hybrid ship uses batteries to optimize engines and power system and reduce fuel consumption, but does not bunker electricity from shore. Today more than 320 hybrid/plug-in hybrid ships are in operation or on order. Shore-based infrastructure for charging is limited today, but progress has been made in certain regions[5,6] (e.g. /26/).

Electrification of ships will result in tank-to-wake emission reductions that depend on the proportion of electrical energy consumed. The reduction will be 100% when all ship consumption is powered by electricity. To obtain close to zero lifecycle emissions, the electricity itself must be produced by a zero-emission energy source, or by using CCS.

The amount of electrical energy which can be transferred from shore to ship depends on several factors, including on-shore electric grid capabilities, battery-charging facilities, and time spent shoreside. Together with the installed battery capacity on board the ship, these define the potential for electric operation. Battery-system applicability for ship types and operation is discussed in more detail later in the report.

Installing battery systems (incl. replacement after typically 8-10 years) is significantly more costly than traditional diesel engines. In addition, investment in infrastructure on land is required to provide electricity. Considering the range limitations, uncertainty in future electricity prices and the large geographical price variations (/60/), in addition to long pay-back period on the investment, battery systems for high degree of hybridisation can be unattractive or simply not practical for shipowners, especially for deep-sea vessels. It should be noted that to a large extent, fully electric vessels currently in operation have ICEs installed for redundancy purposes.

Table 5-7: Fully electric technology options and properties

Converter	Battery
Component	Electric motor Battery Battery management system
Key challenges	Size and weight High power charging requirements Cost

Pathways

The pathway covering fully electric propulsion covers vessels which are operating almost entirely on electricity with charging from shore power (they will usually have ICE or FC for redundancy purposes). In general, fully electric systems are only feasible for a very limited number of vessel types and sizes with short sailing distance. The pathway is based on a fossil and renewable energy mix for production of electricity, where both cost and emissions exhibit large regional variations. The energy source is therefore defined as an energy mix, and the variations are described where applicable.

Pathway 16: Energy mix – Electricity – Fully electric battery-electric system Fully electric

Out of scope

- Plug-in hybrid and conventional hybrid

5 First for Shore Power in India: http://www.maritime-executive.com/editorials/first-for-shore-power-in-india

6 Shore power, Norway: http://www.tu.no/artikler/havner-vil-fa-hurtigruten-over-pa-landstrom/193818
http://www.mynewsdesk.com/no/enova-sf/pressreleases/140-millioner-til-landstroem-1689508

5.9 Summary of pathways

Below the 16 different pathways covered in this study are summarised:

Pathway	Fuel
Pathway 1: NG – LNG – ICE – 4S LBSI/LPDF Pathway 2: NG – LNG – ICE – 2S LPDF Pathway 3: NG – LNG – ICE – 2S HPDF Pathway 4: NG – LNG – FC	LNG
Pathway 5: NG – H_2 – FC Pathway 6: Renewable - H_2 – FC Pathway 7: NG – H_2 – ICE Pathway 8: Renewable - H_2 – ICE	Hydrogen
Pathway 9: NG – NH_3 – ICE Pathway 10: Renewable – NH_3 – ICE Pathway 11: NG – NH_3 – FC Pathway 12: Renewable – NH_3 – FC	Ammonia
Pathway 13: NG – Methanol – ICE	Methanol
Pathway 14: Fossil – LPG – ICE	LPG
Pathway 15: Biomass – Advanced biodiesel (HVO) – ICE	Advanced biodiesel
Pathway 16: Energy mix – Electricity – Battery-electric system	Fully electric

6 DATA EXTRACTION AND RESULT ASSESSMENT

For each of the selected 16 pathways described in section 4, data on performance on 11 parameters have been extracted and presented in this section. The 11 parameters are divided into the main categories **applicability, economics, environment and scalability.** The data has been extracted based on a comprehensive literature review.

6.1 Applicability

In this section, the energy density, selected safety parameters, technological maturity and international regulations and class rules are analysed to provide information on the applicability of the different fuel options

6.1.1 Energy density

The energy density of a fuel can be specified both in terms of a volumetric energy density (energy content per volumetric unit) and a gravimetric energy density (energy content per mass unit). High volumetric and gravimetric densities imply that the fuel requires less space and has smaller mass, which is advantageous when storing the fuel onboard a vessel. The energy density of a fuel partly determines how applicable the fuel is for certain ship types and ship operations. In Figure 6-1 the volumetric and gravimetric energy densities are specified for various fuels.

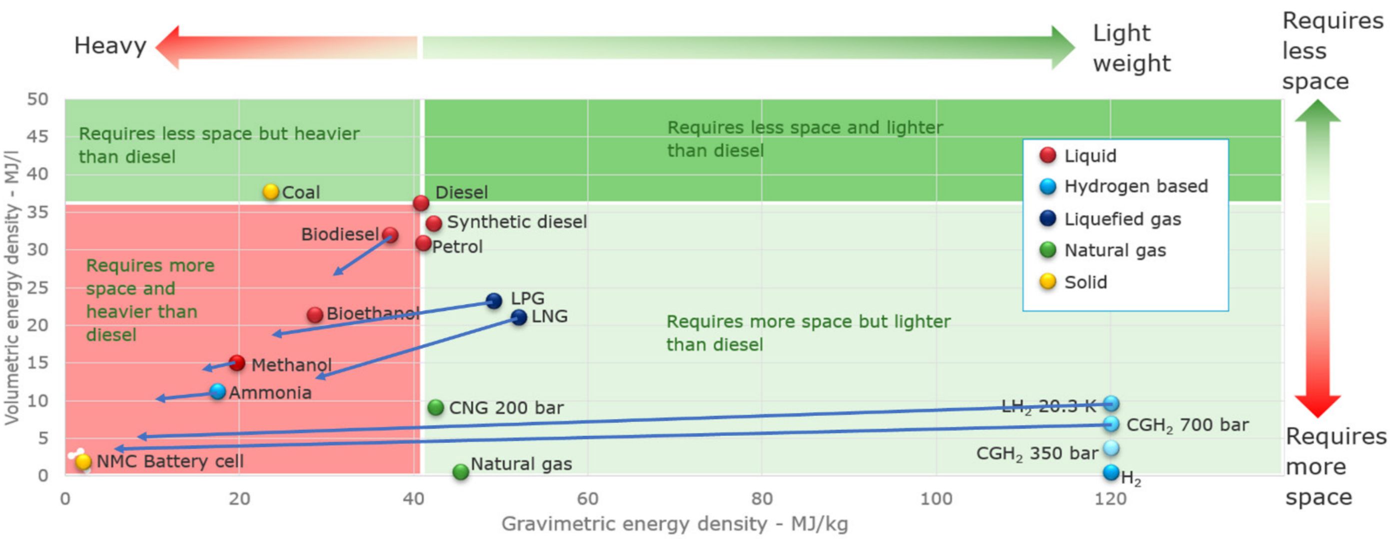

Figure 6-1: Energy densities for different energy carriers (inspired by /49/ /72/ and /73/). The arrows represent the impact on density when taking into account the storage systems for the different types of fuel (indicative values only).

Note that Figure 6-1 illustrates the fuel properties only – when storage tanks and necessary systems are included the picture changes radically for some fuels. This is especially the case for fuels that require refrigerated/cryogenic or pressurized storage, such as H_2 (e.g. gravimetric densities lower than 10 MJ/kg for LH_2 including storage systems, compared to ~120 MJ/kg for the fuel only) and LNG (gravimetric and volumetric densities of ~25 MJ/kg and ~13 MJ/l including storage systems, respectively, compared to ~50 MJ/kg and ~21 MJ/l for the fuel only) (/49/).

The figure illustrates that LNG has around 40 % lower volumetric energy density than diesel, roughly the same as LPG. When accounting for the storage system, LNG has approximately 40% lower volumetric density. Liquid hydrogen, ammonia and methanol have even lower volumetric energy density – around

40-50 % of LNG, however the additional volume needed for storage system for methanol is less which brings it closer to LNG in practice. Ammonia is normally stored in pressurized type C tank, which gives a similar impact on actual ship space utilization as for LNG when accounting for storage systems. LPG is currently stored both in prismatic tanks (refrigerated) and cylindrical tanks (pressurized), the same way as for LNG. Hence the volumetric energy density ratio between ammonia and LPG vs LNG gives a representative picture of what it means to switch from LNG to these fuels. When taking into account the storage system for hydrogen it becomes evident that this impacts the feasibility since the density becomes significantly lower than the other alternative fuels. Biodiesel has a significantly higher volumetric energy density than LNG, with levels almost as high as diesel. Batteries has by far the lowest energy density among the alternatives assessed in this report. Because of its low volumetric and gravimetric densities, employing batteries to propel deep-sea operation in a significant degree is challenging and for most cases not feasible/realistic.

Taking into account both the fuel density and the storage system, the vessel endurance range indicates how often a vessel has to bunker energy, in general irrespective of size. As can be seen below, the intervals range from hours to months, depending on which fuel is being considered.

Table 6-1: Typical bunkering intervals for vessels using different alternative fuels

Fuel	HVO	LNG	LPG	Methanol	Liquid ammonia	Liquid hydrogen	Compressed hydrogen	Fully-electric
Vessel endurance range	Months	Weeks	Weeks	Weeks	Weeks	Days	Hours-days	Hours

6.1.2 Flammability and toxicity

There are many aspects relating to the safe application of alternative fuels onboard ships. In this section we analyse a few key inherent properties of the fuels which influence safety.

The **flash point** of a chemical substance is the lowest temperature at which a liquid can form an ignitable mixture in air near the surface of the liquid. The flash point is an indication of how easy a chemical may burn. Materials with higher flash points are less flammable or hazardous than chemicals with lower flash points. A lower flash point is an indication of fuel that can be ignited at lower temperatures, and in the absence of additional safety measures, this indicate higher risk.

The **autoignition temperature** is the minimum temperature required to ignite a gas or vapor in air without a spark or flame being present.

The **flammability limits** show the range of vapour concentrations of a certain chemical, expressed in volume percent, over which a flammable mixture of gas or vapour in air can be ignited at 25^{o}C and atmospheric pressure. A wide range (such as for hydrogen) indicates a fuel that is flammable under several conditions, and in the absence of additional safety measures, this indicate higher risk.

All properties are given in atmospheric conditions (25^{o}C, 1 atm).

Table 6-2: Overview of flammability and toxicity of different fuels.

Fuel	Flash Point (°C)	Autoignition temperature (°C)	Flammability Limits (volume % in air)	Toxicity
LNG	-188	537	4-15	Not toxic
Hydrogen	Not defined	500	4-74.2	Not toxic
Ammonia	132	630	15-28	Highly toxic
Methanol	11-12	470	6.7-36	Low acute toxicity (dangerous for humans)
LPG	-104	410-580 (depending on the composition)	1.8-10.1	Not toxic
Advanced biodiesel (HVO)[7]	>61	204	Approx. 0.6-7.5	Not toxic
Battery-electric	Not applicable	Not applicable	Not applicable	Not applicable

Sources: /15/, /56/

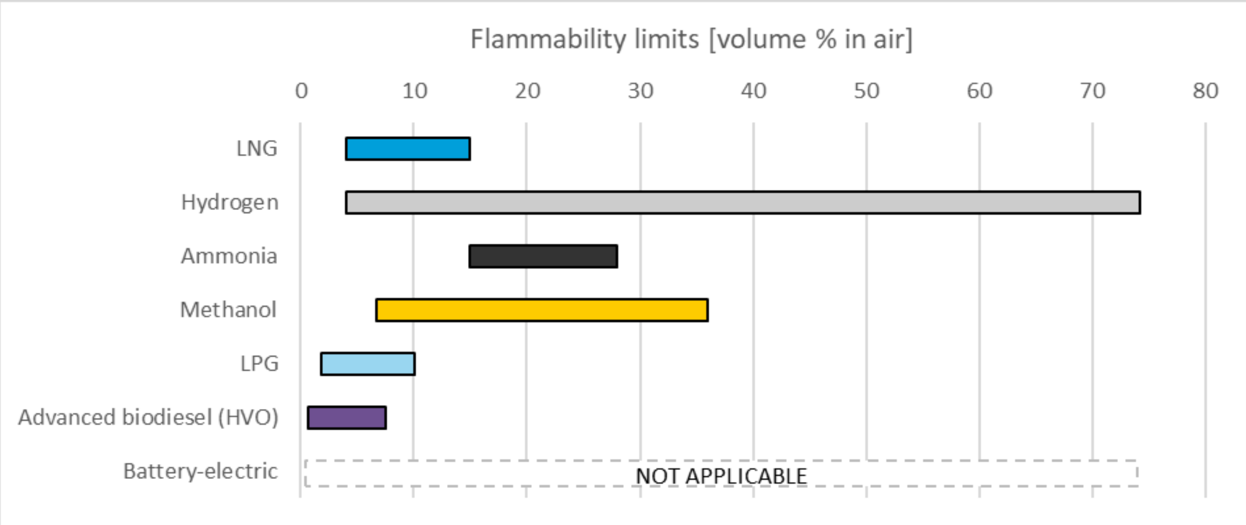

Figure 6-2: Flammability limits for different fuels. A wide range indicates a fuel that is flammable under several conditions, and in the absence of additional safety measures, this indicates higher risk.

