Journal of Cleaner Production 297 (2021) 126651

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Alternative fuel options for low carbon maritime transportation: Pathways to 2050

Hui Xing [a, b, *], Charles Stuart [c], Stephen Spence [d], Hua Chen [b]

[a] Marine Engineering College, Dalian Maritime University, Dalian, 116026, China
[b] Institute of Green Energy for Ships and Marine Engineering, Dalian Maritime University, Dalian, 116026, China
[c] School of Mechanical and Aerospace Engineering, Queen's University Belfast, Belfast, BT9 5AH, Northern Ireland, UK
[d] Department of Mechanical and Manufacturing Engineering, Trinity College Dublin, Dublin 2, Ireland

ARTICLE INFO

Article history:
Received 12 December 2020
Received in revised form
4 February 2021
Accepted 5 March 2021
Available online 9 March 2021

Handling editor: M.T. Moreira

Keywords:
Maritime transportation
Low carbon shipping
Ship emissions
Alternative marine fuels
Biofuels
Methanol

ABSTRACT

Within the context of achieving low carbon shipping by 2050, high hopes are placed on alternative marine fuels in addition to a large number of technological and operational measures. A technological review has been carried out in this paper to determine the most promising alternative marine fuels considering the simultaneous reduction of sulphur oxides, nitrogen oxides and carbon dioxide emissions as well as sustainability. Firstly, potential alternative marine fuel options have been summarized based on a review of published literature. Then, key physicochemical properties, feedstocks, production processes, transportation and storage factors, and end uses of zero carbon or carbon-neutral fuels have been analyzed. Finally, a qualitative ranking of the potential of different marine fuel options is presented based on a multi-dimensional decision-making framework. It was found that zero carbon synthetic fuels including hydrogen and ammonia accompanied by clean production could play a vital role in domestic and short sea shipping, though current costs and infrastructure are not commercially feasible. Methanol (fossil/renewable) appears likely to be the most promising alternative fuel for global shipping instead of other carbon-neutral biofuels such as renewable natural gas, bioethanol, biogenic dimethyl ether and biodiesels, which may be feasible for domestic and short sea shipping depending on local practices. It should be highlighted that marine fuel substitution is a prolonged process. Accordingly, consensus-building and action-adopting in the maritime community as early as possible is important to anchor expectations and achieve the goals of clean maritime transportation.

1. Introduction

Maritime transportation plays an important role for world trade; its contribution to air pollution and climate change cannot be ignored. The current population of the world merchant fleet of 100 gross tonnage and above is about 117,000 vessels and the total gross tonnage is 1.36 billion; the average annual growth was 4.6% by number of vessels and 5.0% by gross tonnage from 2008 to 2018 (EMSA, 2019). During the period from 2007 to 2012, average annual maritime fuel consumption ranged between 250 and 325 million tonnes and average annual emissions of sulphur oxides (SO_x), nitrogen oxides (NO_x) and carbon dioxide (CO_2) were 11.3, 20.9 and 1016 million tonnes respectively. Based on different business-as-usual scenarios, maritime CO_2 emissions in 2050 have been projected to increase by 50–250% compared to 2012 (IMO, 2015).

Accordingly, the International Maritime Organization (IMO) has adopted various regulations through progressive amendments of the International Convention for the Prevention of Pollution from Ships (MARPOL) to control SO_x and NO_x emissions and improve ship energy efficiency (Balcombe et al., 2019; Xing et al., 2020). In particular, to mitigate greenhouse gas (GHG) emissions, IMO adopted the Initial IMO Strategy on Reduction of GHG Emissions from Ships (thereafter named as the Initial IMO Strategy) on 13 April 2018 to fulfil the responsibility of the shipping sector. The ambitions of the Initial IMO Strategy were to reduce the carbon intensity of international shipping by 70% and the total annual GHG emissions by at least 50% by 2050, compared to 2008, whilst pursuing efforts towards phasing them out as soon as possible in this century (IMO, 2018). Consequently, low sulphur heavy fuel oil

* Corresponding author. Marine Engineering College, Dalian Maritime University, Dalian, 116026, China.
E-mail address: xingcage@dlmu.edu.cn (H. Xing).

https://doi.org/10.1016/j.jclepro.2021.126651
0959-6526/

(LSHFO), marine diesel oil (MDO), marine gas oil (MGO) or equivalent exhaust gas cleaning systems (EGCS) are widely employed to control SO_x emissions. Furthermore, liquefied natural gas (LNG, predominantly methane), liquefied petroleum gas (LPG, predominantly propane and butane) and methanol have become the main options for meeting IMO NO_x emissions standards owing to the limitations of further improvements in engine technology and the immature status of EGCS for ship NO_x emissions. In addition, two mandatory mechanisms under MARPOL Annex VI, the Energy Efficiency Design Index for new ships and the Ship Energy Efficiency Management Plan for all ships, have been introduced to improve ship energy efficiency and mitigate CO_2 emissions (Balcombe et al., 2019; Walsh et al., 2017). However, the existing technological and operational measures are not enough to achieve the levels of ambition set in the Initial IMO Strategy (CE Delft and UMAS, 2019). Therefore, by systematically considering the abatement of SO_x, NO_x and CO_2 emissions, alternative marine fuels have been identified as a promising solution for mid-term and long-term objectives (Eide et al., 2013; Brynolf et al., 2014a).

Recent studies have reviewed the possible decarbonization pathways, and the CO_2 abatement potential of alternative marine fuels, such as LNG, methanol, biofuels, hydrogen and ammonia, are regarded as 20–100% (Balcombe et al., 2019; Gilbert et al., 2014), with the exact value being dependent upon the fuel type. LNG has been widely discussed as an alternative fuel in shipping sector under the regulations of MARPOL. The life-cycle emission inventories of LNG and HFO for two ships operating in the Taiwan Strait were conducted and the promising future of LNG as an alternative fuel on board was confirmed (Hua et al., 2017). A Global Energy Model was used to study the use of marine fuels, including HFO/MGO, LNG, fossil methanol, biofuels and liquefied hydrogen (LH_2) in a carbon-constrained world (Taljegard et al., 2014). The results showed that the cost-effective choice was to phase out fuel oil and make the transition to LNG and methanol as early as possible, and the application of biofuels in the shipping sector is not advisable due to limited supply and being less competitive compared to other energy sectors. However, it has gradually been realized that the CO_2 abatement capabilities of LNG are not sufficient to deliver the necessary climate impact. Three alternative measures complying with the SECA regulations and IMO NO_x Tier III standards based on life-cycle assessment were evaluated, where HFO combined with an EGCS and an selective catalytic reduction (SCR), MGO combined with SCR, and LNG were investigated (Brynolf et al., 2014b). The results showed that none of them had significant advantages on climate impact compared to HFO. Meanwhile, the life-cycle environmental performances of LNG, liquefied biogas (LBG), methanol and biomethanol were assessed (Brynolf et al., 2014a). The use of LNG or methanol yielded significant environmental improvements compared to HFO, but only the use of LBG or biomethanol has the potential to significantly improve climate impact. Overall, LNG tends to be considered as a transition fuel; methanol, biofuels, hydrogen and ammonia are future targets, but more studies are required. The pathways to climate-neutral Danish shipping by 2050 were presented in reference (Brahim et al., 2019). LNG is an alternative intermediate solution with a short period of opportunity; hydrogen, methanol and ammonia are the most suitable options from a socio-economic cost perspective, but there is no clear winner due to the high cost uncertainties. It was also recognized that battery storage is only an option for short ranges. The physicochemical properties of methanol-biodiesel-diesel blends were analyzed and it was concluded that a blend with 10% biomethanol and 20% biodiesel was the most suitable alternative marine fuel (Paulauskiene et al., 2019). The potential for decarbonization through the use of LNG, biofuels, hydrogen, nuclear, and carbon capture and storage (CCS) were reviewed (Balcombe et al., 2019). Significant barriers were identified regarding their economics, resource potentials and public acceptability. The combustion characteristics and air pollution performances of compression-ignition engines using alternative fuels, which include alcohols, natural gas (NG), biodiesel and dimethyl ether (DME), have been reviewed (Geng et al., 2017a), but performance on CO_2 emissions were not covered. A life-cycle analysis methodology was employed to determine the well-to-wake emissions of methanol (Corbett and Winebrake, 2018). The results indicated that life cycle CO_2 performance of methanol may be similar to LNG, LSHFO, and heavy fuel oil (HFO). However, in terms of air pollution, methanol performs similarly to LNG and better than conventional petroleum fuels. It is worth noting that more types of feedstocks, comparative fuels and pollutants need to be covered in further studies. Electrofuels, which are carbon-neutral synthetic fuels produced from CO_2 and water by storing electricity from renewable energy sources, could be used in combustion engines and may not require significant investments in new infrastructure. However, the production costs of electrofuels were found to be higher than fossil fuels and biogenic fuels. Consequently, electrofuels do not seem to be commercially viable without strong and sustained policy support (Brynolf et al., 2018).

