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Article

Criteria and Decision Support for A Sustainable Choice of Alternative Marine Fuels

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Abstract: To reach the International Maritime Organization, IMO, vision of a 50% greenhouse gas (GHG) emission reduction by 2050, there is a need for action. Good decision support is needed for decisions on fuel and energy conversion systems due to the complexity. This paper aims to get an overview of the criteria types included in present assessments of future marine fuels, to evaluate these and to highlight the most important criteria. This is done using a literature review of selected scientific articles and reports and the authors' own insights from assessing marine fuels. There are different views regarding the goal of fuel change, what fuel names to use as well as regarding the criteria to assess, which therefore vary in the literature. Quite a few articles and reports include a comparison of several alternative fuels. To promote a transition to fuels with significant GHG reduction potential, it is crucial to apply a life cycle perspective and to assess fuel options in a multicriteria perspective. The recommended minimum set of criteria to consider when evaluating future marine fuels differ somewhat between fuels that can be used in existing ships and fuels that can be used in new types of propulsion systems.

Keywords: marine fuels; emission reduction; GHG; multicriteria analysis; alternative fuels

1. Introduction

The present ambition to fulfil the 1.5 °C goal [1] of global warming is affecting all sectors in society. In the transport sector, shipping is regarded as a very energy efficient means of goods transportation, but still, shipping contributes to almost 1 million tons of fossil CO₂ annually [2]. The challenge to decrease this is treated within the International Maritime Organization, IMO, who adopted a vision document in April 2018 including a global goal of 50% reduction in greenhouse gas (GHG) emissions from shipping by 2050, compared to 2008 [3]. There are also follow up actions discussed to reach the vision. In 2018–2023 measures will be developed, including energy efficiency, assessment of fuels, technical cooperation, and national action plans. In 2023–2030 the measures will be developed, including an implementation program for the uptake of low-carbon and zero-carbon fuels [4].

The discussion on fuel choice is often confused. The criteria for selection vary, as do the driving forces for a change. There is also a large degree of confusion on what is meant by “alternative marine fuels”. The term is often used for fuel that is not heavy fuel oil (HFO) or marine gas oil (MGO) but also for a fuel with low or zero GHG emissions [5–9]. In addition, the term “decarbonization” is somewhat confusing, where it sometimes refers to a reduction of fossil fuels and sometimes a reduction of carbon emissions, regardless of origin (see also Section 1.2).

Another way to group fuels is based on the potential energy conversion technology. A fuel may be used in different energy conversion technologies and perform in different ways but still have the

same impact in production and distribution. In general, fuels are often evaluated with regard to the possible energy conversion technology, which include:

- ◇ Combustion engines—diesel, dual fuel, Otto, gas turbine;
- ◇ Fuel cells;
- ◇ Electric engines.

There are several different fuels and energy carriers that can be used in the two first energy conversion technologies, whereas electric engines are dedicated for one energy carrier only (electricity). There are, furthermore, several different ways to produce the wide range of fuels and energy carriers. The fuels can have different primary energy sources—fossil, biomass of different types, or be synthetic based on electricity.

The selection of energy conversion technology provides a basis of evaluation for decisions in ship building or retrofit. However, when the technology is selected the fuel must be assessed depending on fuel source and production.

1.1. Criteria for Fuel Choice

The question “what are the parameters you/a shipowner consider(s) when selecting a marine fuel to be used in a new build or after conversion of a ship?” or simply “what is the future shipping fuel?” has been included by the authors in recent interviews with shipowners and class society experts concerning fuel choice. The large majority of ship owners answer “we use the fuel and technology that fulfil the regulations at lowest cost”. This shows the influence of regulations, but also the economic reality. The importance of economic criteria was also shown in Hansson et al [6], where shipowners ranked economic criteria as the most important, with special emphasis on the sub-criterion fuel prices [10]. The fuel cost is a large part (approximately two-thirds of a vessel’s voyage cost and over one-quarter of a vessel’s overall running cost [10]) of the operational cost of a cargo ship, and there is a price competition. However, to use only current fuel cost at current prices as the main criterion for a long-term decision is not relevant. Even the fuel prices of present well-established fuels are varying strongly over time. The fuel cost situation has been turbulent since at least around 2005, see Figure 1 showing the situation for the primary energy sources oil (Europe Brent spot price) reflecting the price for, e.g., HFO and MGO as well as natural gas (Henry Hub spot price) and also the price for liquefied natural gas (LNG) (US export price). If the alternative liquid methanol (made from natural gas) available at the market today is added, the confusion becomes even larger, since it also is a widely used intermediate in the chemical industry. It is uncertain if the current and expected cost for methanol is valid to use also in a case with large-scale demand of methanol as fuel. The possibility for large ship owners to negotiate long-term contracts and discounts for fuel makes it even more complex. There are of course many more criteria considered in a real decision situation, and when changing to an “alternative” fuel that is not well-established, there are many parameters that can influence the long-term sustainability of the alternative fuel options.

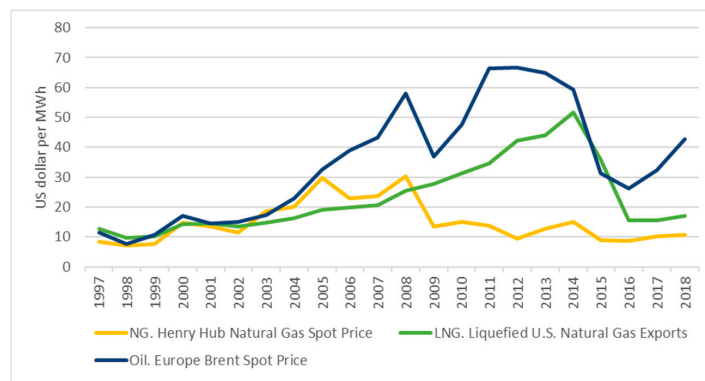


Figure 1. Development of fuel prices between 1997 and 2018. Sources: Energy Information administration (EIA) [11,12].

The wide use of HFO historically is due to the fact that it has been the most economical choice, also when taking the need for heating of the fuel on-board, fuel purification, and handling into account. Emission regulations for sulphur and nitrogen oxides have set new demands on the HFO and MGO quality. A continued use of the fossil marine fuels could be possible, but needs to be combined with a carbon capture capability (CCS) on-board and provisions for storage and handling of captured CO₂. The potential for use of CCS in shipping is investigated in an ongoing research project [13].

In the future, when the choice of fuel will include different non-fossil fuels, or at least fuels with a large percentage of non-fossil fuels, the price situation is also difficult to predict. A summary of some studies on the possible cost of production for alternative fuels is given in Figure 2. As indicated in the figure, even though there are price estimates for non-fossil alternative fuels that are relatively low, these can be expected to remain at a higher price than HFO for some time, perhaps 2–3 times higher, due to the more complicated process technology and cost of extracting raw material. However, since there is no large-scale production and infrastructure for the alternatives today, a future technology development and up-scaling can be expected to decrease the future price (mid and lower level of the price estimates). At the same time, the competition in the whole transport and energy sectors for non-fossil energy carriers is increasing. Low production cost and availability of raw material can be expected to be important parameters for future prices of alternative fuels, but there are several others [14].