It is important to note that rule developments for marine application of alternative fuels must be expected to be based on the equivalent safety principle, and increased risk levels (frequency x

[7] Depends heavily on the production method. Values from Neste Oil have been used: https://www.neste.com/sites/default/files/attachments/nexbtl_renewable_diesel_version3.0_safetysheet.pdf

consequence) will likely not be accepted. Worse score on flammability and toxicity hence should be expected to translate into appropriate risk mitigating measures, with resulting impact on e.g. costs and operational restrictions.

6.1.3 Technological maturity

Technological maturity refers to the maturity of engine technology and systems. For each converter (including all necessary components) a technical maturity level is assigned. A maturity level of 1 indicates high maturity and a technology that is commercially available, and 4 indicates low maturity and a technology that is not even on a pilot stage. The technical maturity level is evaluated per today's status.

Interpretation of technical maturity levels:

1. Measures that are off the shelf and commonly used on new ships
2. Measures that are commercially available, but not fully mature
3. Measures that are under piloting, and/or with only a few commercial applications
4. Measures that have not been tested in full scale and no piloting or full-scale testing underway.

From Table 6-3, we see that the fuel cell systems are typically immature. Also, the technical maturity of hydrogen and ammonia systems are low.

Table 6-3: Technical maturity levels.

Fuel	Converter	Components	Maturity
LNG	ICE 4-stroke Lean Burn Spark Ignition/Dual Fuel Low Pressure (4S LBSI/LPDF)	Engine Storage tanks Process system	1
	ICE 2-stroke Dual Fuel Low Pressure (2S LPDF)	Engine Storage tanks Process system	1
	ICE 2-stroke Dual Fuel High Pressure (2S HPDF)	Engine Storage tanks Process system NOx reduction system (EGR/SCR)	1
	FC	Fuel cell Storage tanks Electric motor & reformer Battery	3
Hydrogen	FC	Fuel cell Storage tanks Electric motor & reformer Battery	3
	ICE	Engine Storage tanks Process system	4
Ammonia	FC	Fuel cell Storage tanks	3-4

Fuel	Converter	Components	Maturity
		Process system Electric motor & reformer Battery	
	ICE	Engine Storage tanks Process system NOx reduction system (EGR/SCR)	3-4
Methanol	FC	Fuel cell Storage tanks Electric motor & reformer Battery	3
	ICE 2-stroke Dual Fuel High Pressure	Engine Storage tanks Process system NOx reduction system (EGR/SCR)	2
	ICE 4-stroke	Engine Storage tanks Process system	2
LPG	ICE – 2-stroke	Engine Storage tanks Process system NOx reduction system (EGR/SCR)	2-3
	ICE – 4-stroke	Engine Storage tanks Process system	4
HVO	ICE	Engine Storage tanks Process system	2
Battery-electric	Battery	Electric motor Battery Battery management system	1

Note that the maturities of the energy source and processing parts of the presented pathways are not covered here but discussed in section 6.4.2 Availability.

6.1.4 International regulations and class rules

Shipping is an international industry, and international environmental and safety standards for shipping are developed by the UN's International Maritime Organization (IMO).

The International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF Code) is the mandatory IMO instrument that applies to all gaseous and other low-flashpoint fuels in shipping, and to all gas-powered ships other than gas carriers. The use of low-flashpoint fuels in gas carriers is covered by the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IMO IGC Code).

The IGF Code was adopted by the IMO in June 2015 (MSC.391[95]) and came into force on 1 January 2017. It is compulsory for all gas-fuel and other low-flashpoint-fuel ships and currently has detail provisions for natural gas in liquid or compressed form (LNG, CNG). Regulations for methanol and low-flashpoint diesel fuels as well as for maritime fuel cells are under development.

The IGF Code contains mandatory provisions for the arrangement, installation, control and monitoring of machinery, equipment and systems using low-flashpoint fuels. It addresses all areas that need special consideration for the usage of low-flashpoint fuels, taking a goal-based approach, with goals and functional requirements specified for each section to provide a basis for the design, construction and operation of ships using this type of fuel. Technical provisions for other low-flashpoint fuels than natural gas, and other energy arrangements such as fuel cell systems will eventually be added to the code as new chapters.

For the time being, ships installing fuel systems to operate on other types of low-flashpoint fuels will need to individually demonstrate that their design meets the IGF Code’s general requirements. The alternative design approach as outlined in IMO MSC.1/Circ.1455 (guidelines for the approval of alternatives and equivalence as provided for in various IMO instruments) must be followed and be accepted by the flag administration of the vessel. This individual, and in some cases complex process introduces uncertainty and increases cost, and it will have a slowing effect on the introduction of alternative fuels not yet explicitly covered by the IGF Code.

The presence of relevant class rules may however ease this situation significantly, since a simplified process may be applied if the flag accepts the class rules as providing a safety level equivalent to that of the IGF Code.

DNV GL rules addressing the requirements of the IGF Code include:

- Mandatory Class Notation “GAS FUELLED”: Rules for classification of ships, Part 6, Chapter 2, Section 5, Gas fuelled ship installations – Gas fuelled
- Voluntary Class Notation “GAS READY” for ships prepared for later gas fuel retrofit: Rules for classification of ships, Part 6, Chapter 2, Section 8, Gas ready ships – Gas ready

DNV GL rules for ships using low-flashpoint liquid fuels (e.g. methanol) and for fuel cell installations:

- Mandatory Class Notation “LFL FUELLED”: Rules for classification of ships, Part 6, Chapter 2, Section 6, Low flashpoint liquid fuelled engines – LFL fuelled
- Mandatory Class Notation “FC (Power)” or “FC (Safety)”: Rules for classification of ships, Part 6, Chapter 2, Section 3, Fuel cell installations – FC

DNV GL is currently also developing rules for use of LPG as fuel.

In addition, DNV GL was the first classification society to develop rules for lithium-ion battery installations on board ships:

- Mandatory Class Notation(s) “BATTERY (SAFETY)” and “BATTERY (POWER)”: Rules for classification of ships, Part 6, Chapter 2, Section 1, Battery power

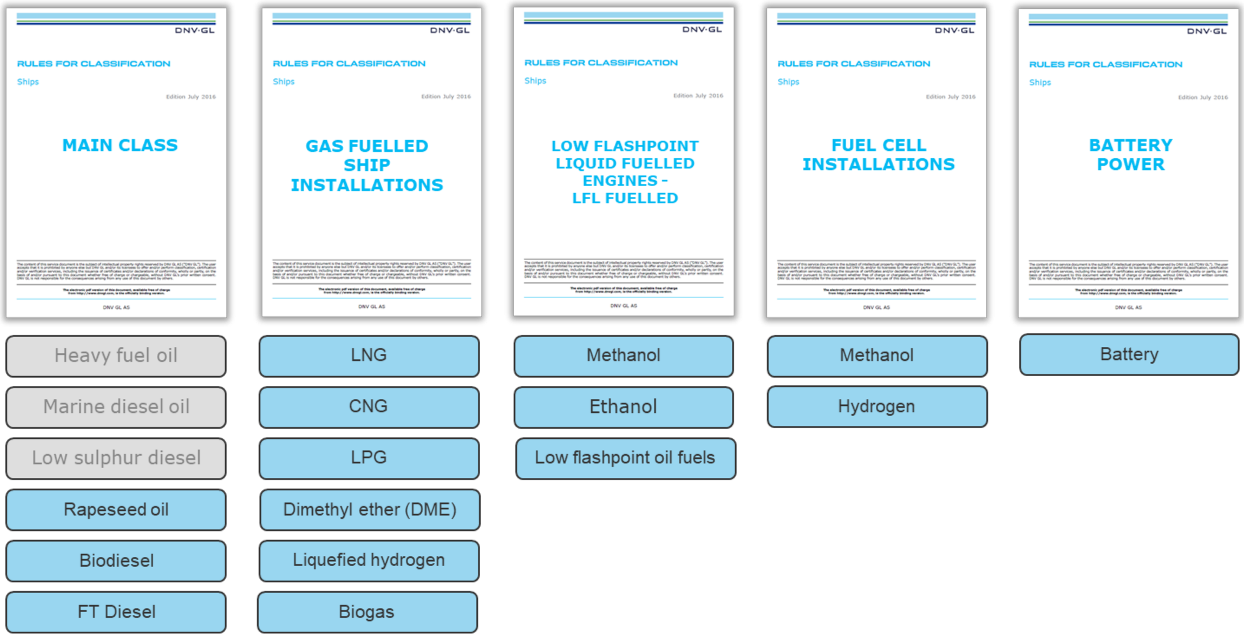

Figure 6-3: Overview of DNV GL class rules for different alternative fuels

Fuels not covered by these codes can be used by following the alternative design approach in accordance with SOLAS Regulation II-1/55 to demonstrate an equivalent level of safety.

Regarding bunkering standards, these are often subject to national regulations and there is a lack of standardization.

Regarding liquid biofuels, there is no upper limit for blend-in of HVO according to the ISO 8217:2017 fuel standard. It allows for up to 100% HVO as long as the fuel fulfils the requirements in the standard /58/.

6.2 Economics

A key feature of any alternative fuel is its economic feasibility. The two main economic parameters are the energy cost and the capital cost, which are analysed in the following. Other economic parameters such as maintenance cost etc. are not covered in this study.

6.2.1 Energy cost

Data on energy costs have been extracted from available sources and converted to USD/MWh shaft output, enabling a direct comparison of costs for the different energy carriers. The system efficiency and the specific energy content of the fuel were used in the conversion.

For both hydrogen and ammonia, production from renewable sources is highly dependent on the electrolyser load factors (number of running hours per year) and the cost of electricity. A load factor of 50% and electricity costs ranging between 20 and 60 USD/MWh have been utilized in this study. At load factors below 50%, the price increases exponentially. For the hydrogen and ammonia pathways to derive from renewable energy sources, the electricity used in production must originate in renewables.

For some of the pathways, only the commodity price is given and not the price of delivered fuel. This is the case for hydrogen, ammonia and HVO. When considering the cost of liquefaction/compression, distribution, storage and bunkering facilities, as well as mark-up, it is evident that the price of delivered fuel will be higher than what is presented for the relevant pathways. DNV GL's experience is that distribution cost for LNG, from LNG terminals to the receiving ship, typically range between 40-120 USD/m3 which is the equivalent of approx. 15-40 USD/MWh shaft output. For a given case the cost of transporting ammonia should be fairly similar to transporting LNG, measured on a per volume basis. Adjusting for the lower energy content of ammonia this translates to approx. 20-70 USD/MWh, which comes in addition to what is presented below. Transport costs for LPG would be slightly lower than for LNG due to the slightly higher energy density, and the price of LPG carriers are typically also somewhat lower than comparable LNG carriers.

A differentiation on liquefied vs. compressed hydrogen has not been made, but according to /45/, liquid hydrogen is approximately 30% more expensive than compressed hydrogen. It should be noted that for fully electric systems, the price exhibits large regional and seasonal variations.