Several studies have assessed potential alternative marine fuel options based on certain decision-making approaches. Qualitative assessment based on literature data and industrial experience was the commonly used method. The life-cycle environmental impact of HFO, MGO, biomass-to-liquid (BtL) fuel, rapeseed methyl ester, LNG and LBG for short sea shipping were compared based on four criteria, i.e., local and regional environmental impact, overall environmental impact, infrastructure, and fuel cost (Bengtsson et al., 2014). LNG was found to have the lowest local and regional environmental impact but LBG had the lowest overall impact. A life-cycle assessment on LNG, methanol, LH_2, biodiesel and straight vegetable oil (SVO) was presented, whilst possible biomass sources of some fuels and CCS technology were considered (Gilbert et al., 2018). The results showed that there is no readily available fuel option for the mitigation of ship emissions at present and viable alternative fuel options are constrained by distinct barriers, such as feedstock supply and fuel production. A comparison of alternative marine fuels including hydrogen, ammonia, methanol, LPG, hydrotreated vegetable oils (HVO) and electricity in batteries was delivered (DNV GL, 2019). No clear selection of alternative marine fuels was given for future shipping but the comparison and analysis provided references for further study by other professionals in the sector. In addition, the quantitative evaluation methods including the multi-criteria decision analysis (MCDA) approach and the analytic hierarchy process (AHP) method were also employed. The sustainability of three alternative marine fuels including LNG, methanol and hydrogen were assessed using the MCDA approach, with eleven criteria being considered (Ren and Liang, 2017). The sustainability was ranked in the order of hydrogen, LNG and then methanol. With the aim of technological comparison of alternative marine fuels, methanol, ethanol, LNG and hydrogen were evaluated based on the AHP method and eleven comparison criteria (Deniz and Zincir, 2016). The results showed that LNG was the most suitable alternative marine fuel, and methanol and ethanol had the lowest ranking due to a lack of availability, whilst the future potential of hydrogen was highlighted. Seven alternative marine fuels, i.e., LNG, LBG, fossil methanol, biomethanol, fossil H_2, electrolysis H_2 (from renewable energy) and HVO, were investigated and their prospects were assessed and ranked based on ten criteria (Hansson et al., 2019). In addition, different weightings of stakeholders were considered when the AHP method was employed. Different conclusions were reached about alternative marine fuel options depending upon the preferences of stakeholders.

In summary, the limitations of existing studies and the needs that should be addressed by future studies could be summarized as follows:

(1) Existing studies lack objective constraints and targets for CO_2 emissions abatement, especially the levels of ambition set in the Initial IMO Strategy and the overall objective of zero carbon maritime transportation.
(2) Existing studies lack consideration of a broader range of alternative fuel options. More types of alternative fuels have been developed and applied in transport sectors and extensive assessment and comparison of their viability in the shipping sector is necessary.
(3) Existing studies mainly focus on the effects of alternative marine fuels on NO_x and SO_x emissions. Synergistic reductions of CO_2 emissions along with NO_x, SO_x, and other air pollutants should be an important focus of future studies.
(4) Very few studies were conducted based on life-cycle assessment. More studies are needed that consider the well-to-wake carbon footprint of alternative marine fuels.
(5) The best choice among multiple alternative marine fuels involves multiple complex criteria. However, the multi-criteria decision-making approach does not seem to solve this problem effectively owing to uncertainties around the weightings of criteria and the preferences of the different stakeholders involved.
(6) More robust research conclusions require more detailed data from the shipping sector combined with a broader view of other sectors, including the feedstock, production, transportation and consumption sectors of energy and fuels, and even the sustainability issues of human society.

Therefore, this paper aims to present a review of alternative marine fuels, including their physicochemical properties, combustion and emissions performance, as well as feedstock, production, transportation, storage and end uses. This study has attempted to determine the most likely alternative fuel for low carbon maritime transportation towards 2050 based on a review of current literature and a multi-dimensional decision-making framework. Identifying the viable alternative marine fuel options and locating the crucial barriers are the main purposes of this study, which could clarify the research direction and expedite the adoption of alternative marine fuels. Cooperative efforts and sharing experiences on key challenges in this field are steps that are expected to accelerate low carbon maritime transportation in a cost-effective manner for global benefit.

2. Technological contexts

2.1. Power source solutions for maritime transportation

The world maritime fleet has been powered by fossil energy sources for more than one century. Nowadays, alternative energy sources for maritime transportation include wind-assistance, photovoltaic systems and nuclear energy. Possible power sources for ship propulsion are shown in Fig. 1. In the competition with internal combustion engines, gas turbines (GTs) and steam turbines with boilers have had no competitive advantages in merchant marine propulsion due to their lower fuel economy. Although there are a large number of advantages of nuclear-powered marine propulsion (Hirdaris et al., 2014), such as no exhaust gas emissions, no frequent refuelling required and higher power generation, low public acceptance (Schøyen and Steger-Jensen, 2017) and low cost-effectiveness (Freire and de Andrade, 2015) restrict the potential for widespread use. Between 1 and 32% energy substitution for wind-assistance (Balcombe et al., 2019; Halim et al., 2018) and 0.2–12% energy substitution for photovoltaic systems (Bouman et al., 2017) are claimed to be achievable. However, low substitution levels, limited availability of ship types and restricted distributions of wind and solar resources dictate that wind energy and solar energy could only constitute an auxiliary power source. In addition, the applications of battery-electric systems for deep sea shipping are restricted due to the low energy densities and short range, which means other power sources, e.g., internal combustion engines (ICE) or fuel cells (FC), might still be required as auxiliary power units and on board fuels would still be needed. Therefore, the main power source options are still conventional fuel-consuming plants. But innovative propulsion systems, novel engine technologies and emerging prime movers are inevitable. Dual fuel engines, FC power systems, hybrid power systems and electric propulsion are the main research and development directions for ship propulsion. Currently, seven types of hydrogen fuel cells, including alkaline fuel cell, proton exchange membrane fuel cell (PEMFC), high temperature PEMFC, phosphoric acid fuel cell, direct methanol fuel cell, molten carbonate fuel cell (MCFC), and solid oxide fuel cell (SOFC), have been under development and demonstration for maritime applications (Xing et al., 2021). However, PEMFC including high temperature PEMFC, MCFC and SOFC are deemed as the most promising options for the maritime sector (Inal and Deniz, 2020; Tronstad et al., 2017). Any kinds of transport fuels, from hydrogen, ammonia to carbon-containing fuels, could be used by hydrogen FC, once the necessary pre-processing units are incorporated.

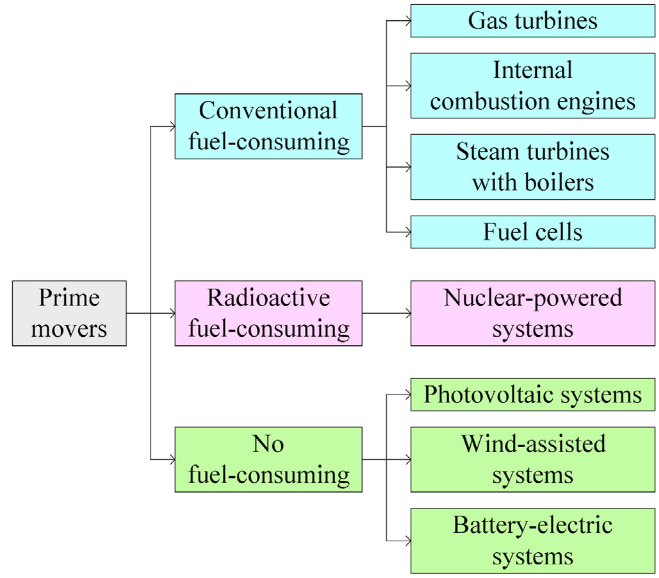

Fig. 1. Possible power sources for ship propulsion.

2.2. Possible marine fuel options

Ships have been fuelled by conventional marine fuels, such as HFO, MDO and MGO, for more than one hundred years. In the past two decades, some types of non-conventional marine fuels, such as LSHFO, LNG, LPG and methanol, have been used as alternative marine fuels owing to the maritime regulations on ship SO_x and NO_x emissions. In the coming three decades, emerging alternative fuels including carbon-neutral biofuels and zero carbon synthetic fuels such as hydrogen and ammonia are expected to be the main options for future low carbon or zero carbon shipping. Biodiesels include ester-based biodiesel (fatty acid methyl esters, FAME), HVO and Fischer-Tropsch (F-T) diesel from all kinds of feedstock. Some other transport fuels, e.g., SVO, bioethanol, synthetic natural gas (SNG) and DME, have been discussed in some references. The typical physicochemical properties and emissions performance of different marine fuels are shown in Table 1. Eight kinds of exhaust gas emissions from ships are considered in IMO GHG studies, but exhaust gas emissions other than CO_2, SO_x, NO_x and particulate matters (PM) are neglected in this paper due to their small quantities. Under the context of current shipping practice, SO_x and PM emissions could be neglected as well due to low sulphur in fuels or application of EGCS. Therefore, CO_2 and NO_x emissions are the primary considerations for the emissions performance of alternative marine fuels.