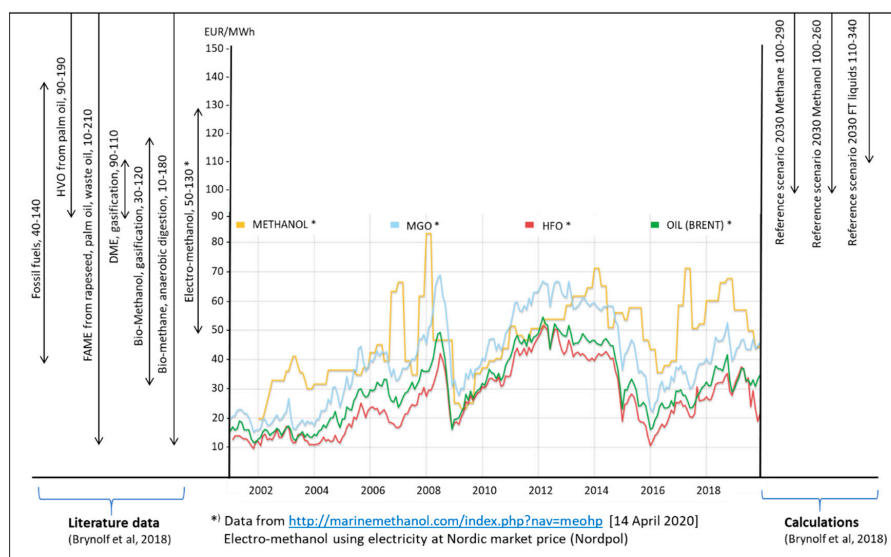


Figure 2. Market prices of conventional fuels 2002–2019 and estimates of production costs of some non-fossil alternative fuels. Literature data and calculations from Brynolf et al. [14].

In Figure 2, the costs of non-fossil fuels are presented and compared to the price development of fossil fuels and fossil-based methanol. Note that a default discount of 13% is applied to the “conventional” methanol price. According to Platts (<https://www.spglobal.com/platts/en/market-insights/latest-news/petrochemicals/022315-rollover-expected-for-us-march-methanol-contracts-sources>), this should reflect an estimated contract price.

To find decision support to make a sustainable long-term fuel choice that is the most economical from a long-term perspective is probably not possible due to the uncertain future fuel prices. There will also be more criteria to consider, some of these have not been an issue for HFO and MGO, like competition with food, infrastructure availability, or safety of gas handling. The decision process needs to be improved by a more systematic view on the sustainability of energy carriers and energy conversion technology alternatives, taking a larger scope of parameters into account.

1.2. What is “Decarbonization”?

The issue of gases contributing to global warming is complex and includes CO₂, which is part of the natural carbon cycle, but for which the total amount is increased by release of carbon from “sinks” in the geosphere, where the origin is fossil hydrocarbons (petroleum, coal, natural gas). Among the GHGs there are also other naturally existing compounds like methane, nitrous oxide (N₂O), water vapor, and others. Some of the other GHGs are much more potent than CO₂—methane is one example. The word decarbonization in this context is somewhat confusing, since there is a natural carbon cycle that is needed for life on Earth. The goal is not to go towards “zero carbon” but to stop moving carbon from fossil fuel sinks into the natural carbon cycle and, since the release of fossil carbon has resulted in a larger amount in circulation, also try to remove carbon from the cycle. You cannot tell the color of the carbon atoms, there is no “green” or “black” carbon, when in the cycle they are all alike. It is about mass balance. This also implies that it is not the combustion engine in itself that is the problem, it is using fossil fuels that leads to global warming and also acidification of the oceans. In addition, there are other issues with combustion, leading to emissions that have to be considered for other reasons, like nitrogen oxides and particles. In this study we have used the definition of “decarbonization” as a reduced use of fossil fuels.

1.3. Definitions of “Alternative Fuels”

In order to define the term “alternative fuels”, it can be good to first describe what a fuel is. A fuel is described in Brynolf et al. [15] as “a broad term that is used for a material such as coal, oil, or gas that can be converted to various usable forms of energy, such as thermal, mechanical or electric energy”. Furthermore, the authors suggest that “a fuel is considered to be associated with a specific primary energy source and processing options, whereas an energy carrier only represents the compound or phenomenon that carries the energy”. This means that several different fuels may have the same type of energy carrier. An example of this is liquefied natural gas (LNG) and liquefied biogas (LBG), which both have methane as the energy carrier. The name of the fuel does not always describe the primary energy source in a transparent way. Primary energy sources are unrefined energy sources that can be found in nature, including, for example oil, biomass, and wind. If the primary energy source is fossil the fuel produced is typically called fossil, while fuels produced from renewable energy sources such as biomass are called renewable fuels.

Mixtures of fossil and non-fossil primary energy are not only found when using methane (as in the example above with LNG and LBG), but can also be found when using methanol and “electrofuels” (the latter produced from electricity, sometimes called power-to-X or “liquid battery”, see more below) which can be renewable if the methanol is produced from biomass, or in the case of electrofuels, if the electricity used is renewable. In Figure 3, some possible production pathways for fuels are illustrated.

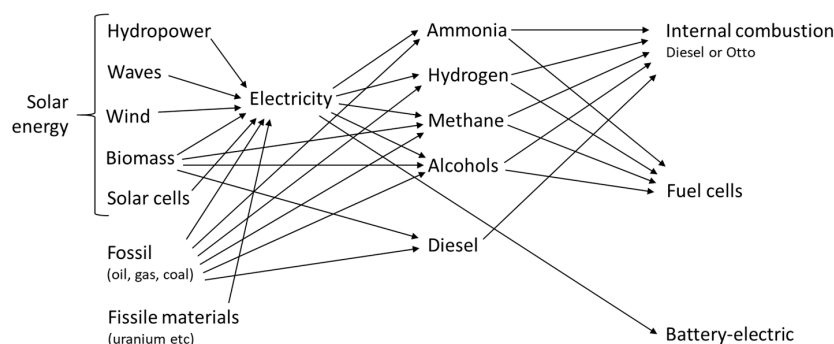


Figure 3. Examples of fuel production pathways and energy conversion technologies for marine fuels.

There are both fossil fuels and renewable fuels among the fuels proposed for reducing GHG, and these are often called alternative fuels. This may have a historical explanation in the fact that the initial driving force for replacement in the European Union and in the US was to reduce the petroleum dependence, not to reduce GHG. In Europe, it was phrased as “alternative fuels are urgently needed to break the over-dependence of European transport on oil”, where alternative fuels are defined as: electricity, compressed natural gas (CNG), hydrogen, LNG, Liquefied Petroleum Gas (LPG), biofuels, and synthetic fuels (EC, 2019–11-27 ec.europa.eu/transport/themes/urban/cpt_en). The US EPA defines alternative fuels as “derived from sources other than petroleum” and mention the following: biodiesel, ethanol (E85), CNG, propane, and hydrogen (EC, 2019–11-27 ec.europa.eu/transport/themes/urban/cpt_en). Due to the earlier rules on sulphur and nitrogen oxide emissions, fuels providing low emission of these elements/compounds in combustion have also been discussed as “alternative”.

The definition of “renewable” when using waste as the energy source can also differ and be a result of local legislation. As an example, in Sweden, electricity produced from waste incineration is defined as partly renewable, taking the amount of fossil-based materials like plastics in the waste into account. In other countries, waste-based fuels are regarded as entirely renewable and “renewable” liquid fuels are produced and marketed. One example is the “waste to fuel” production in Edmonton, Canada (https://www.edmonton.ca/programs_services/garbage_waste/biofuels-facility.aspx).