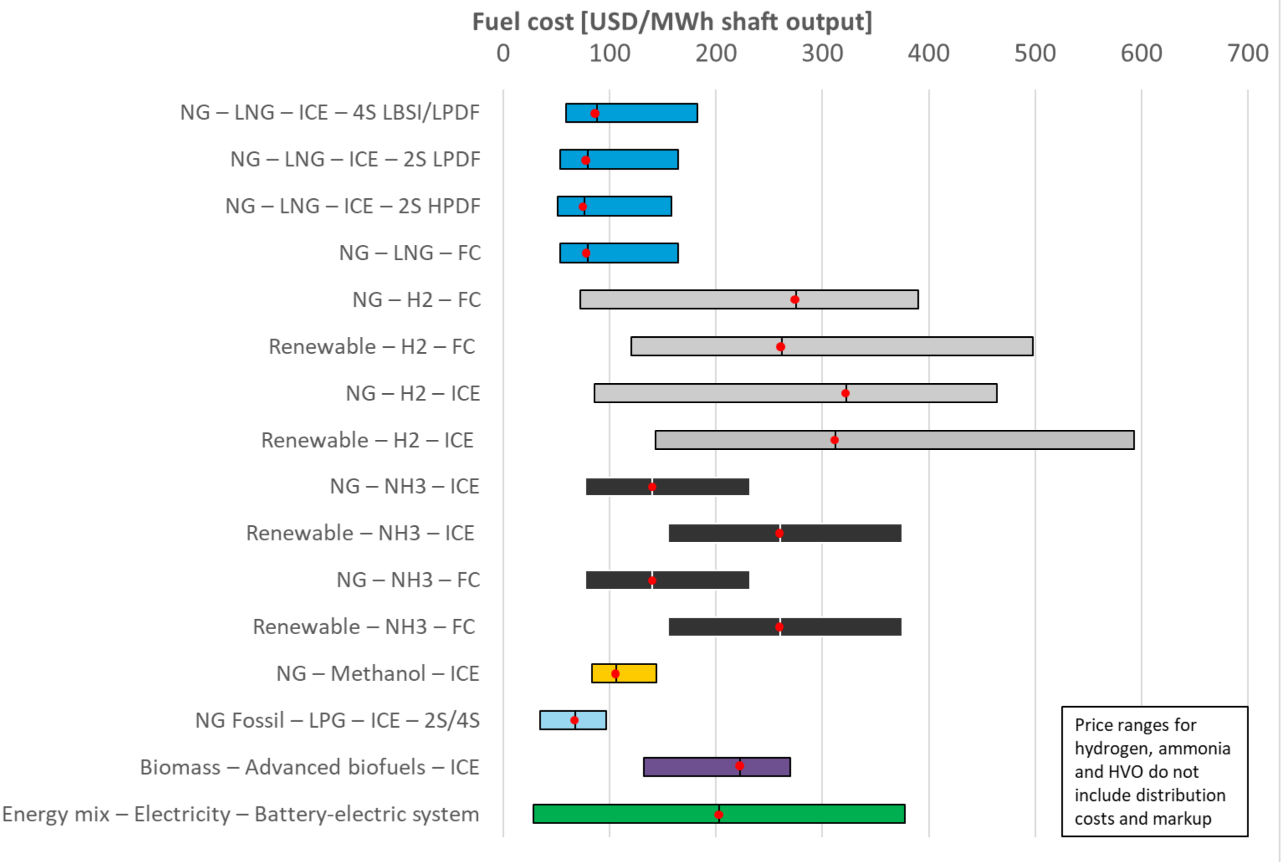

Figure 6-4: Energy cost for the fuel/technology pathways, taking into account the energy content and system efficiency [USD/MWh shaft output]

From Figure 6-4 it is clear that LNG, methanol and LPG are competitive in terms of energy costs, while HVO is significantly more expensive. Hydrogen and ammonia are also far more expensive, and the large cost range indicates a significant uncertainty in terms of pricing. Figure 6-4 may give the impression that hydrogen produced from renewables is likely to be cheaper than when produced from natural gas. However, there are few available sources and the only source that gives prices for both suggests than hydrogen from renewables is 50% more expensive.

Sources: See Appendix B – Sources used for assessment of each parameter

Liquefied Biogas (LBG) and synthetic methane (from Power-To-Gas process) represents carbon drop in fuels for the LNG pathways, but has not been part of the scope for this literature review. LBG is produced in limited volumes today and is mainly used for heavy duty vehicles and buses. LBG is therefore competing with road diesel, and e.g. in Norway LBG is currently therefore priced at approximately three times the price of LNG. Hurtigruten was the first company to sign a long-term contract for a large volume of LBG supply to their cruise vessels[8]. The price of synthetic methane is estimated to be at least as costly, based on current technology. That puts the price of these fuels in the same order of magnitude as hydrogen, ammonia and biodiesel.

6.2.2 Capital costs

The additional capital costs primarily comprise of cost for converter, storage system and process system. It was found that cost for process system is in general not given in available literature, so in the following, only the cost for converter and storage system are included.

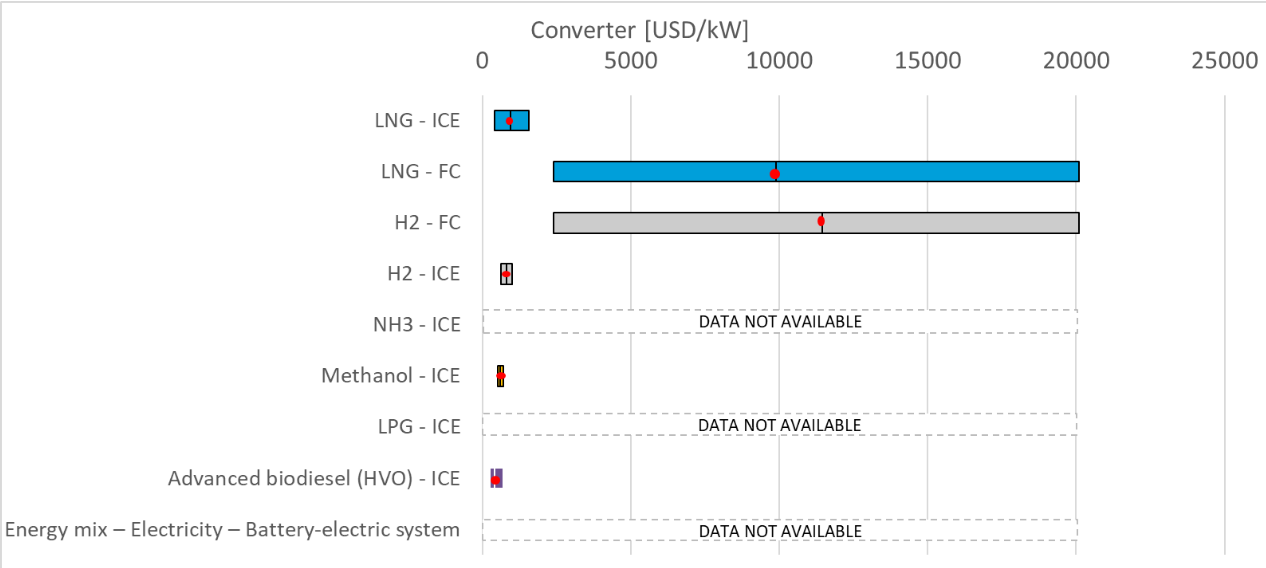

Figure 6-5: Capital cost of converter for the different fuel/technology pathways

It is evident from Figure 6-5 that fuels cells are currently many times more expensive than the internal combustion engines. Moreover, the big range in cost for fuels cells indicates a large degree of uncertainty. This is likely much due to the low maturity of fuel cells and subsequent low sales volume in today's maritime industry. Another aspect that is not reflected in the shown capital cost for fuel cells is that the life expectancy of the fuels cells means that the fuel cell stack needs replacement after a period of operation. The available data for the number of operation hours before a cell stack replacement is needed varies greatly. /63/ gives a range of 10 000 – 90 000 hours with a representative lifetime of 47 500 hours (/63/). This would typically translate to stack replacement about every 10 years for main engines on deep sea vessels (depending on ship type and market conditions). Shell states that the life expectancy for the two most promising fuel cell technologies is 60 000 hours for proton-exchange membrane (PEM) fuels cells, and up to 90 000 hours for solid oxide (SO) fuel cells (/72/). The cell stack replacement entails a cost, given by /63/ as 60% of the capital cost of the fuel cell, while DNV GL operates with 50% of the fuel cell cost.

Although there is no available data for specific costs for technology for using ammonia, Lloyd's Register have found the additional system cost to be approximately 2-60% for internal combustion engine and 8-

[8] https://www.hurtigruten.com/us/press-releases/2018/hurtigruten-to-power-cruise-ships-with-dead-fish/

300% for fuel cell, relative to a conventional HFO-fuelled vessel (/44/). With such high degree of uncertainty, it is clear that more work is needed on this topic. The same study indicates that biofuel does not have any additional investment costs compared to the conventional vessel. This is supported by DNV GL who state that there is no additional investment cost reported when running on advanced HVO (/22/). For LPG, DNV GL have found the cost of installing LPG systems on board a vessel to be roughly half that of an LNG system if pressurized type C tanks are used in both cases (/22/). Ammonia is transported by multi-cargo gas carriers which can also transport LPG, hence equipment and costs for transporting ammonia can be estimated from the cost of LPG. The cost of the electric motor has not been included since it is insignificant in comparison to the batteries and related systems, see costs for storage tanks for more information.

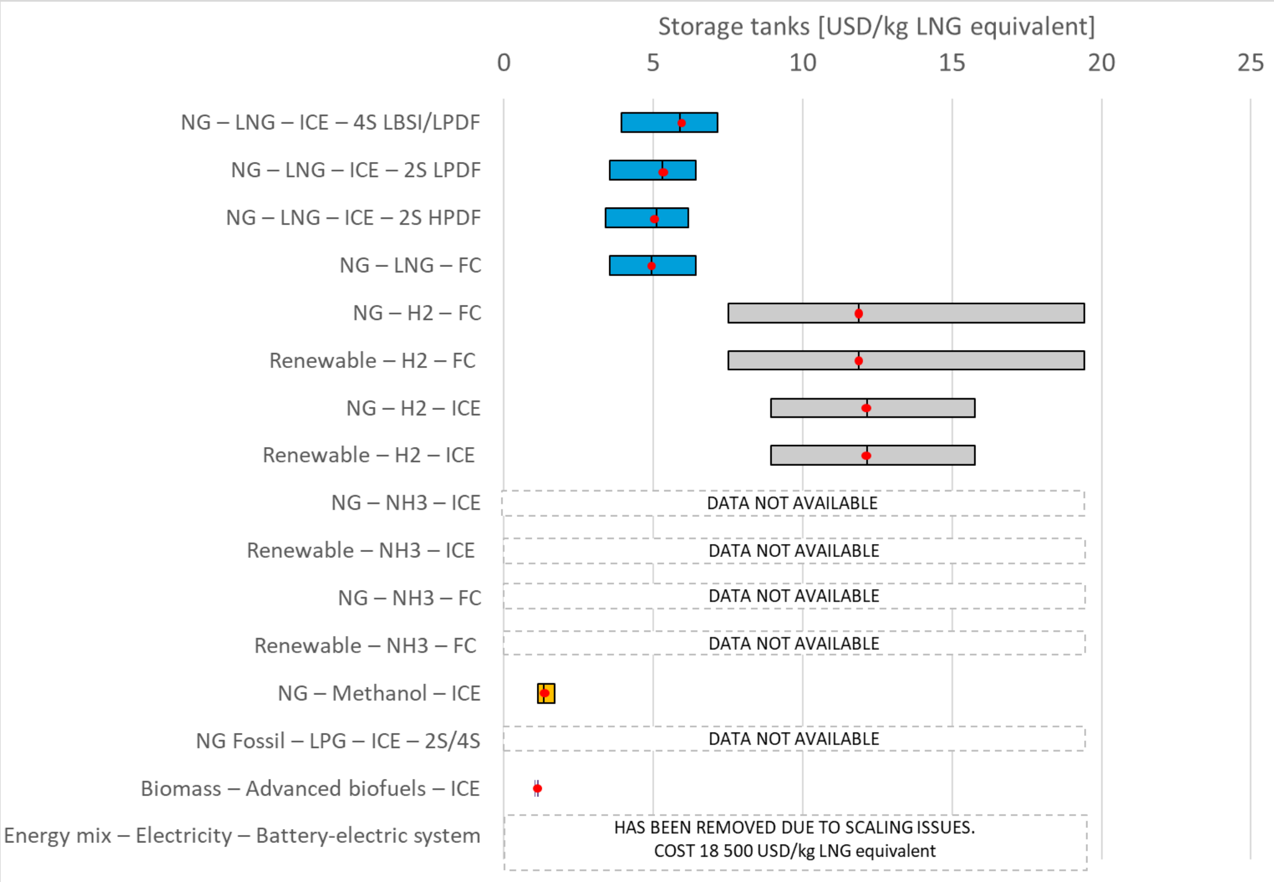

Figure 6-6: Capital costs of storage tanks for the different fuel/technology pathways, taking into account energy content, system efficiency, utilization of storage system and storage system lifetime [USD/kg LNG equivalent]

When comparing storage costs, the converter efficiency, tank storage utilization factor and storage lifetime has also been considered. This is why the cost for LNG tanks vary slightly depending on engine type (and fuel cell). Adjusting for storage lifetime for batteries (assumed to be 1/3 of fuel tanks) has a significant impact on results but is to some respect mitigated by the almost twice as high system efficiency compared to ICEs.

A differentiation on liquefied vs. compressed hydrogen has not been made when comprising data for hydrogen, since the sources often do not specify which technology the cost is given for. However, DNV GL have found tanks for liquefied hydrogen to be significantly more expensive due to lower storage temperatures, higher insulation quality and fewer maritime applications. With current technology, hydrogen seems limited to shortsea shipping when considering costs of tanks and range limitations due to its low density.