2.3. Overview of energy chains of potential marine fuels

The energy chains for ship power sources connected to conventional fuel-consuming prime movers from a well-to-wake perspective are shown in Fig. 2. There are three groups of feedstocks for energy vectors: fossil raw materials, including crude oil, NG and coal; biomass, including first-generation biomass such as edible crops, second-generation biomass such as agricultural residues and wastes, forest residues, municipal wastes and energy crops, and third-generation biomass such as algae crops; and water. The production processes of energy carriers require the input of heat or electricity from primary energy sources including conventional fossil energy, nuclear energy and renewable energy such as bioenergy, wind energy, solar energy, hydro energy, ocean energy and waste energy. With the gradually reduced dependence on fossil energy by more and more countries, the increased proportion of renewable energy in the world energy mix improves the competitiveness of renewable fuels such as hydrogen, ammonia, renewable natural gas (RNG) and renewable methanol, the sustainability of which is also ensured by the diversity of feedstock. The primary production processes include: thermochemical processes, such as refining, reforming, gasification, transesterification, hydrotreatment and the F-T process, with additional pre-treatment and after-treatment processes; biochemical processes, such as fermentation and anaerobic digestion; and electrolytic processes. The conditions for distribution, storage and bunkering cover ambient, cryogenic and pressurized conditions, which means that extra equipment, energy consumption, costs and a high standard of operations may be required. The plants to use these fuels could be mono-fuel ICE, dual-fuel ICE or FC.

3. Well-to-wake analysis for zero carbon or carbon-neutral fuels

There is a wide range of alternative marine fuel options. So far, it is not clear which of them is the most competitive and available option for future shipping due to various uncertainties. Before selecting the target fuels, some assumptions were employed in this study. Firstly, based on the discussion in Section 2.1, only ICE and FC were selected as prime movers for ship propulsion and fuel-consuming equipment, but GTs, steam turbines, nuclear-powered systems, wind-assistance systems, photovoltaic systems and battery-electric systems were excluded due to their respective limitations. Secondly, considering the IMO sulphur limit from 1 January 2020, low sulphur content is the mandatory requirement for alternative marine fuels investigated in this section; on board EGCS was assumed to be not acceptable. In addition, CCS technologies were assumed to be not available on board ships due to space limitations for carbon capture and conditioning systems and for the temporary storage of captured CO_2. Although the HyMethShip project in the European Union's Horizon 2020 program declared that the closing CO_2 loop concept is technically available and economically feasible (Malmgren et al., 2020), the assumption of no on board EGCS and CCS was made in this paper because simplified systems and operations on board would mean fewer equipment failures, fewer human errors, less on board investment and operational costs, increased ship safety, increased payload, and more straightforward integration in terms of ship autonomy considering the trend towards autonomous vessels. Based on the above assumptions, fossil fuels including mineral oils, NG and coal could not be used on board directly. In addition, other carbon-containing fuels produced from fossil fuels, such as LPG, fossil-based alcohols and F-T fuels, etc., were excluded in this section. Therefore, the only carbon-free fuels from fossil feedstock or renewable energy under consideration are hydrogen and ammonia, assuming that land CCS systems were in place for production. Other carbon-neutral fuels including biomethane, biomethanol, bioethanol, bioDME and biodiesel are discussed in this section as well. Except for biodiesels and fossil diesel, the typical physicochemical properties of other fuels from biomass or renewable energy and from fossil feedstock, e.g., RNG and methane, renewable methanol and methanol, bioethanol and ethanol, bioDME and DME, etc., are regarded to be the same since they have the same chemical formulas.

Table 1
Typical physicochemical properties and emissions performance of marine fuels. Data: Chemical formula (Douvartzides et al., 2019); density (Noor et al., 2018; Ashraful et al., 2014; Zamfirescu and Dincer, 2008); cetane number (Noor et al., 2018; Yusri et al., 2017); auto-ignition temperature (Dimitriou and Tsujimura, 2017; Yusri et al., 2017); flammability limits in air (Dimitriou and Tsujimura, 2017; White et al., 2006); DME (Liu et al., 2010); combustion emissions in ICE (Gilbert et al., 2018).

Fuels	Chemical formula	Density at 15 °C, kg/m^3	Cetane number	Boiling point, °C	Auto-ignition temperature in air, °C	Flammability limits in air, vol%	Combustion emissions in ICE			
							CO_2	SO_x	NO_x	PM
LSHFO	C_8–C_{25}	975–1010	>20	>180	230	0.6–7.5	high	medium	high	medium
MDO	C_{10}–C_{15}	796–841	>35	>180	210	0.6–7.5	high	low	high	low
NG	CH_4	0.78	130 *	−162	540	5.0–15.0	medium	low	medium	low
PG	C_3H_8&C_4H_{10}	1.90	94-112*	−42	450	2.1–9.5	medium	low	medium	low
Methanol	CH_3OH	792	<5	65	464	6.7–36.0	medium	low	medium	low
Ethanol	C_2H_5OH	789	5–15	78	365	3.3–19.0	medium	low	medium	low
DME	CH_3OCH_3	665	55–65	−25	350	3.4–27.0	medium	low	medium	low
Hydrogen	H_2	0.09	>130 *	−253	585	4.0–75.0	low	low	high	low
Ammonia	NH_3	0.73	120 *	−33	651	15.0–28.0	low	low	high	low
SVO	C_{14}–C_{22}	900–960	30–45	>180	424	0.6–7.5	high	low	high	low
FAME	C_{16}–C_{18}	860–900	45–55	>180	261	0.6–7.5	high	low	high	low
HVO	C_{15}–C_{18}	770–790	>70	>180	204	0.6–7.5	high	low	high	low
F-T diesel	C_{15}–C_{18}	774–782	74–80	>180	204	0.6–7.5	high	low	high	low

Note: *-octane number. PG-Petroleum gas.

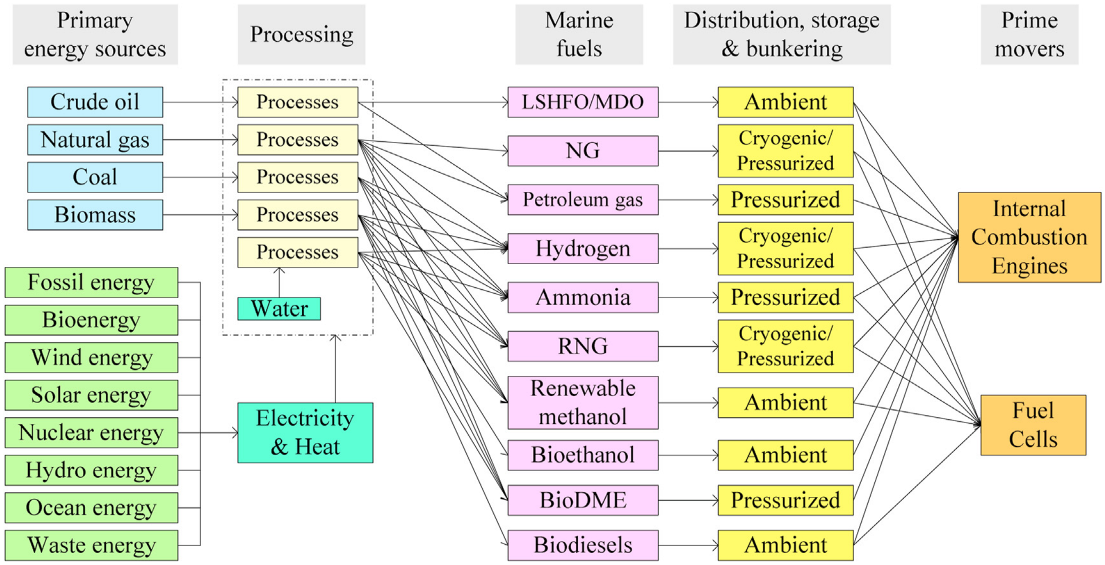

Fig. 2. Simplified illustration of the energy chains for internal combustion engines and fuel cells.

3.1. Hydrogen

Hydrogen, the simplest and most abundant element on earth, offers the best energy-to-weight storage ratio of all fuels. But it usually exists in compound forms, which means that energy consumption is required for its extraction. The feedstock for hydrogen production includes fossil fuels, such as NG, mineral oil and coal, biomass and water. There are a number of different processes for hydrogen production (Balat, 2008; Chaubey et al., 2013; Holladay et al., 2009), as shown in Fig. 3.

Production processes suitable for large capacity plants include NG reforming, coal gasification with CCS and electrolysis with an alkaline electrolyser. Production processes suitable for medium capacity plants include biomass gasification, electrolysis with renewable energy (known as 'Power-to-Gas'), high temperature thermochemical hydrogen, photolysis (photoelectrochemical) and photobiological conversion (Mazloomi and Gomes, 2012).