The fuel alternatives can also consist of a range of various compounds, mixed into conventional fuels, and if the final fuel mix fulfils the conventional fuel standard, the different compounds are referred to as “drop-in fuels”. This is currently discussed for land-based vehicles but potentially provides an option also for shipping. Bio-based drop-in fuels that have been considered in the Swedish “Future Fuels project” are, e.g., oxymethylene dimethyl ether (OME), n-octanol, 2-methyltetrahydrofuran, 2-ethylhexanol, n-decanol, and 2-propylheptanol. All these can be produced from feedstocks like ligno-cellulose (e.g., from paper pulp production), starch, sugar, oil from plants, or as electrofuels [16].

1.4. Different System Perspectives

There is a need for a systems perspective in the evaluation of alternative energy carriers, taking the upstream processes from the energy source to the use on-board into account. When evaluating the alternative fuel, not only the primary energy source, but also the system boundaries of the evaluation are of importance. If only the energy conversion technology on-board is taken into account, the data on GHG emissions may be misleading. This can be exemplified with methanol produced from natural gas, which has lower GHG emissions during combustion on-board the ship compared to MGO and HFO, but higher when the fuel production is included as well [17]. Another example is LNG, with the potential to reduce the direct CO₂ emissions to some degree due to higher hydrogen to carbon ratio in the fuel compared to HFO and MGO, but this reduction can easily be counteracted by emissions of methane upstream (as well as during combustion) [18]. This illustrates that the production and distribution of the fuel may be a source of large GHG emissions as well. Unfortunately, the national (and thus also international) emission and fuel use statistics collected for different sectors, including

the shipping sector, are usually only for the final energy conversion and not for the fuel production and distribution. This makes it possible to report low GHG emissions from the ship while causing high emissions upstream. This situation is shared with the problem of emissions from imported products, where the production emissions are in another geographical location than the use and show the need to include all relevant emissions within the system boundary of the assessment.

The systems perspective is handled in environmental assessments with a life cycle perspective. Some evaluations for marine fuels are found in literature, although the number of parameters evaluated differs [8,19–22].

1.5. Goal of the Study and Approach

In order to make a vision come true, there is a need for action and decisions. A ship has a long lifetime, and although retrofits are both possible and implemented to some extent already, they come at a cost. A shipowner deciding on a fuel and energy conversion system today needs to consider the possibility to fulfil the requirements valid when the ship is ready in some years, as well as the possibility to adapt to future demands during a lifetime of around 30 years [23].

The goal of this paper is to get an overview of what type of criteria are included in present assessments of potential future marine fuels, to evaluate these, and to give recommendations of what criteria that are most important. This is done using three approaches: (i) a structured literature review investigating which terms are included in titles and abstract of scientific articles about marine fuels, (ii) a detailed review of selected scientific articles and reports by classification societies and other organizations published between 2017–2019, and (iii) insights from the authors' own experience of working with assessments of marine fuels for more than ten years. The relevance of the criteria used in literature are discussed and suggestions on additional criteria are given with the goal of identifying the criteria that are most valid for a selection of future sustainable fuels. This would imply fuels leading to a minimization of GHG emissions while fulfilling far-reaching demands on sustainability from an economic, social, and environmental point of view.

2. Sustainability Assessments of Marine Fuels

Besides the emission of fossil carbon and its climate impacts, there are many other environmental impacts as well as other factors that are necessary to fulfil in order to achieve the sustainability goals. The 17 United Nations Sustainable Development Goals (SDGs, <https://sustainabledevelopment.un.org/?menu=1300>) and their 169 targets illustrate how many different criteria there are to consider on the road to increased sustainability. Thus, it is a challenge to assess future fuels that consider all sustainability aspects. Some of the parameters in a decision on fuel change were identified as part of the EFFSHIP project, see Figure 4 [18,24]. Here, only internal combustion engines and possible retrofit of existing engines were considered. The process of parameter identification was performed in a multi-disciplinary panel with participants from industry and academia. As can be seen in Figure 4, several parameters were identified in different areas, covering technical, economic, environmental, and other criteria. An insight for the participants was that the number of parameters and areas to consider was much larger than expected and that it covered aspects not so often discussed linked to fuel and propulsion choices. Also, the process of discussing and identifying possible criteria and parameters in a larger group was a useful process. In this exercise, there was no formal evaluation of the fuels against each other, the aim was to identify criteria and possible alternatives worth testing further, based on a discussion. The criteria agreed upon during the EFFSHIP project are shown in Figure 4.

If a broader spectrum of fuels and energy conversion technologies was included in the assessment, that would much likely have made Figure 4 even more complex, especially in the technical criteria. A later version of this figure also includes the sub-criteria of maintenance demand and engine adaptation [15]. There are many other criteria among the ones identified in Figure 4 that may be “showstoppers” or make the fuel less sustainable from a long-term perspective. Different shipping

segments as well as geographical areas also have different opportunities and challenges, giving different outcomes of an assessment. For example, batteries are most suitable for short-sea shipping, fuels requiring larger space on-board partly due to lower energy content may be less suitable for long-distance shipping, and the local/regional supply of different renewable fuels will vary. The decision situation for a shipowner and potential buyer of new ships today is thus very challenging when it comes to finding solutions that are economically favorable from a short- and long-term perspective while fulfilling the demands of sustainability and fulfilment of future regulations and demands. The life-time of a new built ship planned today will stretch into the time after 2050, and the initial targets of GHG reduction by the IMO is to decrease CO₂ emissions per transport work “as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008 . . . ” [3]. The criteria are of different importance and can be in a range from “necessary” to “desirable”, “causes no problem”, “includes new challenges”, to “possible showstopper”.

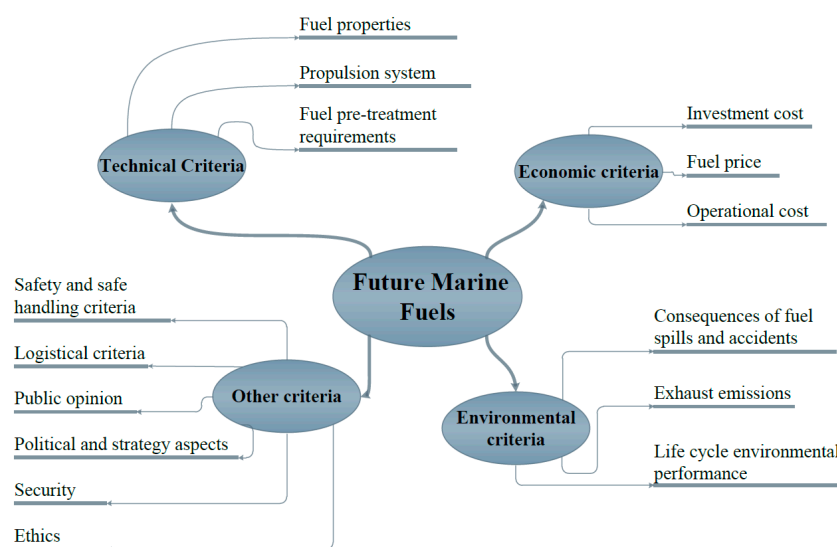


Figure 4. Parameters in multicriteria assessment of marine fuels [18].