Sources: See Appendix B – Sources used for assessment of each parameter

Batteries

DNV GL has extensive experience with battery-electric system, especially through the rapid developing ferry market in Norway the past few years. The battery cost, including battery management system (BMS) has typically been in the region 550-1400 USD/kWh, depending on cell chemistry. In addition comes power conversion hardware at approximately 160 USD/kW. Potential additional costs related to propulsion system and ship design compared to conventional alternatives may also arise – however this is highly case dependent and difficult to quantify generally. As shown in Figure 6-1, both gravimetric and volumetric density of batteries are very low. This means that batteries often become large and heavy, and application for maritime use needs to be evaluated closely on a case-by-case basis. Sandia has investigated the practical application of batteries where a set of vessels were mapped and evaluated for use of batteries (/66/ They found that five out of 14 vessels investigated had sufficient mass/volume available for one or more one-way trips. A selection of these 14 vessels is presented in Table 6-4 to show the span between deep-sea and short-sea shipping, and vessels with and without sufficient mass/volume. The study assumes that the battery capacity must be twice the estimated energy consumption for a normal single trip, to account for operational limitations of the battery. The results with regards to *available* versus *required* volume and mass for battery-electric propulsion is shown below for these selected vessels. In addition, the battery cost has been calculated by DNV GL using the lowest above-mentioned price estimates for maritime batteries. For reference, the 2018 average price for batteries for the automotive industry as reported by Bloomberg was approx. 30% of the estimate applied in the below table[9]. Bloomberg estimates a further halving of the 2018 average price within 2030 (i.e. 15% of the assumption applied below).

Table 6-4: Energy need, available versus required mass and volume for fuel, and cost of batteries for a selection of vessels. Data, excluding battery cost, has been extracted from (/66/).

Vessel	Emma Maersk	Atlantic Klipper	Zalophus
Vessel type	Container Deep-sea	Cargo vessel Short-sea	Passenger boat
Main engine power, MCR [MW]	80.1	14.3	0.8
Energy storage need single trip [MWh]	18 500	144	0.97
Ship deadweight [dwt]	156 257	15 692	Not found
Available volume for fuel [m3]	18 615	2 285	40
Available mass for fuel [tonnes]	15 082	2 841	28
Battery volume single trip [m3]	284 000	2 140	15
Battery mass single trip [tonnes]	246 000	2 220	13
Volume needed vs. available for fuel	15.3	0.94	0.38
Mass needed vs. available for fuel	16.3	0.78	0.46
Battery cost [USD]	10 090 000 000	79 000 000	528 000

[9] https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

From these figures it is evident that application for deep-sea is not feasible in terms of either mass or volume with current battery technology. For Emma Maersk the estimated battery mass by far exceed the deadweight of the ship, taking up far more than the entire cargo carrying capacity. Further improvements in energy density are expected, which is a key factor for the projected price reduction, but still not to a degree that will make a case like Emma Maersk realistic. Furthermore, application for short-sea has to be evaluated closely, especially taking into account the cost of batteries for a specific vessel. As can be seen for the Atlantic Klipper, the application of a battery-electric system is feasible in terms of mass and volume, but the cost makes it an unrealistic alternative. Only for the Zalophus case could potentially mass, volume and costs be feasible. Whether the battery cells would need to be exchanged during the lifetime of the ship is also an issue to consider. Battery degradation is both a function of number of cycles and age, and it must be considered on a case by case basis. For deep sea vessels the number of charging cycles will be fairly low, but aging over 30 years may be an issue.

6.3 Environment

A key feature of many of the alternative fuels being considered for use in the shipping industry is the potential for better environmental performance within some or all emission aspects, making them options for ship owners to comply with current and future environmental regulations. In the following, two of the most central environmental aspects are covered; GHG emissions and local emissions (SOx, NOx and PM). Other environmental parameters such as oil spill risk or noise are not covered.

6.3.1 Well-to-wake GHG emissions

The well-to-wake GHG emissions includes emissions from production, transport and storage of each fuel, as well as combustion/conversion to mechanical energy onboard the vessels. The resulting comparative measure of well-to-wake emissions is the mass of CO2 equivalent emissions per unit of shaft output energy. This implies that the well-to-wake emissions within each of the 16 energy carrier and converter pathways in this study will vary greatly, depending on how and where the energy carriers are produced, mode of transport and storage, and onboard system efficiency. In Figure 6-7, an overview of well-to-wake GHG emissions are shown. For each pathway, a range with minimum and maximum values is presented, as well as an average of averages for the considered study results.

It is important to bear in mind that the assumptions and scenarios on which the results are based, e.g. production, means of transport and vessel specs, are not equal. This implies that the use-cases themselves embody a varied representation of well-to-wake scenarios, implying that the different pathway emission values are not directly comparable. However, DNV GL have tried to collect data from probable use-cases to supply a representation of realistically comparable GHG well-to-wake emissions.

In addition to differences in use-cases and scenarios, there will also be large uncertainties when estimating the life-cycle emissions for various energy carrier and converter pathways. This must also be kept in mind when considering the comparative Figure 6-7.

For some of the pathways there is little, if any, available literature on GHG emission data. These pathways are shown without ranges in Figure 6-7 .

Very few studies are available on projected or assumed potentials for lifecycle emission reductions for any of the pathways. Thus, Figure 6-7 only illustrates the current picture on well-to-wake emissions. In line with the international drivers towards necessary future emission reductions in the maritime industry, it is expected that incentives to reduce other parts of the lifecycle pathway emissions will also come in place.

The results show wide ranges of potential lifecycle emissions for some of the pathways, illustrating large variations in modes of production, transport and storage, or simply that there is significant uncertainty when modelling lifecycle fuel emissions. Generally, the pathways driven by renewables or those that derive from biomass are associated with lower well-to-wake GHG emissions than those originating in fossil sources of energy.

The production and storage of hydrogen requires a considerable amount of energy, so its competitiveness with regard to GHG emissions largely depends on low-emission energy production.

It should be noted that for electricity, the emissions from regional electricity mixes are presented. This means that the figures represent the regional averages based on all modes of production from fossil to renewable. Thus, within the regions the variation in emissions from electricity production can be significant. As an example, the lowest number given in Figure 6-7 is for European electricity mix, where some countries have a near zero emission electricity production, although this is not visualised when presenting the average for Europe.

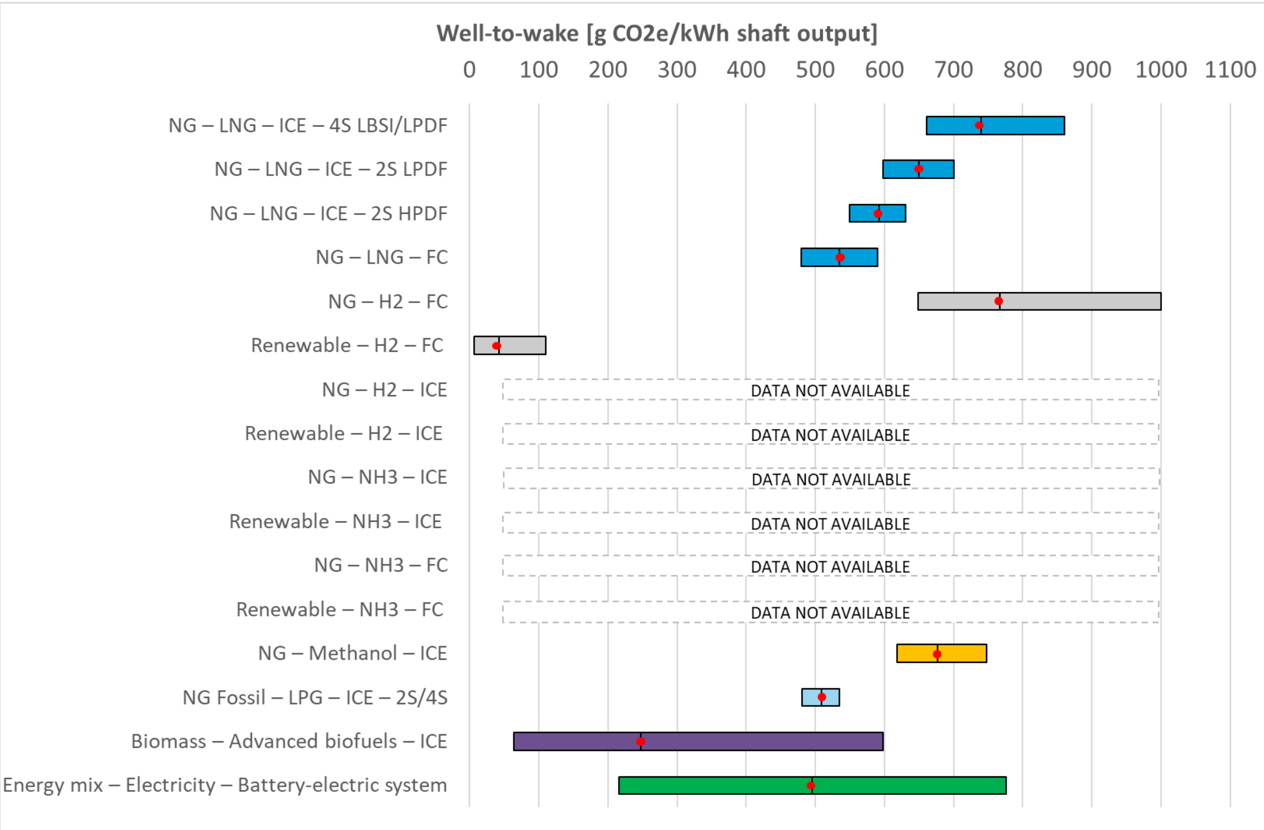

Figure 6-7: Well-to-wake emissions for fuel/technology pathways, taking into account energy content of fuel and system efficiency [g CO2e/kWh shaft output]

Sources: See Appendix B – Sources used for assessment of each parameter

Liquefied Biogas (LBG) and synthetic methane (from Power-To-Gas process) represents carbon drop in fuels for the LNG pathways, but has not been part of the scope for this literature review.

6.3.2 Local emissions - SOx, NOx and PM

Emissions of sulphur oxides (SOx), nitrogen oxides (NOx) and particulate matter (PM) from ships depend on the fuel used and the engine/converter used. The table below summarizes the onboard emissions from a range of fuels and converters. Only on-board emissions are accounted for.

Many sources provide only relative reduction factors compared to HFO/MGO, so the following baseline levels have been assumed to be able to convert to g/kWh for the purpose of comparison: NOx: Baseline is Tier II limit at relevant rpm, SOx: HFO sulphur content 3.5%, MGO sulphur content 0.1%, SFOC 175 g fuel/kWh; PM 7.6 kg/tonne fuel (/13/).

The next three figures show the tank-to-propeller NOx, SOx and PM emissions for the different fuels. Notice that for many of the fuels of interest, limited data is available.