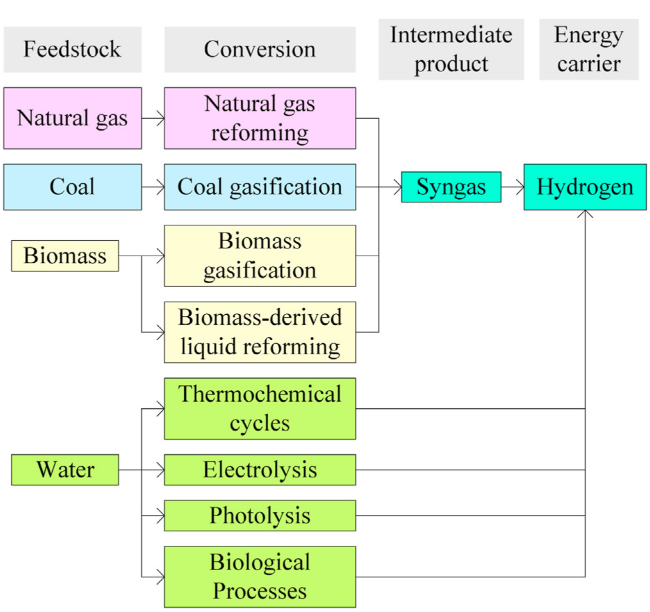

Fig. 3. Processes schematic for hydrogen production.

Production processes suitable for small capacity distributed production include NG reforming, electrolysis with proton exchange membrane, alkaline or solid oxide electrolyser, biomass-derived liquid reforming and microbial biomass conversion (Mazloomi and Gomes, 2012; Wang et al., 2018). Currently, the majority of hydrogen production depends on NG reforming, which is a CO_2 intensive process. Photoelectrochemical, photobiological and microbial biomass conversion are still at an early stage of research and development but offer long-term potential for carbon-neutral hydrogen production. The intermediate product of hydrogen production from fossil raw materials and biomass is syngas, namely a gaseous mixture of hydrogen and carbon monoxide, which is also used for the production of SNG and methanol.

Transportation and storage of hydrogen is highly affected by its volumetric energy density. Due to its low volumetric energy density, more volume for transportation and storage is required. Hence, compressed hydrogen and LH_2 are necessary for practical applications. Even so, 10–20 times more storage space, depending on the pressure (250–700 bar), is required for compressed hydrogen than for marine fuel oils. LH_2 with cryogenic storage at very low temperatures (−253 °C) requires 4–5 times more storage space than that for marine fuel oils, and more additional space for the equipment and insulation is required to maintain the low temperatures. High pressure and ultra-low storage temperature mean demanding requirements for transport vehicles and fuel tanks, as well as high operational costs. Reduced space for payload and frequent refuelling further reduce the economic competitiveness of hydrogen.

As for the energy producing plants, hydrogen can be used in both ICE and FC systems. Its carbon-free attributes and unique combustion characteristics make hydrogen an excellent fuel for the clean and efficient operation of ICE, with the only harmful emissions being NO_x (White et al., 2006). Due to the high auto-ignition temperature, pure hydrogen engines work most effectively in spark ignition mode, and use port-fuel-injection or direct-injection of gaseous hydrogen, similar to gasoline engines. The low flammability limit of hydrogen makes it ideal for lean combustion, which leads to low NO_x emissions and stable operation under low load conditions. But the low ignition energy and wide flammability limits increase the possibility of abnormal combustion, such as pre-ignition and knock (Dimitriou and Tsujimura, 2017). Regardless of the benefits, hydrogen-fuelled spark ignition engines have less priority for heavy-duty applications than compression ignition engines (Boretti, 2011). However, pure hydrogen compression ignition engines are constrained by limited operating range due to the high auto-ignition temperature. Surface ignition by a glow plug or pre-injection with pilot hydrogen or diesel into a pre-chamber preceding the main hydrogen injection are employed. Smooth operation is difficult to achieve and significant efforts need to be made to achieve performance improvements and a feasible production design for the commercial market (White et al., 2006; Boretti, 2011). Currently, hydrogen engines working in dual-fuel mode seem to have better overall performance in terms of efficiencies, power output and emissions, etc., where the hydrogen fraction of the energy release might be 0–100% (Yan et al., 2018). However, pilot demonstration of a hydrogen engine on board a ship has not been reported so far. Due to the demands for high power densities and low CO_2 and NO_x emissions for future shipping, hydrogen-enriched fuels engines for maritime applications may be a focus of research and development, especially engines using high energy density and low carbon fuels, such as LNG, biodiesels and biogenic alcohols. Another pathway for the utilization of hydrogen is the FC system. FC power systems for maritime applications have been demonstrated by several projects. PEMFCs are directly fuelled by hydrogen and the technologies and applications are mature. Notable fuel cell projects in the maritime sector include ZemShip-Alsterwasser, Nemo H_2, Class 212A/214 Submarines, SF-BREEZE, etc. (Tronstad et al., 2017). However, hydrogen-fuelled PEMFCs could only be used for auxiliary power or propulsion power of small ferries and commercial yachts due to low output power per module, whilst MCFC and SOFC power systems combined fuels with higher energy densities are considered to be more applicable for long-distance shipping (Xing et al., 2021).

Currently hydrogen as an energy carrier has a high carbon footprint from a life-cycle perspective. Hydrogen-using energy technologies face several challenges and hydrogen is costly to produce, transport and store. However, the diversity of potential feedstocks and high proportion of renewable electricity make hydrogen a promising energy carrier in the future. The growth and success of the hydrogen economy depends on technical maturity, infrastructure investment, stringent legislation and policy support in coastal states.

3.2. Ammonia

Out of the synthetic chemicals produced globally, ammonia has one of the largest production capacities. It is mainly used for the production of fertilizers. However, ammonia is also used as a carbon-free fuel and the life-cycle CO_2 emissions depend on the energy sources for ammonia production. Ammonia production is typically based on the Haber-Bosch process, where ammonia is synthesised from nitrogen and hydrogen on Fe-based catalyst at high temperature (300–500 °C) and high pressure (200–350 bar) (Giddey et al., 2017). Nitrogen is normally separated from the air through pressure swing absorption or the membrane filtration method. The feedstock and production of hydrogen are the same as the discussion in Section 3.1, i.e., NG reforming, coal gasification and biomass gasification or reforming are all used for ammonia production. Other approaches for synthesising ammonia include: electrochemical processes using either solid-state electrolytes or molten salts, where the feedstock is nitrogen and hydrogen or nitrogen and water; photosynthetic processes, where ammonia is synthesised from nitrogen and water but that process is currently economically unfeasible (Lan et al., 2012; Amar et al., 2011). Therefore, green ammonia production, similar to hydrogen production, depends on simultaneous CO_2 sequestration and utilization of renewable electricity.

Ammonia is stored on a large scale at −33 °C and ambient pressure in insulated tanks. Small quantities of ammonia are stored in the same manner as LPG and in stainless steel spheres, at ambient temperature and 8 bar vapour pressure. Due to the risk of explosion and high toxicity of liquid ammonia, safety in transportation and end uses are very important considerations (Klerke et al., 2008). Ammonia as an energy carrier has been promoted by its safe storage in solid form such as metal amine salts, e.g., $Mg(NH_3)6Cl_2$ and $Ca(NH_3)_8Cl_8$, ammonium carbonates or urea, which solves the safety issues arising from liquid ammonia with slightly increased volumetric density and storage mass (Lan et al., 2012). Ammonia stored in solid form can be released by heating, reaction or hydrolysis. However, recycling of metal salts or CO_2 emissions produced during ammonia regeneration would result in new challenges and additional costs.

The power producing systems utilizing ammonia include directly fuelled ICE, directly fuelled FC systems and indirect hydrogen storage materials. Using pure ammonia as a fuel for ICE has been tried and investigated by several researchers (Rehbein et al., 2019). However, glow plugs or pilot fuels have to be used to initiate the combustion process in both spark ignition and compression ignition engines due to the high auto-ignition temperature, low flame velocity and narrow flammability limit (Giddey et al., 2017). To improve combustion performance, mixtures of ammonia and other fuels in direct fuel or dual-fuel engines may be a better choice. Of course, the challenges of possible NO_x, ammonia and CO_2 emissions still exist, and continuing effort is required to maximize efficiency and minimize emissions. Ammonia could be used as direct fuel for FC systems, where ammonia-fuelled SOFC attract more research interest due to the decomposition of ammonia under high operating temperature and over catalysts (Ni et al., 2009; Cinti et al., 2016). Direct ammonia alkaline/alkaline membrane FC and direct hydrazine/ammonia borane FC systems are also possible options (Lan et al., 2012; Afif et al., 2016), but are probably not suitable for ship propulsion due to low power densities. Ammonia is easier and less expensive to transport and store than hydrogen, and has higher volumetric energy density, well-established infrastructure and relatively mature operational experience. Therefore, there is an increasing interest in using ammonia as an indirect hydrogen carrier (Amar et al., 2011). As a hydrogen carrier, ammonia can be decomposed or cracked with the support of a heat source and catalyst to produce hydrogen and nitrogen. Hydrogen separation and purification technologies may also be required for scrubbing nitrogen and residual ammonia depending on the intended use of the hydrogen and the supporting heat source and catalyst purity level.