The number of scientific publications assessing marine fuels has increased in recent years; this can be illustrated by a search in Scopus (Figure 5). Figure 5 also illustrates which types of terms are most commonly used when assessing marine fuels. Environmental aspects and emissions are considered in most of the assessments, economic aspects have increased since 2010, and there is a potential trend towards an increased focus on climate since 2017.

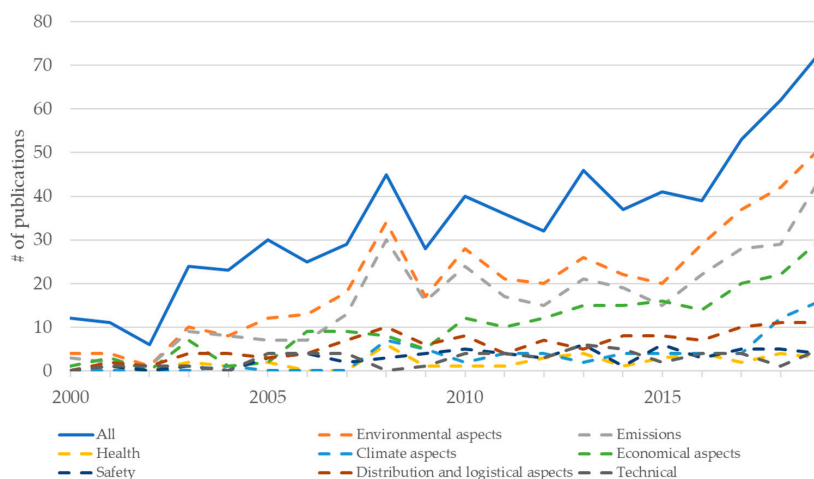


Figure 5. Studies of marine fuels during 2000–2019 found on Scopus in April 2020, using the search

string TITLE-ABS-KEY (“marine fuel *” OR “maritime fuel *” OR “shipping fuel *”). The dashed lines represent subsets of the literature search, including environmental aspects (environment * OR emissions), the word emissions, the word health, climate aspects (climate OR “global warming” OR GWP OR GHG * OR “greenhouse gas *”), economic aspects (cost OR economic * OR economy OR price), the word safety, distribution and logistical aspects (availability OR “fuel distribution” OR logistics OR bunkering OR infrastructure), and the word technical.

2.1. Multicriteria Decision Analysis, MCDA, and Marine Fuels

The studies investigating marine fuels use many different approaches and methods and it is therefore natural that they do not consider all aspects. Multicriteria decision analysis (MCDA) is a tool for making sustainability assessments in a structured way and there are several methodologies developed, allowing various types of evaluations. All full MCDAs typically include the steps of problem formulation, selection of criteria and alternatives, scoring of the alternative against the criteria, and weighting of the criteria against each other to generate a ranking of the alternatives.

There are many ways proposed to handle a weighting of a mixture of quantitative and qualitative parameters [25]. MCDA has been used for a wide variety of areas, and also for marine fuels [6,7,26,27], but only one assessment that specifically focused on the influence of different stakeholders has been found in literature [6] and in this study different stakeholders were asked to prioritize criteria for marine fuel selection. From the study it was obvious that different stakeholders have different priorities. Industry representatives from ship-owners, fuel producers, and engine manufacturers see economy and, in particular, fuel price, as the most important parameter. For representatives from government authorities, the environmental criteria, specifically GHG emissions, and the potential to meet regulations, are seen as the most important [6].

The different views on the importance of criteria underlines the need for a structured and transparent presentation of an assessment of a new fuel in order to be able to proceed to a decision. The result also makes the economic reality visible, supporting the need for economic incentive combined with regulations in order to achieve “decarbonization” in a sustainable manner. The literature review shows that there are some recent assessments and reviews of future marine fuels performed by various research groups, class societies, and organizations. Almost none of the assessments found in scientific literature from 2017 to 2019 performed a formal multicriteria assessment, but there are several that compared fuels from different criteria (see Figure 5, Table 1, and Table 2, which present the criteria mentioned in each study). During the review the following types of studies were identified: studies that discussed different criteria for the selection of marine fuels, but used other methods than MCDA for the assessment (type 1); studies that discussed different criteria and scored the alternatives against the criteria (type 2); studies that performed formal MCDAs (type 3). It is also worth noting that life cycle assessment (LCA) is a specific type of MCDA method traditionally mainly focusing on environmental and resource criteria. Most LCAs are type 2 studies and score the alternatives against a set of environmental impact categories and do not provide a final ranking of the alternatives by weighting of the impact categories against each other. Type 3 LCAs are also possible but not as common [18].

Table 2. Criteria discussed in assessments by class societies and other organizations 2017–2019.

		Policy Analyses and Class Society Overviews				
		DNV GL 2017, 2019	Bleuanus 2019 (DNV GL)	Ryste 2019 (DNV GL)	Kramer et al. 2018	Kirstein et al. 2018
Technical						
Fuel Properties	Energy Density	x		x		
	Stability	x				
	Corrosivity					
	Viscosity					
	Flash point	x				
	Standardization	x				
Maintenance Demand						
Possible Engine Adaption/Fuel Flexibility		x				
Fuel Pre-treatment						
Technology Readiness		x				
Bunkering Intervals		x				
Economic						
Investment cost	Engines	x				x
	Auxiliary Systems	x				
	After Treatment Systems					
Fuel Price		x		x		
Fuel Production Cost		x				
Operational Cost	Maintenance					
	Operation	x				
	Crew					
Incentives/Taxes						
Environmental						
Life Cycle Performance	Global Warming Potential	x	x	x		x
Life Cycle Assessment	Primary Energy Use					x
Exhaust Emissions	NO _x		x			x
	SO _x		x			x
	Particles		x			x
	Other					x
Spill and Accidents						
Systems Perspective/Well to Propeller/Wake				x		
Other						
Logistical Criteria	Infrastructure	x				
	Market/Availability	x				
	Flexible Production					
Safety and Safe Handling	Risk of Explosion/Fire	x				
	Health Hazards	x	x			
Public Opinion						
Political and Strategic Aspects						
Ethics						
Security						
Regulation		x				

2.2. Assessments of Marine Fuels in Scientific Literature Published During 2017–2019

The assessments found in the scientific literature during 2017–2019 are often focused on one fuel or a group of fuels, although the pathway to decarbonization is also a common theme.

Balcombe et al. [28], categorized as a type 2 study, gave an ambitious overview with the aim of informing on pathways to achieve decarbonization and the mechanisms with greatest potential to reduce emissions and to identify research gaps. The assessment covers some important parameters, mainly environmental, economic, and regulatory/policy aspects. The evaluation was, to a large degree, performed by a cost comparison.

The focus is on emissions from the operation of the ship in the assessment, although the authors also included total life cycle emissions in the literature survey. The fossil fuel LNG is discussed as a means of reducing SO_x and NO_x emissions and to reduce particle and CO₂ emissions, since the high hydrogen-carbon ratio of methane makes the combustion efficient, but it is mentioned that the GHG reduction may be negated by methane slip in the engine and along the distribution chain. The loss of energy in liquefaction (8%–12%) is also mentioned. The difficulty to simultaneously have low NO_x (Tier III) and low methane slip in LNG dual fuel engines is mentioned, and that the engines may require SCR for NO_x reduction. The conclusion is that LNG needs to be combined with other measures to obtain a 50% reduction of GHG emissions.