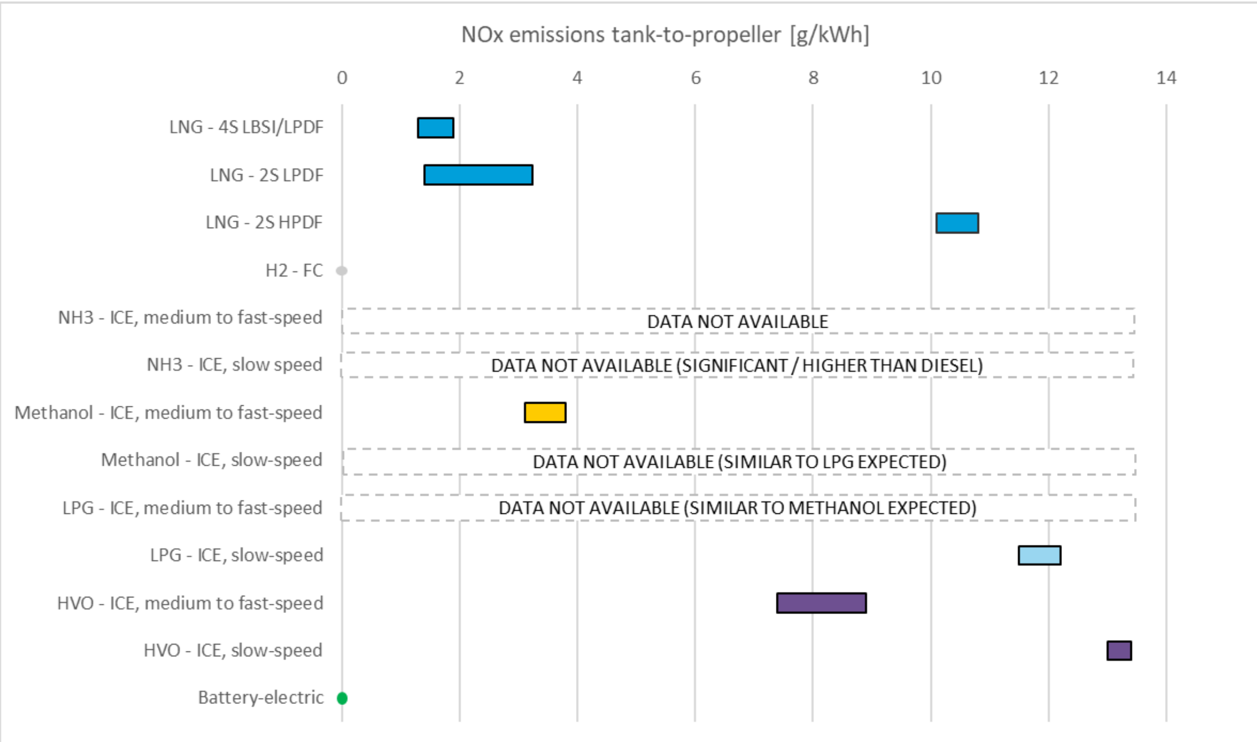

Figure 6-8: Tank-to-propeller NOx emissions for different fuel/converter options

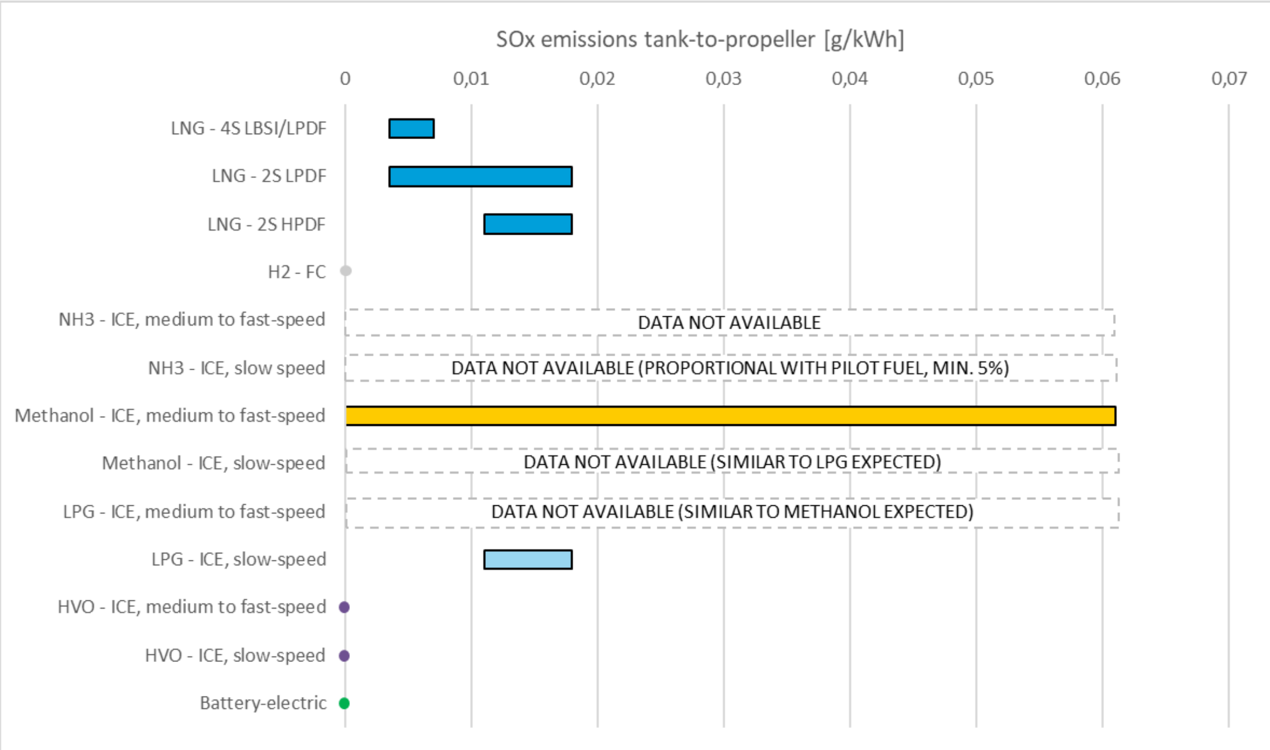

Figure 6-9: Tank-to-propeller SOx emissions for different fuel/converter options

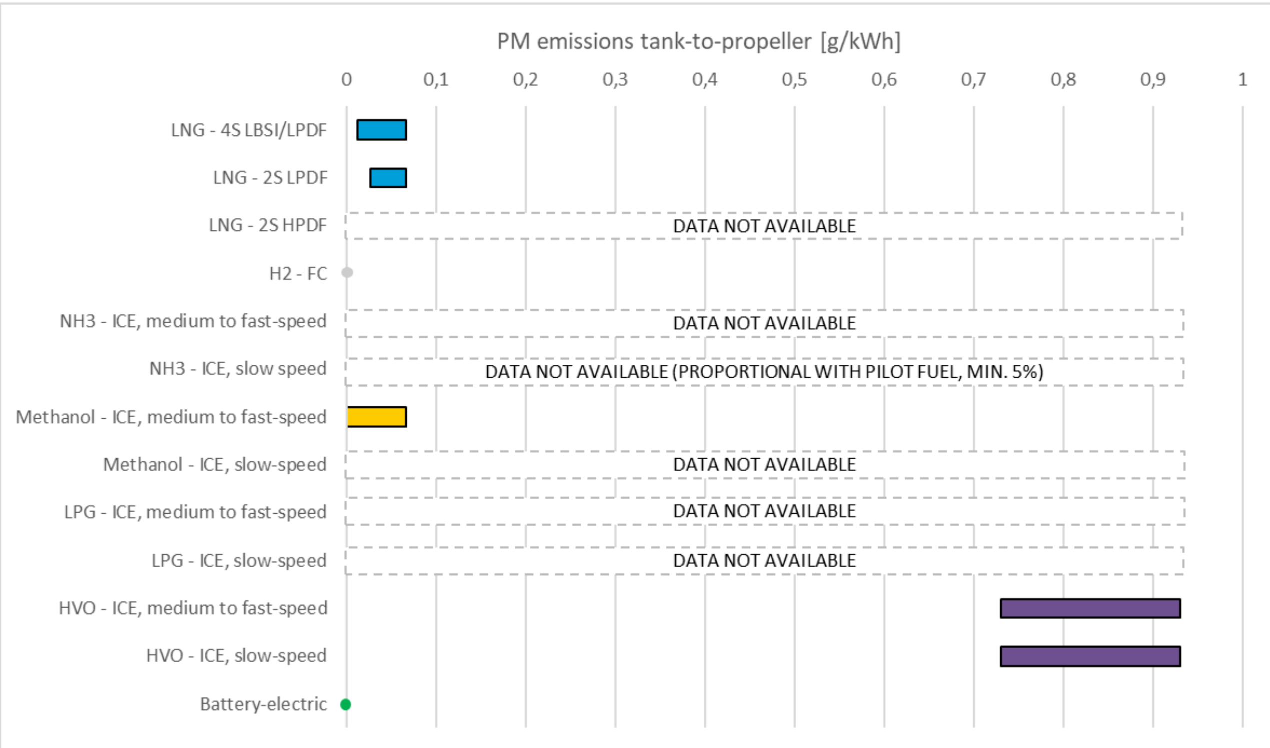

Figure 6-10: Tank-to-propeller PM emissions for different fuel/converter options

Converters running by the Otto combustion principle have in common that emissions of local pollutants are very low and at least meet the current strictest emission requirements such as the IMO Tier III NOx limit, regardless of fuel type. For converters running by the Diesel cycle (high pressure), emissions of all types of local pollutants are typically higher than for converters running by the Otto combustion principle. For SOx and PM the somewhat higher emission levels relates to the higher share of pilot diesel fuel required to ignite the gas, however it is important to highlight that both concepts reduce such emissions more than 95%. For NOx the higher emission levels relates to the Diesel combustion principle, and exhaust gas after treatment is necessary to comply with Tier III (normally standard available solutions with SCR or EGR). Ships powered by fuel cells or batteries have no emissions of local pollutants.

Sources: See Appendix B – Sources used for assessment of each parameter

6.4 Scalability

Different alternative fuels/pathways will have different possibilities for **maturing and scale-up,** depending on factors such as cost (section 6.1), environmental performance (section 6.3), and applicability (section 6.1). In addition, factors such as current usage, availability and global production are important for scalability, and they are closely linked to supply chain development and infrastructure on land. These factors are covered in the following sections.

6.4.1 Main current usages

The main current usage of the alternative fuels is dominated by the LNG and electrification (charging batteries using shore power). Application of the other alternative fuels addressed in this report is limited or non-existent (**Table 6-5**).

Table 6-5: Main current usages

Fuel	Main current usages
LNG	LNG is usually re-gasified and distributed through gas networks when it reaches its destination (import terminal) – just like gas from pipelines. Currently the largest uses of natural gas are for power generation (35%), followed by residential (22%) and manufacturing (17%) usage. LNG is also increasingly used as fuel in transportation, and China already has over 300,000 LNG-fueled trucks and busses on the road. There are 165 LNG-powered ships in operation (excluding LNG carriers and inland waterways vessels) as of July 2019, and 154 confirmed orders for vessels that will be built in the next five years. In addition, there are approx. 500 LNG carriers in operation using LNG as fuel. Approximately 6.5 million tonnes LNG is consumed by ships (around 2% of the total marine consumption), of which around ¾ is consumed by LNG carriers, presumably in the form of boil-off gas. After more than 18 years of phasing in LNG (for non-LNG carriers) it still represents less than 1% of the global ship fuel consumption derives from LNG. However, the LNG consumption is projected to increase significantly over the next years due to the phasing in of new LNG-fuelled ships, including the introduction of larger ships such as container and cruise ships.

Hydrogen	Currently, 65 % of the hydrogen demand globally is from the chemicals sector, and 25 % by the refining sector for hydrocracking and desulphurization of fuels. About 55 % of the hydrogen is used for ammonia synthesis (chemicals sector), and 10 % for methanol production (refining sector). Hydrogen is also used by other industry sectors, such as producers of iron and steel, glass, electronics, specialty chemicals and bulk chemicals, but their combined share of total global demand is small. Use of hydrogen in shipping is currently negligible, but several projects are under development, for use of both liquified and compressed hydrogen. The planned applications are in the short sea segment.
Ammonia	Currently, 80% or more of the ammonia produced is used within agriculture (as fertilizer). Ammonia is also used to produce plastics, fibers, explosives, nitric acid and intermediates for dyes and pharmaceuticals. It is also used in selective catalytic reduction (SCR) systems to reduce nitrogen oxide (NOx) emissions from industrial plants and ships. Use of ammonia as fuel in shipping is currently non-existent, but the shipping industry is beginning to evaluate the fuel's use in combustion engines and fuel cells.
Methanol	Methanol is a basic building block for hundreds of essential chemical commodities and is also used as fuel in the transportation sector. In 2018, 25% of methanol was consumed in the production of formaldehyde, followed by 19% for production of alternative fuels and 12% for production of methyl tert-butyl ether (MTBE). There are currently 12 methanol-fueled ships in operation or on order.
LPG	In 2015, domestic (residential) use of LPG was 44%, followed by chemical industries at 26%, industry 12%, transport 9%, refineries 8% and agriculture 1%. Of the fuel used for transportation, half is consumed in South Korea, Turkey, Russia, Thailand and Poland. Use as fuel for transportation has increased by 24% from 2009 to 2014. Uptake of LPG-fuel for ships is in its infancy, with two newbuilding orders for Very Large Gas Carriers (VLGC), and four existing LPG carriers to be converted in 2020[10].
HVO	There is currently limited uptake of HVO in shipping. HVO is used by three ferries[11,12] operating in Norway, without reported negative effects. Limited availability of biomass for production of HVO can also lead to a lack of available fuel for maritime use, in competition with road and aviation use.

[10] https://www.maritime-executive.com/corporate/first-lpg-powered-dual-fuel-engine-receives-order
https://worldmaritimenews.com/archives/259798/bw-lpg-to-retrofit-4-ships-to-lpg-propelled-dual-fuel-engines/
[11] Ruter: https://ruter.no/om-ruter/miljo/gassdrevne-passasjerferger/
[12] TU: http://www.tu.no/artikler/de-blir-verdens-tre-forste-ferger-pa-kun-biodrivstoff/275609

Electricity	The first fully electric car ferry, MF Ampère, has been in service between Lavik and Oppedal on the west coast of Norway since 2015. The next fully electric car ferry started operating between Pargas and Nagu in Finland in 2017. [13] About 70 plug-in hybrid car ferries with a high degree of electrification (90–100% of the energy output) are currently contracted for future ferry operation in Norway, and several more are anticipated. . Today around 200 ships with batteries are in operation or on order, and approx. one third of these operates close to fully electric (car/passenger ferries mostly). 166 ships with batteries are in operation, of which 34 are fully electric. Limited shore-based infrastructure for charging is available today, but progress is made in certain regions.