3.3. Renewable natural gas (RNG)

NG, in either liquefied or compressed gas states, has been used as a substitute for marine fuel oils to meet the regulations on ship SO_x and NO_x emissions. NG as a marine fuel has the maximum energy density by mass and minimum carbon emissions per unit of energy release among hydrocarbon fuels. Theoretically it is capable of reducing 20–25% carbon footprint compared to conventional marine fuel oils (Fernández et al., 2017), although practically it is supposed to achieve 12–20% carbon emissions reduction considering possible methane slip with a global warming potential (GWP) of 25 (Ushakov et al., 2019; Hwang et al., 2019). However, using fossil NG, improving ship energy efficiency and using alternative energy sources are not enough to attain the levels of ambition in 2050 set in the Initial IMO Strategy (CE Delft and UMAS, 2019). Therefore, fossil NG would inevitably need to be substituted by zero carbon or carbon-neutral fuels, or carbon-neutral feedstock and synthesis approaches would need to be used to produce RNG.

NG could be synthesised from fossil fuels, biomass or power-to-gas systems. Considering the limited long-term potential of fossil NG, RNG produced from biomass or power-to-gas systems is investigated in this section. The feedstocks for RNG from biomass include all kinds of biomass containing proteins, lipids, carbohydrates, cellulose and hemicelluloses as main components, such as agricultural wastes, municipal wastes, crop residues and energy crops (Weiland, 2010). Anaerobic digestion is the predominant technology for methane production compared to other biochemical and thermochemical processes, e.g., thermal gasification of organic biomass or the Sabatier reaction. Four stages are involved in the biomethane (known as 'biogas') fermentation process, i.e., hydrolysis, acidogenesis, acetogenesis and methanogenesis (Appels et al., 2008; Zheng et al., 2014). RNG from power-to-gas systems is similar to the production of other electrofuels, e.g., hydrogen and methanol, and excess power or off-peak power from renewable energy sources can be used. Hydrogen produced by water electrolysis from renewable energy is combined with CO_2 captured, e.g., from industrial processes, to produce methane through a catalytic or biological methanation reaction (Götz et al., 2016; Bailera et al., 2017).

NG can be stored below -163 °C in the liquefied state or above 200 bar in the compressed gas state. RNG has similar physicochemical, combustion and emissions properties and infrastructure requirements to fossil NG. Therefore, the transportation and storage of RNG in the cryogenic or pressurized state are costly and have low energy-efficiency. Construction of infrastructure, global distribution and bunkering of RNG have many technical challenges.

The end use power plants for RNG include ICE and high temperature FC systems. Currently, NG-fuelled dual fuel ICE, using either compression ignition or ignited by pilot fuel, is the primary option. NG-fuelled compression ignition engines have comparable economics with conventional diesel engines, but aftertreatment technologies are required to reduce NO_x emissions. NG-fuelled ICE with pilot fuel can meet IMO NO_x Tier III standards at the cost of slightly reduced overall fuel economy. Compared to other petroleum fuels, NG has the best emissions performance for low carbon shipping in the near future. So far, several hundred NG-fuelled ships are in operation or on order, since no other options are technically mature or economically viable. NG-fuelled FC power systems used for ships have been demonstrated by some research projects including FellowSHIP and FELICITAS, where MCFC and SOFC were used as the testing platform (Tronstad et al., 2017).

Fossil-based LNG or compressed natural gas (CNG) would inevitably be a transition fuel on the path to carbon-neutral fuels. Fossil NG is relatively competitive with conventional marine fuels in terms of cost, operational safety and emissions performance, and the potential for better life-cycle carbon footprint using RNG has been verified. However, higher price for RNG, limited production volume, and strict requirements for transportation and storage mean that its prospects for maritime applications are not so optimistic. In addition, considering the minimum 20-year lifespan of a ship and uncertain future regulations, the current time window for new-building and retrofit of NG-fuelled ships is short and large-scale investment in infrastructure is not recommended because of this.

3.4. Renewable methanol

Methanol is a low flashpoint and sulphur-free liquid alcohol fuel, with lower exhaust emissions and carbon footprint than conventional marine fuels, but easier to transport and store than NG, DME, hydrogen and ammonia.

Methanol is traditionally produced in three steps, i.e., syngas production, methanol synthesis and processing of crude methanol. The majority of feedstock for methanol production is NG and other feedstocks include coal, oil, biomass, wastes and even CO_2 (Riaz et al., 2013). Renewable methanol, chemically identical to conventional methanol, is mainly produced from second generation biomass, such as forest residues, agriculture residues, municipal solid waste and black liquor produced from the pulp and paper industry (Santasalo-Aarnio et al., 2020). It has the same production process as conventional methanol and is regarded to be carbon-neutral if renewable energy is used for the production processes (Svanberg et al., 2018). Methanol is an important electrofuel which can be produced by catalytic synthesis of CO_2 captured from industrial processes and hydrogen electrolysed by renewable electricity, known as Power-to-Liquid (PtL) (Ganesh, 2014; Varone and Ferrari, 2015). In addition, glycerol, a by-product from biodiesel production, can be used as feedstock for renewable methanol production. Large-scale methanol production based on PtL systems or glycerol have both been operated at scale by some commercial projects (Andersson and Salazar, 2015). Currently, annual production of methanol is estimated to be more than 100 million tonnes, though most of that is not renewable and is derived from NG and coal (Andersson and Salazar, 2015). By comparison, the production costs of renewable methanol are estimated to be 1.5 to 4 times higher than fossil-based methanol production. However, the methanol industry is global and methanol could be made available in major port terminals globally. Considering the sustainable supply and wide distribution, both the mid-term and long-term potential of methanol as marine fuel are worth investigating.

Methanol can remain liquid at ambient temperature and pressure. So, there are no major barriers for transportation, storage and bunkering, compared with conventional fuels apart from minor modifications to accommodate the low flashpoint. No massive investments are required for new infrastructure. However, some disadvantages exist. Primarily, around double the storage space is required due to the energy density of methanol being approximately half that of conventional marine fuels. Secondly, although still involving storage, there is the potential for corrosion issues due to the incompatibility of methanol with some materials (Ellis and Tanneberger, 2015). In addition, methanol is defined as having acute toxicity for humans, necessary protective measures and contingency plans in case of a spill are required to be prepared in advance to avoid potential internal ingestion, skin contact and respiratory inhalation.

The end use power plants for methanol are ICE and FC systems. Methanol has already been used in ICE in road transport due to its better combustion and wide availability. Methanol-gasoline blends used for spark-ignition engines typically have methanol fractions of 10%, 20% and 85% by volume (namely M10, M20, and M85 respectively), and have been successfully commercialized since the 1980s. Due to the low cetane number and long ignition delay of alcohol fuels, it is not viable to use pure methanol in compression ignition engines. Methanol-diesel blends have a typical methanol proportion of 5–30% and additives are required to prevent phase separation (Sayin, 2010; Jamrozik, 2017). Methanol-biodiesel-diesel blends have received considerable attention as well (Paulauskiene et al., 2019; Yilmaz, 2012; Qi et al., 2010b). However, the low content of methanol in methanol-diesel blends limits the potential for reducing carbon emissions. For maritime applications, compression ignition engines fuelled by methanol and diesel have worked in dual-fuel mode. In recent years, a number of research projects have been undertaken using methanol as an alternative fuel in marine diesel engines, e.g., Effship, SPIRETH, Pilot Methanol, MethaShip and LeanShips (Ellis and Tanneberger, 2015). The engine manufacturers Wärtsilä and MAN have developed methanol dual-fuel medium speed four-stroke and slow speed two-stroke marine engines with pilot ignition. Their initial practical applications included the world's first methanol-fuelled Ro-Pax ferry *Stena*

Germanica in 2015 and Waterfront Shipping 50,000 DWT chemical tankers in 2016 (Ellis and Tanneberger, 2015). In addition, a number of research projects have demonstrated methanol-fuelled FC power systems for maritime applications, such as METHAPU Undine, E4Ships Pa-X-ell MS Mariella and RiverCell. The types of FC tested mainly include direct methanol fuel cells, SOFC and high temperature PEMFC (Tronstad et al., 2017).

3.5. Bioethanol

Ethanol is also a low flashpoint and sulphur-free liquid alcohol fuel, with lower exhaust emissions and carbon footprint than conventional marine fuels but with easier transportation and storage than NG, DME, hydrogen and ammonia. Ethanol has similar combustion properties and emissions reduction potential to methanol.

Ethanol can be produced through hydration of ethylene or fermentation of sugars. Nowadays, almost all ethanol is derived from biomass, especially in the United States, Brazil and Europe. The three important groups of feedstocks are (1) starchy and sugar feedstock such as corn, beets and sugarcane (Balat and Balat, 2009; Mojović et al., 2009), (2) cellulosic feedstock such as agricultural residues, grass and wood (Alonso et al., 2010; Haq et al., 2016), and (3) recently algae feedstock including microalgae and macroalgae (Ramachandra and Hebbale, 2020). The area harvested globally, yields and the main producing countries for bioethanol feedstock are shown in Table 2. Currently, bioethanol is the most abundant biofuel produced in the world. The global bioethanol production was about 87 million tonnes in 2019, when the top two bioethanol producers, USA and Brazil, accounted for around 85% of total production. Therefore, the geographical distribution is extremely uneven and the production potential of the rest of the world is limited due to food demands and growth conditions for crops (RFA, 2019; Popp et al., 2014).