Balcombe et al. also discuss other alternative fuels that have larger potential to contribute to CO₂ reduction. Here nuclear, renewables and biofuels are mentioned. The difference in definition between renewables and biofuels is not clearly explained in the text, but renewables seems to be used for electrofuels, using renewable electricity sources.

The biofuels are discussed as first generation (SVO, straight vegetable oil, HVO, hydrotreated vegetable oil, FAME, fatty acid methyl ester, and bio-ethanol). The large-scale production of these is restricted for “sustainability reasons” (competition with food). Waste oils are mentioned as a possible source, although the availability of these is limited. Advanced biofuels use mainly other feedstocks such as wastes and residues from forestry and forest-based industries, non-food cellulosic material. Here, Fischer–Tropsch (FT) Diesel, pyrolysis oil, lignocellulosic ethanol (LC ethanol) bio-methanol, dimethyl-ether (made from bio-methanol), and bio-LNG are mentioned.

Hydrogen is mentioned as having a large potential to reduce GHG emissions, and a potential for producing hydrogen from nuclear power on shore is mentioned, as well as from renewables such as electricity from solar and wind.

A final statement is that there is a need for a combination of fuels, technology, and policy to achieve decarbonization, and subsidies for LNG are recommended to accelerate the implementation until nuclear, renewables, and hydrogen take over.

In summary, the GHG gain by using various fuels is illustrated and a large number of reduction measures are described. The conclusion is that LNG is the main alternative fuel, although it does not give any large reduction of GHG emissions (8%–20% is mentioned). As for biofuels, the conclusion is not clear—the large variation between fuels and availability seems to confuse.

The mix of energy carriers, primary energy sources, and a final recommendation to subsidize a fossil fuel makes the total impression confusing. It may be noted that the study was funded by Royal Dutch Shell, Enagas SA, and “sustainable gas futures project”.

Bouman et al. [29] made a literature review of 150 studies on CO₂ reduction potential in shipping. Other criteria are also discussed but not evaluated, and it is therefore considered as a type 1 study. Most of the measures are energy efficiency related, but the use of biofuels, LNG, and fuel cells are included. One of the conclusions is that most studies on GHG reduction only take CO₂ into account. The possible conflict between regulations on sulphur and NO_x emissions and CO₂ is also noted. The fact that methane and black carbon are not regulated as emissions leads to the result that it is often not considered. They conclude that the climate effect of change from HFO to LNG is not well understood. This study was funded by the Norwegian Research Council.

Brahim et al. [30] modeled pathways for the Danish Maritime sector to achieve GHG neutrality in terms of CO_{2eq} by 2050. This was done by evaluating regulation or carbon pricing. They looked at “fuel technologies” with alternative fuels like hydrogen, methanol, LNG, and ammonia. The environmental and technological advantages and disadvantages were discussed based on literature and in qualitative terms. In the study, a model for cost minimization at a systems level was used and the estimated remaining CO₂ budget was used for limiting the CO₂ emissions and to reach carbon neutrality by 2050. Present data on emissions and bunker index prices were used. Also, emissions from well to tank were included with the aim of fulfilling the present regulations. This study is a type 1 study. Regarding fuel technologies, the study found that hydrogen, methanol, and ammonia are the most suitable from a socio-economic cost perspective, while LNG is not considered as a long-term solution due to methane leakage and high fuel and technology costs, and battery options are only considered an option for short sea shipping.

Gilbert et al. [21] made an LCA of a number of fuels for combustion engines, taking emissions of compounds related to local (or regional) impacts, like sulphur oxides, nitrogen oxides, particulate matter, and climate-impacting compounds like carbon dioxide methane, and nitrous oxide, into account. It is a type 2 study and used LCA as its main method. This shows the difficulty of combining good performance in these two criteria. They also concluded that use of hydrogen or synthetic fuels sets requirements on the energy and feedstock input used. The project was funded within the UK Shipping in Changing Climates Project (EPSRC).

A formal MCDA, type 3 study, including more criteria, was performed by Hansson et al. [6]. Here, economic (investment cost, operational cost, fuel price), technical (available infrastructure, reliable fuel supply), environmental (acidification, health impact, climate change), and social (safety and upcoming legislation) were considered. The ranking was based on estimated fuel performance and on inputs from a panel of maritime stakeholders and presented for different stakeholder groups (authorities, shipowners, fuel producers, and engine manufacturers). LNG, liquefied biogas (LBG), methanol from natural gas, renewable methanol, hydrogen for fuel cells produced from (i) natural gas or (ii) electrolysis based on renewable electricity, and hydrotreated vegetable oil (HVO) as well as heavy fuel oil (HFO) as the benchmark were included in the assessment. The criteria were selected from a longer list of criteria for which the relative importance was assessed in an earlier study [31]. In this study, the order of importance of criteria varied for different stakeholder groups. The outcome of the MCDA was that industry representatives ranked LNG and HFO as the most interesting fuels, while the authority representatives found renewable hydrogen followed by renewable methanol and HVO as the most interesting options.

Kesieme et al. [32] made a technological, environmental, and economic assessment of biofuels for marine applications. It is a type 2 study. They concluded that existing and upcoming environmental regulations can be met by SVO (straight vegetable oil), biodiesel, and LBG. They treated parameters that may limit the potential of biofuels like availability, technological development, technical integration, and operational consequences. The authors also evaluated the environmental impact of biofuel production in the form of SVO from rapeseed or soybeans. The aim was to evaluate the fuels for use in shipping, but no comparison to production of fossil marine fuel was made.

Mohd Noor et al. [33] performed a literature review on biodiesel for shipping, representing a type 1 study. The review covered fuel background, as well as several aspects on performance in engines, including some emissions. Blends of biodiesel were also included. The biodiesel considered was fatty acid oil esters from vegetable oil or animal fat. The literature review showed that the use of biodiesel in the shipping sector would generally increase the fuel consumption and the emissions of nitrogen oxide, while on the other hand reduce other toxic gas emissions. Several issues and challenges were described, including technical and economic ones such as lower energy content, higher viscosity and density, high cost, and competition of raw material. The study concluded that, provided some of the current issues can be solved, biodiesel and its blends will have a bright future in the shipping sector.

Ren and Liang [27] applied MCDA to rank LNG, fossil methanol, and hydrogen for marine use with 11 criteria. The included criteria covered environmental aspects (effect on CO₂ emission reduction, effect on NO_x emission reduction, effect on SO_x emission reduction, and effect on PM emission reduction), economic aspects (capital cost and operational cost), technological aspects (maturity, reliability, and capacity), and social aspects (comply with emission regulations and social acceptance). The MCDA assessment by Ren and Liang gave the result that hydrogen or LNG are the most sustainable marine fuels.

Ren and Lützen [26] used an MCDA approach (a type 3 study) on LNG, nuclear power, and wind power, using 10 criteria. The criteria included technological aspects (maturity, reliability, and energy storage efficiency), economic aspects (infrastructure, capital cost, bunker price), environmental aspects (NO_x reduction and GHG emissions reduction), and social aspects (social acceptability and safety). The study found nuclear power to be the most sustainable alternative energy source for shipping, followed by LNG.