Sources: See Appendix B – Sources used for assessment of each parameter

6.4.2 Availability

To enable sufficient uptake, future alternative marine fuels must be available on the market. The current availability of alternative fuels are far from covering the current energy requirements of the shipping industry, except for LNG and LPG (**Table 6-6**). In addition, infrastructure is lacking or limited for most of the fuels. This is not the case for LNG, where significant regional LNG bunkering infrastructure has already been developed (LNG terminals, truck-loading facilities and LNG bunker vessels). Rapid further developments in LNG infrastructure is seen in many key bunkering locations, to also enable LNG-fuelled deep-sea shipping. Significant LNG infrastructure was first established in Norwegian waters in 2005, before further development was seen in the Baltic Sea and in North West Europe.

In theory, a switch to LNG for the entire global fleet would be possible, since the current LNG production exceeds the shipping industry's current energy requirement, and new production capacity is being developed. In this context it should be noted that the share of LNG in the total gas market is only 10%. LPG could in theory also cover the energy need of the global fleet, but this would require the entire current global LPG production (/20/),(/19/).

In general, existing on-shore power infrastructure can be used to supply electricity to ships. However, llimited shore-based infrastructure for charging is available today, but progress is made in certain regions [14, 15] (e.g. /26/).

[13] Teknisk ukeblad: http://www.tu.no/artikler/eksporterer-batteriteknologi-til-finland/278058
[14] First for Shore Power in India: http://www.maritime-executive.com/editorials/first-for-shore-power-in-india
[15] Shore power, Norway: http://www.tu.no/artikler/havner-vil-fa-hurtigruten-over-pa-landstrom/193818
http://www.mynewsdesk.com/no/enova-sf/pressreleases/140-millioner-til-landstroem-1689508

Table 6-6: Availability of fuel

Fuel	Availability
LNG	LNG is in principle available worldwide (large scale import and export terminals), and investments are underway in many of these places to make LNG available to ships. Dedicated LNG bunkering infrastructure for ships is currently limited but improving rapidly. Continuously updated information is available at afi.dnvgl.com. A large share of LNG bunkering as well as LNG distribution to bunkering locations is still taking place by road. In 2017 and 2018, several LNG bunker vessels where delivered for operation in key locations such as the Amsterdam, Rotterdam, Antwerp (ARA) region, the North Sea, the Baltic Sea and at the coast of Florida. Bunker vessels for other key locations such as the Western Mediterranean, the Gulf of Mexico, the Middle East, Singapore, China, South Korea and Japan recently been ordered or are under development and will likely materialize in parallel with significant orders for LNG-fuelled deep-sea ships within the next years. We expect to see a focus on developing LNG bunker vessels for refueling seagoing ships in the near future. Bunkering by truck and permanent local depots will also continue to grow for certain trades and segments. Dual-fuel engine technology may also offer some flexibility and redundancy as the LNG bunkering network for the deep-sea fleet evolves.
Hydrogen	Currently, infrastructure and bunkering facilities are not developed. Hydrogen production from electrolysis is a well-known and commercially available technology suitable for local production of hydrogen, e.g. in port as long as an adequate supply of electricity is available. This would eliminate the need for long-distance distribution infrastructure. In the future, liquid hydrogen might be transported to ports from storage sites where hydrogen is produced from surplus renewable energy, such as wind power, whenever energy production exceeds grid demand. Hydrogen can also be produced from natural gas, which is globally available.
Ammonia	Ammonia has existing infrastructure for transport and handling, since it is used in large quantities as fertilizer. However, the development of a bunkering infrastructure remains a barrier for the use as ship fuel. Ammonia production from hydrogen and nitrogen is a well-known and commercially available technology suitable for local production of ammonia, e.g. in port if an adequate supply of electricity is available. This would eliminate the need for long-distance distribution infrastructure. In future, liquid ammonia might be transported to ports from storage sites where ammonia is produced from surplus renewable energy, such as wind power, whenever energy production exceeds grid demand.

	Ammonia can also be produced from natural gas, which is globally available. Other feedstocks includes naphtha, heavy fuel oil and coal.
Methanol	Methanol is one of the top five chemical commodities shipped around the world each year. It is readily available through existing global terminal infrastructure and well positioned to reliably supply the global marine industry. However, dedicated bunkering infrastructure for ships is currently limited. Distribution to ships can be accomplished either by truck or by bunker vessel. In the port of Gothenburg, Stena Lines has created a dedicated area for bunkering the vessel Stena Germanica. In Germany, the first methanol infrastructure chain, from production using renewable energy to trucking and ship bunkering through to consumption in a fuel cell system on board the inland passenger vessel MS Innogy, was launched in August 2017.
LPG	A large network of LPG import- and export-terminals is available around the world, but the development of a bunkering infrastructure for ships remains a barrier for the use of the fuel. The established infrastructure already in place could be used as the basis for expanding distribution and bunkering of LPG as a fuel for the marine market. Bunkering can be made available by truck or bunker vessels, from LPG terminals. It is reported that there are more than 1,000 import and secondary terminals for pressurized LPG. Recently more LPG export terminals have been developed in the US to cover the increased demand for competitively priced LPG products.
HVO	Availability for shipping is currently limited, as the result of very low demand. On request HVO has been made available to ferries in Norway following government requirements and for a handful of pilot applications for deep sea ships, mainly centered around Rotterdam. HVO fuel for ships is competing with HVO use for road application. The bunkering infrastructure for HVO (as a drop-in fuel) is the same as for marine oils, so this is not considered an issue.
Electricity	In general, on-shore power supply infrastructure is well developed, also for covering potential needs shipping. However, llimited shore-based infrastructure is available today for *charging*, but progress is made in certain regions.

Sources: See Appendix B – Sources used for assessment of each parameter

Liquefied Biogas (LBG) and synthetic methane (from Power-To-Gas process) represents carbon neutral and zero carbon drop in fuels for the LNG pathways, but has not been part of the scope for this literature review. LBG is produced in limited volumes today and is mainly used for heavy duty vehicles and buses.

6.4.3 Global production capacity and locations

The alternative fuel industry spans the entire globe, with production in Asia, North and South America, Europe, Africa and the Middle East (Table 6-7). For all alternative fuels, except for LNG (and LPG), the current production does not cover the accumulated energy requirements of the shipping industry. A rapid rise in demand would require massive investments in production capacity and infrastructure.

The worldwide production of alternative fuels has a large up-scaling potential as fuels can be produced from various energy sources, such as by electrolysis powered by renewables, or by reforming natural gas, oil or coal. In addition, the use of carbon capture and storage (CCS) can be implemented to generate zero carbon alternative fuels from fossil energy sources.

As hydrogen can be produced from a range of different energy sources including electricity and it is suitable both for distributed small-scale and centralized large-scale production, there are no principal limitations to production capacity that could restrict the amount of available H_2 to the shipping industry. Furthermore, the hydrogen can form the basis for different electrofuels, produced using CO_2 or nitrogen. Electrofuels is an umbrella term for synthetic fuels such as ammonia, diesel, methane, and methanol, which are produced from water, CO_2 or nitrogen using renewable electricity as the source of energy. Such fuels are referred to as drop-in fuels as they often require only limited modification to engine and fuel systems to replace (or blend with) traditional fuels used by internal combustion engines.

Whether ships are fueled by electrofuels to replace marine fuel, or powered by batteries charged at ports, this development will increase demand for electricity production on land (renewable).

Table 6-7: Global production capacity and locations

Fuel	Global production capacity and locations
LNG	LNG has a share of approximately 10% in the overall natural gas market. As of March 2018, global nominal liquefaction capacity totaled 369 million tonnes. Asia Pacific account for 38% of the production, followed by Middle East with 28% and Africa with 19% (in 2017). Capacity under construction amounted to 92 million tonnes as of March 2018. Most of the current liquefaction build-out, led by Australia and the United States, is expected to be completed by 2020. Large volumes of natural gas are available today and in the next decades. There are no principal limitations to production capacities that could limit the availability of LNG as ship fuel.
Hydrogen	About 55 million tonnes of H_2 is produced per year globally. This is equal to the energy content of 165 million tonnes of fuel oil. Hydrogen can be produced from various energy sources, such as by electrolysis powered by renewables, or by reforming natural gas, oil or coal. Today, 95 % of the hydrogen is produced from fossil fuels. The dominating production path is from natural gas (48% of the total), but there is also significant production from oil (30%) and coal (18%). The last 4% is produced from electrolysis. As hydrogen can be produced from a range of different energy sources, including electricity, and is suitable both for distributed small-scale and centralised large-scale

	production, there are no principal limitations to production capacity that could restrict the amount of available H2 to the shipping industry.
Ammonia	There are numerous large-scale ammonia production plants worldwide, producing more than 170 Mt/yr of NH_3 globally, most of it from natural gas. This is equal to the energy content of 76 million tonnes of fuel oil. China produced 32% of the worldwide production, followed by Russia with 9%, India with 8%, and the United States with 8%. Ammonia can be produced from renewable sources, utilizing electrolysis. Production via electrolysis is reported to have been made previously by 10 plants where the electricity was obtained from hydropower. The ageing plants have suffered from price of electricity consumed and the cost for the process equipment, and only three plants may still be in operation. An alternative promising path in an early development stages is ammonia produced from wind energy or solar power.
Methanol	Methanol can be produced from several different feedstock resources, like natural gas or coal, or from renewable resources, such as biomass, CO_2, and hydrogen. The methanol industry spans the entire globe, with production in Asia, North and South America, Europe, Africa and the Middle East. Worldwide, over 90 methanol plants have a combined production capacity of about 110 million tonnes. The energy content is equal to approximately 55 million tonnes of oil. The global methanol demand was approximately 80 million tonnes in 2016, twice the 2006 amount. More than 60 % of the methanol is currently consumed in Asia, where demand has been increasing for the last few years. Approximately 30 % is used in North America, Western Europe and the Middle East, and this figure has been largely stable over the past decade. It is expected that the current production can safely cover the demand for shipping until 2030, if the demand for methanol as ship fuel will grow slowly initially and remain at a moderate level.
LPG	Global LPG production in 2017 was 309 million tonnes. This is equal to the energy content of 354 million tonnes of fuel oil. LPG has two origins: approximately 60% is recovered during the extraction of natural gas and oil, and the remaining 40% is produced during the refining of crude oil. LPG is thus a naturally occurring by-product. As part of the first process - known as flaring – approximately an additional 265 million tonnes of potential LPG is burnt annually. The production increase has been most profound in North America and the Middle East. The production increase in North America in the last few years can be attributed to the substantial increase in shale gas production, which has turned the USA into a net exporter of LPG since 2012.

	The US is the world's largest producer of LPG, in 2017, over half of all US LPG production (67 Mt) was exported.
HVO	In 2017, an output of 5.5 billion litres of HVO accounted for 14% of global combined HVO and biodiesel production (IEA data). Also reported, is that global production of HVO grew an estimated 10% in 2017, from 5.9 billion litres to 6.5 billion litres (REN21 data). Production of HVO is concentrated in Finland, the Netherlands, Singapore and the United States.
Electricity	The global electricity production is currently reported to be 27 382 TWh (approx. 2300 million tonnes oil equivalents, when not adjusting for differences in energy converter efficiency) and is expected to increase by almost 40% by 2030. In 2016 approximately 33% of electricity was generated from other sources than combustible fuels. The renewables share of electricity production is expected to accelerate especially due to onshore wind and solar energy. About 15% of the global population still lives without access to electricity. The electricity access deficit is concentrated in Sub-Saharan Africa and South Asia, followed by East Asia and the Pacific and Latin America and the Middle East and North Africa. At the country level, India alone has a little less than one-third of the global deficit. This will hamper the possibility for global uptake.

Sources: See Appendix B – Sources used for assessment of each parameter

7 CONCLUSIONS AND KEY FINDINGS

The overall ambition of the study has been to assess the commercial and operational viability of alternative marine fuels, based on review existing academic and industry literature. The approach assesses how well six alternative fuels, applied in 16 different fuel technology pathways, perform compared to LNG fuel on a set of 11 key parameters. Conventional fuels are only included in the conclusion of this study for comparative purposes.

A five-step process has been applied in the assessment. First, the relevant pathways *from energy source to fuel to converter* were established (step 1). Then, a comprehensive literature search was performed to assemble a wide range of literature relevant for the selected pathways and assessment parameters (step 2). Through a categorization and evaluation process the most relevant references were selected (step 3). In the data extraction phase (step 4), information and values on the key assessment parameters were collected, converted to common units for comparison and visualized in graphs; illustrating minimum to maximum ranges and average values. Lastly, the results for each pathway were evaluated and compared (step 5). The result of step 1-5 was an assessment based on identifying, summarizing and presenting findings based on existing literature on the topic of alternative fuels.

DNV GL's interpretation and evaluation of the results is summarized in Figure 7-1 and the following key takeaways. In addition the 2020 sulphur cap compliant fuels HFO+scrubber and low sulphur fuel oil (LSFO)/MGO have been added to Figure 7-1 for comparison. These fuels have not been subject to an in-depth analysis on each parameter, and the given colour is based on a simplified assessment by DNV GL.