Bioethanol can remain liquid at ambient temperature and pressure, therefore there are no serious barriers for transportation, storage and bunkering, so it does not require the large infrastructure investment associated with hydrogen or NG. Similar to methanol, it requires more storage space than conventional marine fuel oils due to its lower energy density and there are some compatibility issues due to the corrosion of some materials (Ellis and Tanneberger, 2015).

The end use power system for ethanol is primarily the ICE. Ethanol has been blended with gasoline to meet the requirements of road transport for many years. Ethanol-gasoline blends, with typical ethanol contents of 10%, 15% and 85% by volume (namely E10, E15, and E85 respectively), could be used in gasoline engines directly, but minor engine modifications might be required for the use of high ethanol content blends (Balat and Balat, 2009). Ethanol is not commonly used as the only fuel in compression ignition engines due to the low cetane number. Ethanol-diesel blends with an ethanol content of up to 15% could be used in compression ignition engines without modifications. Significant reductions of NO_x and PM emissions and slightly increased specific fuel consumption compared to diesel oil have been reported by several researchers (Sayin, 2010; Jamrozik, 2017). However, there is a phase separation problem similar to that of methanol-diesel blends, and the limit for being premixed with diesel is less than 30% ethanol content by volume (Torres-Jimenez et al., 2011; Rakopoulos et al., 2008). Therefore, dual-fuel mode is the most promising option for maritime applications, and more demonstrations on bioethanol and its blends are required. So far, no projects have been identified for ethanol applications on marine diesel engines or FC.

3.6. BioDME

DME is a gaseous fuel under ambient conditions physically similar to LPG and can be combined with propane in cooking gas and electricity generation. In recent years, DME has developed as a transport fuel and DME-fuelled heavy duty vehicles have been developed by several vehicle makers (Semelsberger et al., 2006).

There are two pathways for DME production: the indirect method by catalytic dehydration of methanol, which is currently the primary method; and the direct method by synthesis from syngas over a catalyst, which is under development since methanol itself is synthesised from syngas (Peral and Martín, 2015). Therefore, the feedstocks are similar to that of methanol and syngas, and include NG, coal, oil, biomass, wastes and even CO_2. As the name implies, bioDME is produced from renewable methanol or syngas from biomass.

DME can be liquefied at below -25 °C or above 5 bar. The requirements for transportation and storage of DME are less challenging than for LNG and hydrogen; they are similar to LPG and ammonia, and greater than for MDO, methanol and bioethanol.

Table 2
Crops/bioethanol yields and main harvesting country. Data: Area harvested globally in 2017, averaged crop yields and main harvesting country (FAOSTAT, 2019; WBA, 2019); ethanol yields (Ramachandra and Hebbale, 2020; Haq et al., 2016).

Crops	Area harvested globally in 2017 (million ha)	Averaged crop yields (tonnes/ha/year)	Ethanol yields (tonnes/ha/year)	Main harvesting country
Wheat	219	3.5	0.4–0.6	China, India, Russia, USA, France
Maize	197	5.8	0.5–1.5	USA, China, Brazil, Argentina, Indonesia
Rice	167	4.6	0.8–1.7	China, India, Indonesia, Bangladesh, Viet Nam
Barley	47	3.1	0.2–0.5	Russia, Australia, France, Germany, Ukraine
Sorghum	41	1.4	0.3–1.0	USA, Nigeria, Mexico, Ethiopia, India
Sugarcane	26	70.8	2.8–6.3	Brazil, India, China, Thailand, Pakistan
Cassava	26	11.1	1.3–8.7	Nigeria, Congo, Thailand, Indonesia, Ghana
Potatoes	18	20.8	0.8–2.2	China, India, Ukraine, Russia, USA
Sweet potatoes	8	11.4	1.1–6.6	China, Malawi, Tanzania, Nigeria
Sugar beets	5	61.4	1.1–4.3	Russia, USA, Germany, France, Turkey
Sweet sorghum	–	45–80	1.4–4.2	–
Algae crops	–	730	18.5	–
Lignocellulosic materials	–	–	350 *	–

Note: *-million tonnes/year. ha-hectare.

Moderate handling properties make infrastructure and bunkering relatively simple and inexpensive compared to LNG and hydrogen. But double sized fuel storage tanks are required compared to diesel due to the lower volumetric energy density.

DME has been widely tested and applied as an alternative fuel in road transportation. Currently, DME is used as a direct substitute for diesel. The higher cetane number and lower auto-ignition temperature than that of diesel result in better combustion and higher efficiency. In addition, diesel engines operating on DME have reduced emissions, especially NO_x and PM emissions (Zhu et al., 2012; Arcoumanis et al., 2008). Minor modifications to auxiliary engine systems may be required, but no modification to the core engine should be needed. The notable demonstration case for shipping is the SPIRETH project, where DME produced by the conversion of methanol on board is used as fuel in an adapted auxiliary diesel engine (Ellis and Tanneberger, 2015). Direct DME FC are under development (Serov and Kwak, 2009; Vassiliev et al., 2019), but these are not currently significant for maritime applications due to immature technology and a lack of competitiveness compared to other alternative fuels. High thermal efficiency, low exhaust emissions, reduced noise levels, no toxicity and biodegradability are the primary advantages of DME-fuelled ICE. However, as a methanol derivative, bioDME has higher production costs and life-cycle carbon emissions, lower annual production, more challenging transportation and storage, and no better combustion characteristics than methanol and ethanol. Therefore, bioDME as alternative marine fuel is less competitive than renewable methanol and bioethanol. In addition, the current global annual production capacity of DME is approximately 10 million tons (Fleisch et al., 2012). Hence, DME would need to progress significantly in order to be used extensively in the maritime application.

3.7. Biodiesels

There are different types of biogenic diesel, such as FAME, fatty acid ethyl esters, hydrogenation-derived renewable diesel (HDRD) including HVO and F-T diesel, depending on the production processes.

Traditionally, FAME (namely the first-generation of biodiesel) is a mix of mono-alkyl esters of long chain fatty acids with similar chemical composition to mineral diesel (Ahmad et al., 2011; Shahid and Jamal, 2011; Janaun and Ellis, 2010). FAME is typically produced by a chemical reaction between vegetable oils or animal fats and short chain alcohol with or without a catalyst. More than 350 oil-bearing crops are identified to be potential feedstock of biodiesel, which can generally be classified into four groups: edible vegetable oil; non-edible vegetable oil; waste oil; and animal fats (Atabani et al., 2012). The current area harvested globally, yields and main producing countries of biodiesel feedstock are shown in Table 3. Vegetable oils and animal fats mainly consist of triglycerides, diglycerides and a small fraction of monoglyceride with long chains and large size molecules, which results in large molecular weight, high viscosity, low volatility, poor stability and combustion performance (Sakthivel et al., 2018). Therefore, vegetable oils and animal fats need to be processed for better application in conventional diesel engines (Shahid and Jamal, 2011). Four types of process, i.e., transesterification, micro-emulsion, pyrolysis and dilution, could be used to overcome the existing problems of crude vegetable oils and animal fats. However, transesterification is the most commonly used, which is an easy and cheap way for production of high-quality biodiesel (Singh and Singh, 2010; Demirbas, 2009). Types of alcohol used for the transesterification process could be methanol, ethanol, isopropanol or butanol. Methanol is the most commonly used alcohol because of its lower price. Chemically, triglycerides, diglycerides and monoglycerides react with methanol and the final products are FAME and glycerol. Catalysts play an important role in the transesterification process and sodium hydroxide or potassium hydroxide are generally used (Shahid and Jamal, 2011).

Aside from ester-based biodiesel produced by the transesterification process, there are two other types of biodiesel derived from biomass, i.e., HDRD and biogenic F-T diesel, which are often discussed when alternative marine fuels are investigated. HDRD such as HVO, can be produced from the same feedstock as FAME, e.g., vegetable oils and animal fats, through a hydrotreating process. However, HDRD can be produced from a wider range of feedstock than FAME, and lignocellulosic feedstock, such as agricultural residues, forest residues, pulp and paper waste/by-product, are available with additional processing prior to hydrotreatment (Wong et al., 2016). The product of the process is paraffinic diesel and the plant capital costs are higher than that of transesterification process. HDRD has better NO_x emission, storage stability and cold flow properties than FAME. Another advantage of the hydrotreating process is that existing refining technology and equipment used for the production of diesel oil can be applied to produce HDRD. The F-T process, which is traditionally used for the production of liquid fuels from coal or NG, could be used as liquid or gaseous biofuel conversions. Based on a BtL system, the production process of biogenic F-T diesel includes gasification of biomass, conditioning of the produced syngas, and subsequent synthesis of biodiesel. The chemical reactions occur typically at temperatures of 150–300 °C and pressures of one to several tens of atmospheres in the presence of metal catalysts. The F-T process is suitable for all kinds of biomass and the product is paraffin. But the plant capital costs are dramatically higher than that of the transesterification process (Kim et al., 2016; van Vliet et al., 2009). HDRD and F-T diesel might have the same feedstock as biodiesel, yet their chemical composition and physical properties are different to some extent due to different processing pathways. At present, HDRD and F-T diesel are at the early stage of commercial application and more research and testing are required (Noor et al., 2018). However, it may be of interest to mention that HVO, one type of HDRD, is now a commercial product and produced in large quantities by some oil companies, such as Neste in Finland and Preem in Sweden.