Anzer et al. [34] made a techno-economic and environmental assessment of marine biofuel produced from different ligno-cellulosic raw materials in Brazil and Sweden, categorized as a type 2 study. Tanzer et al. compared the technological, economic, and environmental performance of 33 “drop-in” marine biofuels. They did not do a formal multicriteria assessment, but called their method an integrated screening model. The following criteria were included in the assessment: biofuel production yield (as an indication of technical performance), capital expenditure, operating expenses, minimum fuel selling price (as an indication of economic performance), maritime fuel standard compliance, life cycle GHG emissions, life cycle SO_x emissions, life cycle NO_x emissions (as an indication of environmental performance). The conclusion was that marine fuel from ligno-cellulosic biomass may have a price three times higher than MGO or more, and that none of the biofuel options was indicated a clear winner.

Winebrake et al. [20], categorized as a type 2 study, evaluated the trade-offs in pollution from some marine fuels, including distillate fuels compared to natural gas-based methanol, bio-methanol, and LNG. The assessment was focused on environmental impact and trade-offs between emissions. The study reported that natural gas-based marine fuels can provide significant local environmental benefits compared to conventional fuels, but that these fuels contribute to global warming if not produced from renewable feedstock. The study highlighted the importance of controlling methane leakage from the entire natural gas production process and stressed the potential role that renewable natural gas can play in the shipping sector.

2.3. Assessments or Reviews of Marine Fuels Performed by Classification Societies and Other Organisations Published During 2017–2019

Reviews with discussion and recommendations for the shipping sector have been performed by class societies (Lloyds and DNV GL), providing a wider decision support.

DNV GL [35–37] made a comprehensive overview of alternative pathways, technologies, and fuels to achieve the IMO 2050 goals. They also discussed “future proof ships”, and how to find sustainable investment alternatives, and presented case studies for illustration. It was a type 2 study that scored the investigated fuels against the following criteria: technical maturity, fuel availability, infrastructure, rules, capital expenditures, energy cost, volumetric energy density.

The options and limitations of alternative fuels were presented by Ryste [37], also at DNV GL. He gave a comparison based on high priority parameters like energy density, technological maturity, local emissions, GHG emissions, energy cost, capital costs, and bunkering availability, but also flammability, toxicity, regulations and guidelines, and global productions capacity and locations.

Bleuanus [38] developed the DNV GL perspective in a presentation of alternative fuels that can be used in dual fuel engines. The author also discussed different parameters, including technical maturity, fuel availability, infrastructure, rules, capital expenditure, energy cost, and volumetric issues.

Lloyds [39] presented an assessment (or scenario analysis) of the costs and emissions from selected alternatives for three “foreseeable futures” using electricity, hydrogen, and ammonia for shipping, and applied the results for different ship types. The authors identified seven technology options for zero emission. Electric, hybrid hydrogen, hydrogen fuel cell, hydrogen + ICE (internal combustion engine), ammonia fuel cell, ammonia + ICE, and biofuel. This resulted in three alternative regulatory and economic scenarios: (1) Green Electricity: renewable electricity with carbon sequestration giving low CO₂ and high cost; hydrogen produced from fossil fuels giving low cost, ammonia produced from the hydrogen and electricity; third-generation biofuels available, giving zero production emissions; (2) Green Ammonia: widely available ammonia produced with near zero emissions; electricity produced cheaply from fossil fuels; hydrogen from a mix of renewable and fossil fuels; third-generation biofuels available, giving zero production emissions; and (3) Green Hydrogen: hydrogen produced from renewable sources at high cost; fuel cell technology highly efficient; electricity from a mix of fossil and renewable sources; ammonia produced from a mix of green hydrogen and cheap electricity.

The study resulted in a cost and profitability assessment for the different ship types and an assessment of the carbon pricing needed to make zero emission vessels competitive to HFO. The finding was that none of the included options are competitive with conventional propulsion below approximately EUR 230 per ton CO₂, at which the biofuel vessel is competitive, while the ammonia and hydrogen fuel options become competitive at approximately EUR 460 per ton or slightly higher. This is a type 2 study.

Kirstein et al. [40] made a policy analysis for the decarbonization of maritime transport for the OECD ((Organisation for Economic Co-operation and Development) (a type 1 study). They concluded that a mix of measures will be needed to reduce the emissions. They also concluded that there are many fuel alternatives, some not fully developed, but that the current, first-generation, biofuels supply can cover only about 15% of the demand for shipping according to the IEA (International Energy Agency). They quoted different sources with different estimates on the possibility to provide biofuels also advanced biofuels. They discussed the possibility to produce various fuels and found that the use of biofuels should gradually be complemented by other natural or synthetic fuels such as methanol, ammonia, and hydrogen. This is a “qualitative multicriteria assessment” to be compared to the class societies reports [29].

2.4. Summary of the Assessed Articles and Reports

The literature review shows that the parameters discussed are usually quite few (see Tables 1 and 2), the focus of the evaluations varies a lot, and some studies assessed certain parameters in more detail, from only taking CO₂ into account, to including other emissions, economic, and technical aspects as well. More application-oriented studies are usually provided by the class societies, with a focus on recommendations for use by ship owners. It is also noted that the possible use of the same energy conversion technology for several fuels is not very much elaborated in the literature.

The fuels/energy carriers as well as the energy conversion technologies and energy storage that were evaluated are numerous. This implies that there is a large uncertainty in the selection of both fuel and conversion technology. There is also, in some cases, a mixing up between energy carrier and energy conversion technologies. This is especially evident for the fuel cell technology, which is sometimes treated among alternative fuels, in spite of the fact that fuels for fuel cells (e.g., hydrogen or methanol) can be used in combustion technologies as well.

The names of fuels used are also a source of confusion, and in Tables 3 and 4 the name used in the reviewed paper is listed, although the same fuel may occur under different names. In order to explain the origin of the fuels in Tables 3 and 4, the fuels have been sorted under the heading of primary energy source.

Table 3. Fuels treated in assessments in scientific literature 2017–2019.

Fuel Origin	Fuel Names Used	Balcombe et al. 2019	Bouman et al. 2017	Brahim et al. 2019	Brynnolf et al. 2018	Gilbert et al. 2018	Hansson et al. 2019	Kesieme et al. 2019	Mohd Noor et al. 2018	Ren and Lützen 2017	Ren and Liang 2017	Tanzer et al. 2019	Winebrake et al. 2019
Fossil-based	Methanol	x		xF		xI	x				x		x
	LNG	x	x	xF		xI	x			x	x		x
	Ammonia			xF									
	Hydrogen	x		xF		xF	x			x	x		
	LPG												
Biomass	DME	x											
	Biofuels									x			
	Bio-methanol	x					x	x					x
	Biofuel											x	
	Bio-liquids	x											
	SVO soy *					xI							
	SVO rape					xI							
	SVO							x					
	Biodiesel soy					xI							
	Biodiesel rape					xI							
	Advanced biofuels	x											
	Biodiesel				xI				x				
	Biodiesel FT	x							x			x	
	BTL												
	FAME	x											
	HVO	x						x					
	Pyrolysis oil **	x							x				
LC-ethanol ****	x												
LBG	x			xF		xI	x	x					
Electrofuels	e-methanol				x								
	e-FT				x								
	e-gasoline				x								
	e-diesel FT												
	e-OME												
	e methane				x								
	e-h2						x						
	e-DME				x								
Misc.	e-propane FT												
	Fuel cell	x	x										
	Battery												
	Electricity			x									
	Nuclear	x								x			
Wind		x							x				

I = Internal Combustion; F = Fuel Cell; * SVO = Straight vegetable oil; ** no data on primary energy source/raw material; *** Lignocellulose based.