In the report both fossil and renewable pathways are assessed for the ammonia, hydrogen and fully electric options. However, in the following we address only the renewable pathways, as in the long term these energy carriers only make sense when produced from renewable sources. These represent long term solutions with potential for decarbonizing shipping. For LNG, methanol and LPG only production from fossil sources are considered in Figure 7-1. It is worth noting that these energy carriers can also be produced based on renewable sources, but in this report these pathways are not covered in detail.

(1) Taking into account maturity and availability of technology and fuel.
(2) GHG benefits for LNG, methanol and LPG will increase proportionally with the fraction of corresponding bio- or synthetic energy carrier used as a drop-in fuel.
(3) Results for ammonia, hydrogen and fully-electric shown only from renewable energy sources since this represents long term solutions with potential for decarbonizing shipping. Production from fossil energy sources without CCS (mainly the case today) will have a significant adverse effect on the results.
(4) Large regional variations.
(5) Needs to be evaluated case-by-case. Not applicable for deep-sea shipping.

Figure 7-1: DNV GL's interpretation of results and evaluation of status of viability for different alternative fuels (internally rated), within selected assessment parameters (i.e. potential barriers). 2020 compliant conventional fuels have also been included for reference and for these the given colour is based on a simplified assessment by DNV GL.

Time to commercial availability of promising alternative fuels will depend largely on level of R&D efforts, and even more importantly on the level and speed of which environmental regulations are implemented and incentive schemes are developed. As shown in this report, several of the promising alternative marine fuels are far more expensive than current solutions, and adoption rate will be minor/at piloting stage until regulations or incentive schemes makes them more competitive.

In Figure 7-1 a colour scheme using five colours has been applied. The colours represent performance on the key parameters for LNG and the different alternative fuels. The figure does not conclude on the overall performance of the fuels. When evaluating alternative fuels, the specifics for the case being evaluated have to be taken into consideration, such as ship specifications, local conditions, access to energy carriers and so on.

HFO+scrubber/LSFO: The 2020 sulphur cap compliant conventional fuels perform well on most parameters, being well-known and widely used fuels. There are some concerns regarding availability of these fuels post 2020, but compared to the alternative fuels, the availability will still be significantly better. The major downside of using these fuels is the poor environmental performance. There will be investment costs and operational cost of using scrubbers but these are low compared to costs of the alternative fuels.

Hydrogen: The main advantage of hydrogen is the possibility of being a zero emissions fuel if produced from renewables. Furthermore, future hydrogen production capacity fits well with the anticipated energy transition to renewable power production on land. The most prominent challenges for hydrogen are the costs and the lack of bunkering infrastructure. Hydrogen will mainly be produced from natural gas without CCS (as is the case today), until the transition to renewable power production is well under way. However maritime projects opting for hydrogen may ensure use (and contribute to increased production) of hydrogen produced from renewables, at the expense of higher cost and likely slower uptake. Another key challenge for hydrogen is its applicability. This limits the ship segments for which hydrogen can be used significantly. With current technology, hydrogen seems limited to shortsea shipping when considering current costs of tanks and fuel cells and range limitations due to its low density. It should also be noted that costs for required safety systems and mitigating measures (considering the flammability of hydrogen) is not quantified explicitly in the literature and may represent additional costs compared to what is presented in this report. The extent of safety mitigating measures and the cost of these will first be clear once rules have been developed for the use of hydrogen as fuel.

Ammonia: With an energy transition to renewables, ammonia will have the potential to become a carbon free energy carrier with higher density than hydrogen, and in principal technically feasible for deep sea. However, the current maturity is low and green ammonia is expensive, limiting the feasibility for use as an alternative fuel. Moreover, the lack of a bunkering infrastructure represents a barrier for using ammonia as an alternative marine fuel and is likely to remain a barrier for a long time while the market matures. Similarly to hydrogen, GHG emissions from ammonia remains high with the current production from fossil energy sources without CCS, until the transition to renewable power production is well under way. However maritime projects opting for ammonia may ensure use (and contribute to increased production) of ammonia produced from renewables, at the expense of higher cost and likely slower uptake. It should also be noted that costs for required safety systems and mitigating measures (considering the toxicity of ammonia) is not quantified explicitly in the literature and may represent additional costs compared to what is presented in this report.

Methanol: The main upside for methanol is the relatively good performance on applicability, being able to utilize existing converter technology and low tank costs, which further translates into low capital costs. On the other side, a major downside to methanol as an alternative fuel is its environmental performance when produced from fossil sources as assumed in this report. Methanol is priced close to, or higher than MGO in today's market. It is evident from Figure 7-1 that methanol performs very similarly to LPG, but with an expected somewhat slower maturing and uptake due to (presently) lower cost saving incentive. With continued pricing at this level, we expect to see a very limited uptake of methanol as an alternative fuel.

LPG: Low energy cost (close to LNG) and low capital costs make a compelling economic case for LPG. However, operational experience is very limited, thus the maturity level is medium. In addition the lack of bunkering infrastructure is a barrier for using LPG as an alternative marine fuel. Moreover, a major downside to LPG as an alternative fuel is its environmental performance when produced from fossil sources as assumed in this report.

HVO: The applicability of HVO fits well as an alternative fuel since it is considered a drop-in fuel, being a direct substitute for conventional petroleum-based fuels. On the other side, HVO is expensive and there is currently limited production capacity and bunkering availability of HVO, which raises the question of whether this is a scalable fuel for maritime use. In addition, the use of exhaust gas treatment systems to address the issue of NOx and PM emissions must be considered to meet current and future expected requirements.

Fully electric: Fully electric systems have the benefit of zero emissions when using electricity from renewable sources. However, the low energy density and significant storage costs means that fully electric systems are only feasible for a very limited number of vessel types and sizes with short sailing distance.

Although not covered in detail in this study, both LBG (Bio-LNG) and liquefied synthetic methane (from Power-To-Gas process) are promising fuels for shipping. They are fully compatible drop-in solutions which represents carbon neutral pathways for the gas engines and LNG distribution system. The material properties are very similar to LNG and for all practical means they can be considered identical.

The energy cost is a key driver/barrier for the uptake of any alternative fuel and based on existing literature it can be concluded that there is a high uncertainty in expected price/cost for the fuels with significant GHG reduction potential. We currently don't know which of the alternative fuels will become more competitive and available for shipping. This depends not at least on how global mega trends within energy production and GHG abatement develops. But it is not likely that any major uptake of expensive alternative fuels with significant GHG reduction potential can be expected until required by regulations or heavily incentivized. Given current plans and typical development speed of regulations and incentives, no significant move towards such fuels is likely to happen until between 2025-2030 – at the earliest. Towards 2030 will however be a key period for R&D, piloting, rule development, product development and early commercialization.

When assessing the different alternative fuels on the defined parameters, it became evident that there are several gaps in the data available. This pertains especially to ammonia, but also several of the other fuels have certain knowledge gaps. For some of the fuels and parameters, the available data shows a noteworthy span in values from minimum to maximum, meaning that the uncertainty for the specific parameter is significant. Some of these uncertainties most likely reflect solutions which are currently maturing. For these, ongoing research and development, testing and piloting will provide data that will give significantly increased knowledge in the coming years. Suggested further work is therefore to investigate whether such development is ongoing where data is missing or uncertainty is significant, and potentially initiate further studies to provide high quality data for more complete and detailed comparison of the different alternative fuels. There are also highly relevant energy carriers such as liquified biogas and synthetic methane and diesel (and other electrofuels) which are not covered in this study. Including such fuels would give a more complete picture of the fossil and renewable alternatives of all energy carriers.

8 REFERENCES

/1/ P. T. Aakko-Saksaa, C. Cook, J. Kiviaho, T. Repo (2018), "Liquid organic hydrogen carriers for transportation and storing of renewable energy", Journal of Power Sources, Volume 396, 31 August 2018.

/2/ M. Altmann, M. Weinberger, W. Weindorf (2004), "Life Cycle Analysis Results of Fuel Cell Ships. Recommendations for improving cost effectiveness and reducing environmental impacts".

/3/ Ammonia Energy, Bunker Ammonia: carbon-free liquid fuel for ships, https://www.ammoniaenergy.org/bunker-ammonia-carbon-free-liquid-fuel-for-ships/. Accessed in 2019.

/4/ P. Balcombe, I.G. Kerdan, I. Staffell, J.F. Speirs, N.P. Brandon, and A.D. Hawkes, (2018) "Environmental and cost assessment of LNG and other shipping fuels", Submitted to Science of the Total Environment.

/5/ H. Brinks, C. Chryssakis (2017), "LPG as a marine fuel", Group technology & research, position paper 2017.

/6/ E. A. Brohi (2014), "Ammonia as fuel for internal combustion engines?", Master's Thesis in Sustainable Energy Systems, Chalmers University, Sweden.

/7/ S. Brynolf (2014), "Environmental Assessment of Present and Future Marine Fuels".

/8/ S. Brynolf (2017), "Cost-effective choices of marine fuels in a carbon-constrained world: Insights from the Global Energy Transition (GET) model".

/9/ C. Chryssakis, S. Stahl (2013), "Well-To-Propeller Analysis of Alternative Fuels for Maritime Applications" paper no. 265, CIMAC.

/10/ C. Chryssakis, O Balland, H.A. Tvete, and A. Brandsæter (2014), "Alternative Fuels for Shipping" DNV GL strategic research & innovation position paper 1-2014.

/11/ C. Chryssakis, H. Brinks, T. King (2015), "The fuel trilemma: Next generation of marine fuels", DNV GL strategic research & innovation position paper 03-2015.

/12/ J.J. Corbett, J.J. Winebrake (2018), "Life cycle analysis of the use of methanol for marine transportation", prepared for U.S. Department of Transportation, Maritime Administration.

/13/ S. Dalsøren, M. Eide, Ø. Endresen, A. Mjelde, G. Gravir, and I.S.A. Isaksen (2009), "Update on emissions and environmental impacts from the international fleet: The contribution from major ship types and ports", Atmospheric Chemistry and Physics, 9, 2171–2194.

/14/ C. Deniz, B. Zincir (2016), "Environmental and economical assessment of alternative marine fuels", Journal of Cleaner Production 113 (2016) 438-449.

/15/ DNV GL (2012), "Alternative fuels for maritime applications", DNV Internal Report No. 2011-1449, 2012.

/16/ DNV GL (2015), "Vurdering av tiltak og virkemidler for mer miljøvennlige drivstoff i skipsfartsnæringen. Utredning for Klima- og miljødepartementet", rapportnr. 2015-008.

/17/ DNV GL (2017), "Study on the use of fuel cells in shipping", for European Maritime Safety Agency (EMSA), publ. online at www.emsa.europa.eu.

/18/ DNV GL (2018), "Analyse av tiltak for reduksjon av klimagassutslipp fra innenriks skipsfart".

/19/ DNV GL (2018), "Alternative Fuels whitepaper".

/20/ DNV GL (2018), "Alternative fuels in shipping – Position paper"

/21/ DNV GL (2018), "Maritime Forecast to 2050. Energy transition outlook 2018, Past and Present Shipping", https://eto.dnvgl.com/2018/maritime.

/22/ DNV GL (2018), "Assessment of selected alternative fuels and technologies", DNV GL position paper.

/23/ DNV GL (2019), "Alternative Fuels in the Arctic", PAME.

/24/ DNV GL's Alternative Fuel Insight (AFI), online portal (www.afi.dnvgl.com).

/25/ Ecofys (2012), "Potential of biofuel for shipping".

/26/ Ecofys (2015), "Potential for Shore side electricity in Europe".

/27/ E4Tech (2018), "Master plan for CO2 reduction in the Dutch shipping sector: Biofuels for shipping, may 2019".

/28/ C. N. L. Fevre (2018), "A review of demand prospects for LNG as a marine transport fuel", Oxford Institute for Energy Studies, ISBN 978-1-78467-114-3.

/29/ P. Gilbert, C. Walsh, M. Traut, U. Kesieme, K. Pazouki, and A. Murphy, (2018) "Assessment of full life-cycle air emissions of alternative shipping fuels", Journal of Cleaner Production.

/30/ C. W. Gross, S. Kong (2013), "Performance characteristics of a compression-ignition engine using direct-injection ammonia–DME mixtures", Fuel 103 (2013) 1069–1079.

/31/ M. Grahn, M. Taljegård, S. Bengtsson, K. Andersson, H. Johnson (2013), "Cost-effective choices of marine fuels under stringent carbon dioxide targets".

/32/ J. Hansson, M. Grahn (2016), "The Potential Role of Electrofuels as Marine Fuel: A Cost-Effective Option for the Future Shipping Sector?", conference proceedings, Shipping in Changing Climates (SCC), Newcastle, 10-11 Nov., 2016.

/33/ J. Hansson, M. Grahn, and S. Månsson (2017), "Assessment of the possibilities for selected alternative fuels for the maritime sector", conference proceedings, Shipping in Changing Climates (SCC), London, September 2017.