Currently, global biodiesel production is approximately 35–45 million tonnes annually. Meanwhile, the markets and investment in biofuels are growing slowly owing to a number of factors including policy uncertainty, increased competition for feedstock, adverse conditions for crop productivity, and concerns about the sustainability of production. The production capacity influences the future prospects of biodiesels (Popp et al., 2014).

Biodiesel and its blends have been widely used in diesel engines directly, especially in Europe. Currently, primary marine engine makers, such as MAN, Wärtsilä, Yanmar, Cummins, Caterpillar, etc., have claimed that their engines can use 5–30% and even up to 100% biodiesel blends with or without engine modifications (Noor et al., 2018). Biodiesel has good combustion characteristics (dos Santos Prucole et al., 2014) and emissions performance (Xue et al., 2011; Kumar et al., 2013). Reduced carbon emissions on a lifecycle basis make it a promising alternative fuel for future shipping, if environmentally friendly production processes and renewable energy are adopted. Disadvantages of biodiesel compared to diesel include lower volatilities, excessive gum polymerization in engines, lower oxidation stability, relatively higher NO_x emissions (Atabani et al., 2012), some material compatibility issues (Sorate and Bhale, 2015; Fazal et al., 2011), engine durability problems (Fazal et al., 2011), higher production costs (Sadeghinezhad et al., 2013), and growing demand for land and water resources for feedstock supply (Atabani et al., 2012). Therefore, a promising pathway is to use mixtures of biodiesels or dual-fuel systems, with the secondary fuel

Table 3
Crops/biodiesel yields and main harvesting country. Data: Area harvested globally in 2017 and averaged crop yields (FAOSTAT, 2019a; FACTFISH, 2019); oil yields (Atabani et al., 2012, 2013; Ashraful et al., 2014; Mahmudul et al., 2017; Singh and Singh, 2010); main harvesting country (Noor et al., 2018; Atabani et al., 2012; Mofijur et al., 2013; Mahmudul et al., 2017).

Crops	Area harvested globally in 2017 (million ha)	Averaged crop yields (tonnes/ha/year)	Oil yields (tonnes/ha/year)	Main harvesting country
Soybean	123.6	2.9	0.4–0.6	USA, Brazil, Argentina
Rapeseed	34.7	2.2	0.8–1.0	Canada, China, India, Australia, France
Cottonseed	33	1.3	0.2–0.3	India, USA, China, Pakistan, Brazil
Peanut	27.9	1.7	0.8–0.9	China, India, USA, Nigeria
Sunflower	26.5	1.8	0.5–0.6	Russia, Ukraine, Argentina, Romania, China
Palm	21.3	3.1	0.9–1.9	Indonesia, Malaysia, Nigeria, Thailand
Coconut	12.3	4.9	3.1–3.2	Philippines, Indonesia, India
Olive	10.8	1.9	0.9–1.3	Spain, Tunisia, Italy, Morocco, Greece
Linseed	2.8	1.1	0.5–1.0	Kazakhstan, Russia, Canada, India, China
Castor	1.3	1.4	0.5–1.0	India, Mozambique, Brazil, China
Jatropha	–	–	2.0–3.0	India, Indonesia, Philippines, Thailand, China
Mahua	–	–	1.0–4.0	India
Jojoba	–	–	1.6	Mexico
Algae	–	–	52.8–123.2	–
Waste oil	–	–	–	USA, UK, China, Japan, Mexico
Animal fat	–	–	–	Canada, Ireland, Mexico, New Zealand

including diesel (Chauhan et al., 2013; Geng et al., 2017b; Qi et al., 2010a; Ali et al., 2016; Bajpai et al., 2009; Kalligeros et al., 2003), methanol (Mat Yasin et al., 2014; Jiao et al., 2019) and some low carbon gaseous fuels. Several projects have demonstrated the viability of diesel-fuelled FC systems, e.g., E4Ships-SchIBZ MS Forester, US SSFC and MC-WAP (Tronstad et al., 2017). However, considering the production process on land, and reforming and purification prior to the use on board, biodiesels are not recommended by this study to be used as fuels of FC for maritime applications due to the immature technologies of FC, the complexity of on board fuel processing systems and the high costs. The focus of research and development should be on the optimization and improvement of biodiesel-fuelled internal combustion engines.

4. Comprehensive evaluation on alternative marine fuels

4.1. Review on evaluation criteria

Different alternative marine fuels have different performances in terms of technical, environmental, economic and social perspectives. Technical characteristics, environmental performance as well as costs, feedstock security, transportation, storage and infrastructure vary for different fuels, which means that the upstream and downstream elements of the industrial chain of alternative fuels would influence their potential for maritime applications. However, the criteria for evaluating these fuels often conflict with each other, which makes it difficult for shipping stakeholders to select the best option from a wide range of alternative marine fuels. According to existing studies, the possible evaluation criteria for decision making regarding alternative marine fuel options are shown in Table 4.

4.2. Determination of decision-making framework

Traditional decision-making tools for dealing with maritime issues, e.g., cost-benefit analysis and marginal cost analysis, are not suitable for the selection of alternative marine fuels due to the complexities of the problem, particularly the extra political and social considerations. Consequently, the MCDA (Ren and Lützen, 2017; Ren and Liang, 2017; Hansson et al., 2019) and AHP (Deniz and Zincir, 2016; Guerra and Jenssen, 2014) methods have been employed by several researchers. However, interrelations amongst sub-criteria, linguistic deviations, preferences of experts and preferences of stakeholders make it difficult to deliver a convincing conclusion (Ölçer and Ballini, 2015). In particular, the preferences of stakeholders could significantly influence the weighting of different criteria, which could lead to conclusions that are not perceived as impartial and acceptable by the wider maritime industry, causing delays and reducing the effectiveness of policies and regulations. Generally speaking, government authorities prioritize environmental and social criteria. But ship owners or ship operators, fuel providers and equipment manufacturers give priority to the economic and technical criteria (Hansson et al., 2019). Therefore, a viable option must meet a wide range of criteria and any of the technical, environmental, economic and social aspects should not be ignored. However, goal-based decision making should be the first principle and achieving the goal of emissions reduction over its life-cycle is the principal requirement for the adoption of policies and regulations.

As a consequence of the above, a decision-making framework incorporating multiple dimensions (including theoretical and practical considerations, technical, environmental, economic and social aspects, global and country specific interests, as well as in-sector and out-of-sector factors), rather than an approach for evaluating the individual trade-off options, is considered by the authors to be more viable for the selection of alternative marine fuels, especially in light of the fact that urgent action is required to facilitate early adoption. In order to avoid the delays associated with attempting to reconcile innumerable interrelations and conflicts amongst sub-criteria, a decision-making framework is suggested here and shown in Table 5. The approach taken revolves around the creation of simplified (but representative) evaluation criteria and appropriately sub dividing the life-cycle pathways for alternative marine fuel options, allowing different treatments to be utilized for the different criteria as required. By simplifying the chosen approach in this way, meaningful qualitative or quantitative evaluation can be conducted for the various alternative marine fuel options.

4.3. Analysis on key characteristics

To evaluate the potential of certain alternative fuels, technical availability and low climate impact are taken as the principal criteria in this study, whilst economic and social aspects are put in a secondary position. Correspondingly, three key characteristics are given special attention, which are feedstock security, applicability on board a ship and GWP. These three characteristics are chosen as the key performance indicators to answer the following three

Table 4
Possible evaluation criteria for alternative marine fuel options.

Sources	DNV GL (2019)	Hansson et al. (2019)	Ren and Liang (2017)	Deniz and Zincir (2016)
Criteria	**Applicability:** • energy density • technological maturity • flammability and toxicity • regulations and guidelines **Economics:** • energy costs • capital costs **Environment:** • climate change • air pollution **Scalability:** • main current usages • availability • global production capacity and locations	**Technical:** • available • infrastructure • reliable supply of fuel **Economic:** • investment cost for propulsion • operational cost • fuel price **Environmental:** • acidification • health impact • climate change **Social:** • safety • upcoming legislation	**Technological:** • maturity • reliability • capacity **Economic:** • capital cost • operational cost **Environmental:** • CO_2 emissions • NO_x emissions • SO_x emissions • PM emissions **Social:** • compliance with regulations • social acceptance	• ship safety • global availability • bunker capability • durability • adaptability • compliance with regulations • engine performance • engine emissions • engine components • commercial issues • costs

Table 5
Decision making framework for alternative marine fuel options based on a life-cycle pathway.