Table 4. Fuels treated in reviews and assessments by class societies and other organizations 2017–2019.

Fuel Origin	Fuel Names Used	DNV GL 2017, 2019	Bleuanus 2019 (DNV GL)	Ryste 2019 (DNV GL)	Kramer et al. 2018	Kirstein et al. 2018	DNV GL 2017, 2019
Fossil-based	Methanol				x		
	LNG		x	x I	x		x
	Ammonia	x F I	x I	x I	x		x
	Hydrogen	x F I H	x		x		x
	LPG				x		
	DME						
Biomass	Bio-methanol						
	Biofuel	x					
	Bio-liquids						
	SVO soy *						
	SVO rape						
	SVO						
	Biodiesel soy						
	Biodiesel rape						
	Advanced biofuels	x					x
	Biodiesel			x			
	Biodiesel FT						
	BTL			x			
	FAME			x			
	HVO			x	x I	x	
	Pyrolysis oil **						
	LC-ethanol ****						
LBG			x	x I			
Electrofuels	e-methanol		x			x	
	e-FT						
	e-gasoline					x	
	e-diesel FT		x			x	
	e-OME					x	
	e-methane		x			x	
	e-h2					x	
	e-DME					x	
	e-propane FT					x	
Misc.	Fuel cell						x
	Battery						
	Electricity		x	x	x		x
	Nuclear	x	xx			x	x
	Wind						x
	Solar						x

I = Internal Combustion; F = Fuel Cell; H = Hybrid; * SVO = Straight vegetable oil; ** no data on primary energy source/raw material; *** Lignocellulose based.

3. What Criteria are Important to Consider When Assessing Marine Fuels?

After having gone through recent literature, it becomes clear that there are many aspects of fuels treated (Figure 5 and Sections 2.2 and 2.3), but these vary between the assessments, as do the fuels included and the names of fuels (Tables 3 and 4). Fuel selection thus seems at risk to be non-structured, or to be considering only the present situation, although the aim is a long-term sustainable solution. So, what could be of main importance to a ship owner and for the society?

3.1. Technical

As can be seen from Tables 1 and 2 the technical criteria, ranging from demands on engine to energy density of fuel, are not very much discussed. This is also supported by the literature search presented in Figure 5. It is obvious that the focus in the articles and evaluations on fuel selection is very much on environmental issues and on the properties that are regulated at present and with forthcoming CO₂ restrictions added. The technical criteria seem to be taken more or less for granted in many assessments. This can, for example, be illustrated by the following statement about installing a dual-fuel Diesel-engine on a ship: “the ship in practice can burn nearly any fuel feedstock that becomes available in the future with a high thermal energy efficiency” [41]. For fuels with well-known and tested properties, like the biodiesel fuels, there are no large problems. Only minor differences from the fossil fuels can be expected like, for example, a higher tendency to biological decomposition and thus a shorter storage time [33].

When it comes to fuel types that have not been in use on a large scale or are not known from shipping, like alcohols, the technical issues are more obvious. Although the energy conversion technology in principle is similar, many issues can arise from differences in physical properties of the fuel. In combustion engines there can be a need for other fuel injection systems and the viscosity and lubrication properties also have to be taken into account. The energy density is lower for these fuels and construction materials may be affected by corrosion.

Gases introduce other technical challenges, where the technology is quite well developed for natural gas/LNG, and a conversion of a traditional diesel system can be done, although at a high cost. For ammonia, the technology readiness level is very low [42]. Anhydrous ammonia is a gas that requires high pressure/low temperature storage like LNG, although not at such a low temperature. Although it is a very common chemical to use as fuel, or as a hydrogen carrier, it has only been tested in a few cases and not with present technologies. The development of modern engines and technologies for ammonia fuel is thus ongoing, but the technologies are much less mature than for biodiesel or methanol. There may, for example, be problems when combusting ammonia in internal combustion engines, as it is not so easy to ignite [43]. Technical issues also arise when using hydrogen. This has been discussed and tested in combustion engines [13], although the main energy conversion technology proposed is fuel cells.

In summary, well proven solutions and technologies that allow the use of different fuels with only minor modifications are likely to give a more predictable and possibly lower cost from a long-term perspective. There is a need for pioneers that introduce and test new solutions, but this comes at a cost.

3.2. Economical

Most economic evaluations focus on the fuel price or the production cost of fuels that are not on the market. However, also investment and maintenance cost may be different when selecting a new fuel. The production cost and the market price are not similar, making the comparison of existing fuels and those that are not in large-scale production very difficult. The traditional fossil fuels have a market and infrastructure and thus market prices, although they vary over time, depending on the demand. For the alternatives, there is usually no present market, for some there is no full-scale production or, in some cases, not even pilot plant production. The logistics of fuel delivery may be shared with traditional fuels, but when this is not the case, the need for an infrastructure may affect the price as

well. Thus, the fuel price, which is often mentioned as the most important parameter in the selection of energy conversion technologies and energy carriers, is not easy to predict even short-term for the conventional fuels, and still more difficult for fuels that are not produced commercially today.

What can be done in terms of estimates of fuel production cost? A general observation is that the number of process steps and transport of raw material will be likely to influence the cost as well as the cost of the raw material itself. Biofuels are sensitive to the amount of work performed in growing and harvesting, synthetic fuels to the energy losses in process steps. In Hansson et al. 2019 [6] we tried to use a similar approach for estimating fuel prices 2030. We compared historical and current fuel prices as well as production cost estimates as well as raw material prices in connection with the conversion efficiencies of the fuel production.

3.3. Environmental

As mentioned before, the environmental criteria and particularly GHG emissions are those that have mainly been in focus recently. The main confusion when trying to compare different studies is that the fuels can be evaluated from a “tank-to-propeller” or “well-to-propeller” perspective. Also, other choices in terms of system boundaries, like what to include, for example, in the production of electricity for the processes (in particular the use of fossil fuels or renewable energy sources or a mix), can affect the results. A limited focus on on-board use (tank-to-propeller) may lead to an intentional move of emissions upstream. That is, a fuel that generates low emissions from the energy conversion technology on-board, but emits a lot during the upstream production phase from raw material to useful fuel, may be chosen if the upstream emissions are not included in the regulation policy. Unfortunately, the emission statistics and regulations today are, to a large degree, related to the use phase and thus can overestimate the reduction of environmental impact.

An example of this confusion is the earlier mentioned use of the fossil fuel LNG, which is claimed to reduce the GHG emissions by up to 20% due to an efficient combustion. This may be possible from a tank-to-propeller perspective if the methane slip in the engine is minimized by engine design, but in order to have an effect on global warming, there is a need to ensure that there is no methane slip in the whole chain from well to tank as well. Every process and transfer between tanks represents a potential loss of methane, a GHG with a warming potential to the order of 30 times that of CO₂. A 20% gain in the combustion is easily counteracted by 2%–3% loss of methane upstream [18,41].

Another example is the production of very “clean” fuels that are produced by energy-demanding processes. Fischer–Tropsch fuels are examples of this [44]. In order to better guide actors making decisions on fuel choices and avoid potential suboptimal solutions it is important to consider all GHG emissions from the entire fuel life cycle.