/34/ C.C. Hsieh, C. Felby (2017), "Biofuels for the marine shipping sector", IEA Bioenergy.

/35/ Hydrogen Europe (2019), "Hydrogen in Industry", https://hydrogeneurope.eu/hydrogen-industry. Accessed May 1, 2019.

/36/ IEA (2017), "Renewable Energy for Industry".

/37/ IEA (2018), "World Energy Prices, An Overview".

/38/ IEA (2019), "Renewables 2018, Market analysis and forecast from 2018 to 2023", https://www.iea.org/renewables2018/transport/.

/39/ International Council on Clean transportation (ICCT) (2017), "Greenhouse gas emissions from global shipping, 2013–2015".

/40/ International Gas Union (IGU) (2018), "2018 World LNG Report. 27th World Gas Conference Edition".

/41/ IRENA (2018), "Hydrogen from renewable power – Technology outlook for the energy transition".

/42/ ISPT (2017), "Power to Ammonia".

/43/ Lloyd's Register (2014), "Global Marine Fuel Trends 2030".

/44/ Lloyd's Register (2017), "Zero-Emission Vessels 2030. How do we get there?".

/45/ LMG Marin, CMR Prototech, Norsk Energi (2016), "Potensialstudie – Energieffektiv og klimavennlig passasjerbåtdrift".

/46/ MAN (2013), "Costs and Benefits of LNG as a Ship Fuel for Container Vessels. MAN & GL joint study".

/47/ MAN (2016), "Costs and Benefits of Alternative Fuels for an LR1 Product Tanker. Key results from a DNV GL and MAN Diesel & Turbo joint study".

/48/ MAN B&W (2018), "MAN B&W ME-LGIP dual-fuel engines".

/49/ MariGreen (2018), "Perspectives for the Use of Hydrogen as Fuel in Inland Shipping. A Feasibility Study".

/50/ Marintek (2014), "Uttesting av 2G Polar biodrivstoff på marine dieselmotorer", rapportnummer 302001917-1.

/51/ Maritime Knowledge Centre, TNO and TU Delft (2017), "Framework CO_2 reduction in shipping".

/52/ S. Månsson (2017), "Prospects for renewable marine fuel", Master's Thesis 2017:04, Chalmers University of Technology, Department of Energy and Environment.

/53/ Methanex (2017), "Methanol as a marine fuel"

/54/ Methanol Institute (2019), Methanol Supply/Demand (Excel sheet)

/55/ Methanol Institute (2019), The Methanol Industry https://www.methanol.org/the-methanol-industry/

/56/ Neste (2016), "Renewable Diesel Handbook", https://www.neste.com/sites/default/files/attachments/neste_renewable_diesel_handbook.pdf

/57/ Norwegian Environment Directorate (2018a),Metodikk for tiltaksanalyser, Metodenotat, Vedlegg I. Veileder M-1084

/58/ Norwegian Environment Directorate (2018b), "Kunnskapsgrunnlag for omsetningskrav i skipsfart", rapport M-1125

/59/ OECD/IEA (2011), "Technology Roadmap. Biofuels for transport".

/60/ OECD/IEA (2015), "Technology Roadmap. Hydrogen and Fuel Cells".

/61/ OECD/ITF (2018), "Decarbonising Maritime Transport. Pathways to zero-carbon shipping by 2035".

/62/ O. Özgun (2019), internal calculations and estimations from DNV GL Global Technology & Research.

/63/ C. Raucci (2017), "The potential of hydrogen to fuel international shipping".

/64/ A.J. Reiter, S.C. Kong (2011), "Combustion and emissions characteristics of compression-ignition engine using dual ammonia-diesel fuel", Fuel 2011;90(1):87-97.

/65/ REN21 (2018), "Renewables 2018 Global Status Report. Market and Industry Trends", http://www.ren21.net/gsr-2018/chapters/chapter_03/chapter_03/.

/66/ Sandia (2017), "Practical Application Limits of Fuel Cells and Batteries for Zero Emission Vessels".

/67/ Schuller, O., B. Reuter, J. Hengstler, S. Whitehouse, and L. Zeitzen, (2017) "Greenhouse Gas Intensity of Natural Gas", Thinkstep AG: Natural & Bio Gas Vehicle Association (NGVA) Europe.

/68/ SEA\LNG (2018), "LNG as a marine fuel - the investment opportunity"

/69/ A. Sharafian, P. Blomerus, and W. Mérida, (2019) "Natural gas as a ship fuel: Assessment of greenhouse gas and pollution reduction potential", Energy Policy, under review.

/70/ J. Sharples (2019), "LNG Supply Chains and the Development of LNG as a Shipping Fuel in Northern Europe".

/71/ Shell (2019), "Shell LNG Outlook 2019".

/72/ Shell/Wuppertal Institut (2017), "Shell Hydrogen Study. Energy of the Future? Sustainable Mobility through Fuel Cells and H_2".

/73/ J. Speirs, P. Balcombe, P. Blomerus, M. Stettler, N. Brandon, and A. Hawkes, (2019) "Can Natural Gas Reduce Emissions From Transport?".

/74/ D. Stenersen, O. Thonstad (2017), "GHG and NOx Emissions from Gas-fuelled Engines: Mapping, Verification, Reduction Technologies".

/75/ M. Taljegård, S. Brynolf, J. Hansson, R. Hackl, M. Grahn, K. Andersson (2015), "Electrofuels – A possibility for shipping in a low carbon future?".

/76/ Thinkstep AG (2019), "Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel".

/77/ TØI (2016), "Fornybare drivstoffer – Fornybar diesel: HVO". TØI-rapport 1475/2016, mars 2016, ISSN 0808-1190.

/78/ Transport and Environment (2018), "Roadmap to decarbonizing European shipping".

/79/ UMAS (2018), "LNG as a Marine Fuel in the EU, Market, Bunkering Infrastructure Investments and Risks in the Context of GHG Reductions".

/80/ Wikipedia (2019), https://en.wikipedia.org/wiki/Ammonia_production. Accessed 2019.

/81/ WLPGA (2016), Annual Report 2016.

/82/ WLPGA (2017), "LPG for Marine Engines – The Marine Alternative Fuel".

/83/ WLPGA (2019), Annual Report 2018.

/84/ The World Bank (2017), "Electricity access report 2017".

APPENDIX A – INPUT TO CALCULATIONS

The following assumptions have been used for conversion of units, where applicable:

Table 0-1: Assumptions used for conversion of units

Fuel-converter	Efficiency [%]			Storage system utilization [%]
	Low	Average	High	
LNG – ICE – 4S LBSI/LPDF	40%	45%	49%	80%
LNG – ICE – 2S LPDF	48%	50%	51%	
LNG – ICE – 2S HPDF	50%	52%	53%	
LNG – FC	50%	50%	80%	
H2 – FC	50%	50%	80%	80%/90% (LH2/CH2)
H2 – ICE	?	42% [16]	?	
NH3 – ICE	50%	50%	50%	90%
NH3 – FC	50%	50%	80%	
Methanol – ICE	50%	52%	53%	100%
LPG – ICE	50%	52%	53%	90%
Advanced biofuels – ICE	Same as a diesel engine – 50% chosen			100%
Electricity – battery-electric system	87.5%			50%

Table 0-2: Energy content of different alternative fuels used for conversion of units

Fuel	Energy content [GJ/tonne]
LNG	49
H2	120
NH3	19
Methanol	20
HVO	43
LPG	47
Batteries	

[16] Data is very limited. Reported efficiency in MariGreen (2018), Perspectives for the Use of Hydrogen as Fuel in Inland Shipping- A Feasibility Study, Oct 2018, has been used.

APPENDIX B – SOURCES USED FOR ASSESSMENT OF EACH PARAMETER

Table 0-1: Sources used for energy cost

Pathway	References
NG – LNG – ICE – 4S LBSI/LPDF	/46/, /47/, /63/, /68/, /79/
NG – LNG – ICE – 2S LPDF	
NG – LNG – ICE – 2S HPDF	
NG – LNG – FC	
NG – H2 – FC	/18/, /19/, /36/, /63/
Renewable – H2 – FC	/19/, /60/
NG – H2 – ICE	/18/, /19/, /36/, /63/
Renewable – H2 – ICE	/19/, /60/
NG – NH3 – ICE	/36/, /42/
Renewable – NH3 – ICE	/36/, /42/
NG – NH3 – FC	/36/, /42/
Renewable – NH3 – FC	/36/, /42/
NG – Methanol – ICE	/14/, /45/
NG Fossil – LPG – ICE – 2S/4S	/47/, /48/
Biomass – Advanced biodiesel (HVO) – ICE	/57/, /27/
Energy mix – Electricity – Battery-electric system	/37/

Table 0-2: Sources used for capital cost

Pathway	Reference(s)
NG – LNG – ICE – 4S LBSI/LPDF	/7/, /8/, /31/, /63/, /79/
NG – LNG – ICE – 2S LPDF	
NG – LNG – ICE – 2S HPDF	
NG – LNG – FC	/7/, /8/, /19/, /31/, /43/, /45/, /63/, /72/
NG – H2 – FC	/7/, /8/, /19/, /31/, /43/, /45/, /72/
Renewable – H2 – FC	/7/, /8/, /19/, /31/, /43/, /45/, /72/
NG – H2 – ICE	/7/, /8/, /31/, /49/
Renewable – H2 – ICE	/7/, /8/, /31/, /49/
NG – NH3 – ICE	-
Renewable – NH3 – ICE	-
NG – NH3 – FC	-
Renewable – NH3 – FC	-
NG – Methanol – ICE	/7/, /31/, /43/, /75/
NG Fossil – LPG – ICE – 2S/4S	-
Biomass – Advanced biodiesel (HVO) – ICE	/7/, /8/, /31/, /63/, /79/
Energy mix – Electricity – Battery-electric system	

Table 0-3: Sources used for well-to-wake GHG emissions

Pathway	References
NG – LNG – ICE – 4S LBSI/LPDF	/4/, /67/, /69/, /76/, /77/
NG – LNG – ICE – 2S LPDF	/4/, /69/, /76/, /77/
NG – LNG – ICE – 2S HPDF	/4/, /67/, /69/, /76/, /77/
NG – LNG – FC	/2/
NG – H2 – FC	/9/, /10/, /29/
Renewable – H2 – FC	/9/, /10/, /29/
NG – H2 – ICE	-
Renewable – H2 – ICE	-
NG – NH3 – ICE	
Renewable – NH3 – ICE	-
NG – NH3 – FC	-
Renewable – NH3 – FC	-
NG – Methanol – ICE	/7/, /11/, /29/, /76/
NG Fossil – LPG – ICE – 2S/4S	/5/, /9/, /51/, /76/
Biomass – Advanced biodiesel (HVO) – ICE	/34/, /59/
Energy mix – Electricity – Battery-electric system	/62/

Table 0-4: Sources used for tank-to-propeller emissions of local pollutants

Fuel	Converter	Source
LNG	LBSI (4s)	/74/
	LPDF (4s)	/74/
	LPDF (2s)	/74/
	HPDF (2s)	/74/
Hydrogen	FC	/29/
Ammonia	ICE, medium-to fast-speed	
	ICE, slow speed	/78/
Methanol	ICE, medium-to fast-speed	/29/, /53/
	ICE, slow speed	
LPG	ICE, medium-to fast-speed	
	ICE, slow speed	/5/
Advanced biodiesel (HVO)	ICE, medium-to fast-speed	/50/, /56/, /77/
	ICE, slow speed	/50/, /56/, /77/
Battery-electric		-

Table 0-5: Sources used for main current usages

Fuel	Sources
LNG	/21/, /24/, /28/, /39/, /71/
Hydrogen	/35/, /41/
Ammonia	/3/, /78/, /80/
Methanol	/22/, /24/, /54/
LPG	/5/, /81/
HVO	/27/
Electricity	

Table 0-6: Sources used for availability of fuel

Fuel	Sources
LNG	/22/, /24/, /40/
Hydrogen	/22/
Ammonia	/22/
Methanol	/22/, /53/
LPG	/5/, /22/, /82/
HVO	/38/, /65/
Electricity	/20/, /19/

Table 0-7: Sources used for global production capacity and locations

Fuel	Sources
LNG	/40/
Hydrogen	/22/, /41/
Ammonia	/1/, /6/, /22/, /80/
Methanol	/22/, /55/
LPG	/5/, /82/, /83/
HVO	/38/, /65/
Electricity	/84/

About DNV GL

DNV GL is a global quality assurance and risk management company. Driven by our purpose of safeguarding life, property and the environment, we enable our customers to advance the safety and sustainability of their business. We provide classification, technical assurance, software and independent expert advisory services to the maritime, oil & gas, power and renewables industries. We also provide certification, supply chain and data management services to customers across a wide range of industries. Operating in more than 100 countries, our experts are dedicated to helping customers make the world safer, smarter and greener.