3.4. Fuel Distribution

A well-developed logistical system for an energy carrier has the potential to contribute to a fast introduction and also sets minor demands on infrastructure. Distribution of diesel-like fuels has an advantage to be distributed in existing infrastructure, with transport vessels and bunkering capabilities. Methanol and ammonia have well-developed logistical systems world-wide, although intended for distribution to chemical industry, waste-water purification plants, etc.

For gases, the distribution is not that well developed. LNG is found in parts of the world, but in order to get availability world-wide, there is a need for developing infrastructure, which comes at a high cost and is time-consuming to build up.

The logistics are also related to the fuel price at the bunkering site in case there is a need for build-up of a new infrastructure for the fuel distribution. Logistic aspects were, to some extent, covered in the reviewed studies. Then, generally represented by availability of infrastructure or availability of fuel on the market.

3.5. Safety and Health

Safety and health issues were only addressed in a limited share of the literature reviewed. The safety issues vary between fuels. For conventional fuels, there is a long experience and there are rules and best practices. For LNG and methanol, which are “low flashpoint fuels”, there are special regulations.

Concerning health impact, aspects like toxicity, carcinogenicity, and mutagenicity must be considered. For fuels that have been used for a long time or are well known and used for other purposes, like methanol, these properties are well known and regulations and recommendations for the current use exist. When introducing less well investigated compounds or fuels that have not been used as marine fuels, e.g., ammonia, there may be need for developing regulations and recommendations.

3.6. Geopolitical Stability

Raw materials for fuels or fuel systems are more or less readily available. A strong dependence on a material found only in a very restricted area may be an issue from a long-term perspective. In some studies, this was potentially included in other aspects, such as fuel availability (fuel distribution), and could also potentially be considered in cost estimates.

3.7. Ethics

In this consideration, the aspects of competition with food production are included. The conditions for this vary over the world, there are areas with local “overcapacity” for food production, where the production of fuel oils like rape-seed oil provides a way of using land and providing income for the local landowners. In other areas, fuel production may be considered more profitable than food production, leading to a lack of food.

Ethical issues may be raised on the use of virgin forests or other areas that have not been farmed earlier and have high biodiversity.

An increased use of ammonia, especially if it is produced at low GHG emissions, may cause a conflict with food production, as it is currently mainly used in the production of fertilizers which are crucial for food production, potentially leading to higher food prices, at least initially.

Other ethical issues can be identified in fuel or raw material production phases performed under poor working conditions. A recent example here is the use of rare metals and lithium in battery production. A large part of the present production of these elements is performed in countries where the working conditions and social responsibility of the companies are questioned. Ethical aspects are rarely included directly in the reviewer papers and reports.

3.8. Public Acceptance

Public acceptance of using and handling a specific fuel can be based on different values in different parts of the world. Today, many countries will not allow nuclear-fueled ships in their ports (New Zealand, the Netherlands, and others).

Other fuels that have been discussed for various reasons are natural gas/methane due to explosion risks [44,45]. The public perception of risk with handling of natural gas varies between countries, where typically risks are judged higher in countries without a widespread use of gas in households and industry.

In some countries, like the US and countries in Asia, acceptance issues have been affecting the use of methanol as a fuel due to the human toxicity and risk of people drinking the fuel, while this is not seen as an issue in Europe. Public opinion was not included in the reviewed reports by class societies and other organizations. However, it was included in a few of the reviewed scientific papers.

3.9. Policy

Policy and regulations were only included in a few of the reviewed papers and reports. In policy issues, there will always be a competition and possible conflict between different interests, as discussed under ethics, health, environment, etc. Since it is generally difficult to design policies and to predict the exact effect of policies there is a risk of a mismatch between the intention and actual impact of policies. In general, long-term goals in these areas are preferred over short-term goals. The demand for scientifically based knowledge is central.

4. Discussion and Conclusions

When investigating the information available to support a sustainable choice of alternative fuels, it becomes obvious that the information is fragmented and not easy to interpret. It is also obvious that there are different views regarding the goal of fuel change as well as regarding the criteria to use for assessments.

There are quite few articles and reports with comparison of several alternative fuels. However, the parameters compared, as well as the kinds of fuels evaluated, vary very much and the naming of fuels and the corresponding production pathways can be confusing. This is most obvious for biofuels, but also for fuels that can be produced both from fossil and renewable sources. The only common denominator in the studies seems to be the potential reduction in CO₂, sometimes only taking the combustion into account. In some of the assessments, fossil fuels are singled out as the most favorable, without really discussing the limited potential for GHG reduction.

For the assessment of an alternative fuel, a “decision tree” with criteria of relevance to the cases may be needed. For example, the criteria are far fewer for a change from fossil diesel to biodiesel than for change to a fuel with different physical and chemical properties, like alcohols or gases.

The use of “the fuel that fulfils regulations at lowest price” is not a very relevant criterion, due to changes in market, competition, and future regulations. What can therefore be criteria that provide support for the selection of a fuel that is sustainable, and also economically attractive, from a long-term perspective? We recommend as a minimum to use the highlighted sub-criteria presented in Figure 6.

Criteria relevant for fuels that can be used in existing ships				Criteria relevant for fuels that can be used in new types of propulsion systems not typically used in shipping			
Environmental criteria	Technical criteria	Economic criteria	Other criteria	Environmental criteria	Technical criteria	Economic criteria	Other criteria
<ul style="list-style-type: none"> Life cycle GHGs considering both 20 and 100 year time perspective Regulated emissions Emissions of harmful substances that may be regulated in the future 	<ul style="list-style-type: none"> Modifications needed of the propulsion system Maintenance demands 	<ul style="list-style-type: none"> Retrofit costs Fuel price Estimated fuel production cost 	<ul style="list-style-type: none"> Safety Infrastructure availability Long term fuel availability 	<ul style="list-style-type: none"> Life cycle GHGs considering both 20 and 100 year time perspective Regulated emissions Emissions of harmful substances that may be regulated in the future 	<ul style="list-style-type: none"> Technology readiness Technology complexity Maintenance demands 	<ul style="list-style-type: none"> Total cost of ownership during the ship life cycle Estimated fuel production cost 	<ul style="list-style-type: none"> Safety Infrastructure availability Long term fuel availability

Figure 6. A minimum set of suggested criteria to consider when evaluating future marine fuels.

In order to make a transition to fuels that have a significant contribution to the goal of GHG reduction, there is a need to make the emission of fossil carbon from a life cycle perspective the first priority and assess fuels that fulfil this criterion in a multicriteria perspective. Since evaluations of stakeholder preferences are showing the large importance of economic factors, more transparent multicriteria assessments are needed. We recommend that when evaluating marine fuels, the primary energy sources used as well as the production pathway considered are clearly stated in the assessment.

When evaluating the climate impact, we suggest using the global warming potential from both a 20- and 100-year time perspective to consider both short-term and long-term climate impact and at least CO₂, methane, and nitrous oxides. It is important that the individual emissions of GHGs are quantified so that other authors can use these and adopt to their preferred type of climate metric

and update if newer climate metrics become available. Furthermore, it is important that the whole fuel life cycle is considered, also for alternatives including new types of propulsion systems (such as battery electric).

To make a GHG reduction occur, emissions will need to be strongly regulated. The voluntary actions are contributing and also driving the market for the alternatives, but the cost competition will most likely make regulations needed.

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