Criteria	Well-to-tank				Tank-to-wake		
	Feedstock	Transportation	Production	Distribution, storage and bunkering	On board storage	End use	
						ICE	FC
Technical availability	✓	✓	✓	✓	✓	✓	✓
Safety	✓	✓	✓	✓	✓	✓	✓
Available infrastructure	–	✓	✓	✓	–	–	–
Reliable supply of fuel	✓	–	–	–	–	–	–
Investment cost for infrastructure	✓	✓	✓	✓	–	–	–
Investment cost for plants	–	–	–	–	✓	✓	✓
Operational cost	✓	✓	✓	✓	✓	✓	✓
Climate change	✓	✓	✓	✓	- **	✓	✓
Air pollution *	–	–	–	–	- **	✓	✓

Notes: √ applicable; - not applicable; * well-to-tank air pollution is neglected supposing effective land-based abatement measures available; ** environmental impact has been covered in end uses.

questions: Is the global supply of the fuel guaranteed? Can the fuel go on board a ship? Can the fuel achieve the goal of emissions reduction? Simplifying a complex issue is believed to help reach a consensus among stakeholders, which is especially important for the international maritime industry that uses multilateral negotiations as a working mechanism. Technical availability covers several indicators. However, owing to the unique requirements of transport applications, i.e., payload and restricted storage space, energy density is an important parameter when the applicability of alternative fuels on board a ship is considered.

4.3.1. Feedstock

To reduce carbon emissions in the shipping industry, conventional fossil fuels including LSHFO, MDO, NG and LPG would eventually need to be excluded, even though NG has the minimum amount of carbon emissions per unit of energy release out of this group. However, fossil raw materials are still important feedstock to produce low carbon or zero carbon fuels such as hydrogen, ammonia, RNG and renewable methanol, once carbon sequestration is available during fuel processing. However, extensive applications of these fuels are limited by technical and economic aspects at present. Biomass is an important kind of feedstock to produce carbon-neutral fuels such as RNG, biomethanol, bioethanol, bio-DME and biodiesels, once renewable energy is used for the well-to-tank process.

Admittedly, it appears unrealistic to substitute marine fuels completely with biofuels because of several constraints. Firstly, regardless of technical and economic aspects, at least 450 million tonnes of oil equivalent marine fuels, about 20 EJ (1 EJ $= 10^{18}$ J) of energy will be needed annually for the shipping sector in 2050 based on the estimated annual fuel consumption in 2012 and projections based on business-as-usual scenarios (IMO, 2015). The transport sector represents nearly 30% of world energy consumption, and was equivalent to about 2.8 billion tonnes of oil consumption in 2017 (IEA, 2018). With the expansion of the world population and the economic growth of developing countries, the fuel demands of the transport sector are expected to increase continually. However, only 13 billion hectares (ha) of land area is available globally, and agricultural land accounts for 37% and forest land accounts for 31% currently. For agricultural land, almost 70% is permanent pastures and meadows, and about 30% is arable land. Based on the yields of agricultural crops and the derived biofuels, all existing arable land in the world could not meet the fuel requirements of the transport sector (WBA, 2019; FAOSTAT, 2019b). Secondly, even if the second and third generation biofuel technologies are well-developed, and non-edible crops, algae, forestry residues, municipal wastes, and agricultural wastes and residues are utilized, the demands for land, water and forest resources still constrain the sustainability of biofuels. The theoretically sustainable potential of global bioenergy is estimated to be 200–500 EJ/year, considering the various constraints (Popp et al., 2014). But most bioenergy is used for cooking, heating and electricity generation, while only a very small share is used to produce transport fuels due to low conversion efficiency and high costs. For example, the share of biofuels was only 4.98 EJ in the total 55.6 EJ of biomass supply in 2017, and the contribution of biofuels to the transport sector was about 3.5 EJ (WBA, 2019). Finally, the uncertainty of fuel supply is a big challenge because almost all energy-consuming sectors need to reduce carbon emissions and especially the growth of crops is dramatically influenced by geographical location, season, climate and other natural conditions outside of human control (Taljegard et al., 2014). Therefore, alternative marine fuels using biomass as the only feedstock are not reliable for fuel supply. Carbon-free fuels from fossil raw materials that employ carbon sequestration during the production process, or carbon-free and carbon-containing fuels from a wide range of renewable feedstock other than fossil raw materials, have stronger potential.

4.3.2. Energy densities

As is the case with most forms of transport vehicles, ships require fuels that deliver high energy release per unit volume and per unit mass in order to maximize the space and weight capacity available for carrying payload. Therefore, the energy density of fuels must be a primary consideration and should not significantly reduce the original range and payload of the vessel. The energy density of different marine fuels is compared in Fig. 4. Hydrogen has a high energy density by mass, but a low energy density by volume, however, its potential for CO_2 saving is dramatic. Therefore, compressed or liquefied hydrogen is only suitable for some ships that are not sensitive to reduced space, e.g., ships for high-density cargo, Ro-Pax, ferries, non-cargo ships and short sea shipping. As a substitute for hydrogen, ammonia is a carbon-free fuel with a more balanced compromise of energy density between mass and volume. 2–3 times more mass and storage space than that for marine fuel oils could be relatively acceptable in the industry. Technical maturity for on board equipment for using ammonia and the upstream availability are the key challenges. From the perspective of energy density, LNG, CNG, LPG, methanol, ethanol, biodiesel and DME are all acceptable.

4.3.3. Global warming potential

GWP indicates the climate impact of greenhouse gas emissions and the total impact of CO_2, nitrous oxide and methane is usually expressed by CO_2 equivalent. The decarbonization potential of an alternative marine fuel depends on its overall life-cycle emissions rather than just the operational emissions. However, upstream or out-of-sector emissions are not typically considered in the maritime sector. Through evaluation and comparison of both well-to-tank and tank-to-wake emissions, the advantages, disadvantages and potential opportunities of alternative marine fuels could be identified. GWP for some typical alternative marine fuel options is shown in Fig. 5. There are no significant differences for tank-to-wake emissions of carbon-containing fuels from fossil raw materials, while the tank-to-wake emissions of carbon-neutral fuels are zero due to the carbon fixation of biomass growth or the uses of renewable energy. However, the well-to-tank emissions of alternative fuels depend strongly on the types of feedstock and the primary energy sources of heat and electricity for fuel production. Hence, the life-cycle emissions of zero carbon fuels could possibly be higher than that of conventional marine fuels (Bhandari et al., 2014). Overall, the life-cycle GWP of biomass-based fuels is better than that of conventional marine fuels, but their limited application is a consequence of their small production quantities and high costs. However, it is hard to say that biofuels are clearly carbon-neutral, even though carbon fixation is happening during the processes of crop growth. Moreover, there are notable GWP differences for biofuels according to the type and origin of the feedstock. The pathways to low carbon maritime transportation depend strongly on the renewable feedstock as well as the renewable energy and carbon sequestration for fuel production.

5. Discussion and perspectives

Diversification and decentralization are perceived to be the inevitable choice of future maritime power and fuels. However, for international maritime transportation, a unified fuel is suggested to be determined as early as possible due to the characteristics of global shipping and the pressure of climate impact. In this paper, the authors focused on finding the promising pathways for future low-carbon maritime transportation based on their understanding of the lifecycle characteristics of alternative fuels and their professional knowledge and experience. Some possible pathways are recommended for global shipping and local or regional shipping, where the emissions performance, volumetric energy densities and global availability of fuel supply are the key evaluation criteria. However, in recognition of the innumerable possible combinations of issues experienced by individual operators, the recommendations are presented as a general profile which cannot possibly cover all specific cases. The authors realize that there are remarkable differences about ship types and trading areas and there are also significant differences about feedstock production and fuel supply in different countries and regions. Consequently, the purpose of the

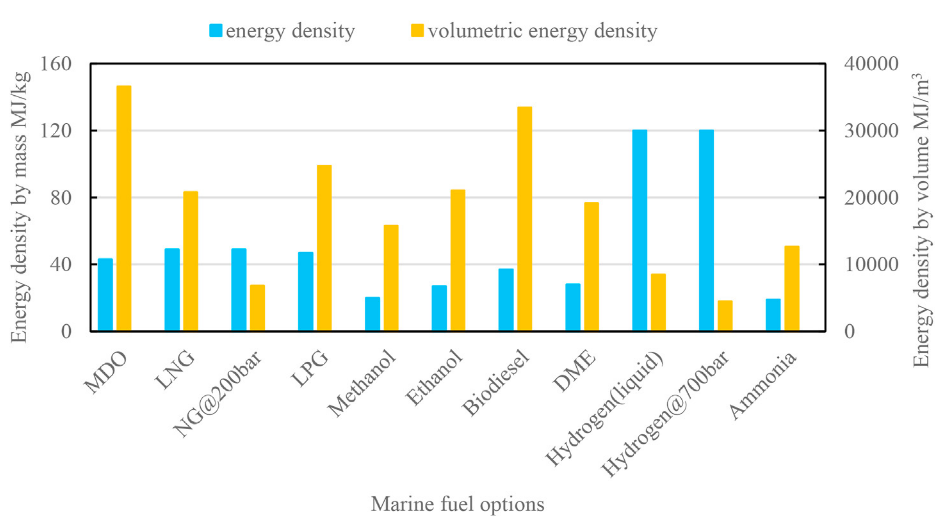

Fig. 4. The comparison of energy densities for different marine fuel options. Data: NG, LPG, methanol, hydrogen and ammonia (Zamfirescu and Dincer, 2008; Reiter and Kong, 2011); MDO, ethanol (Yusri et al., 2017); biodiesel (Noor et al., 2018); DME (Zhu et al., 2012).

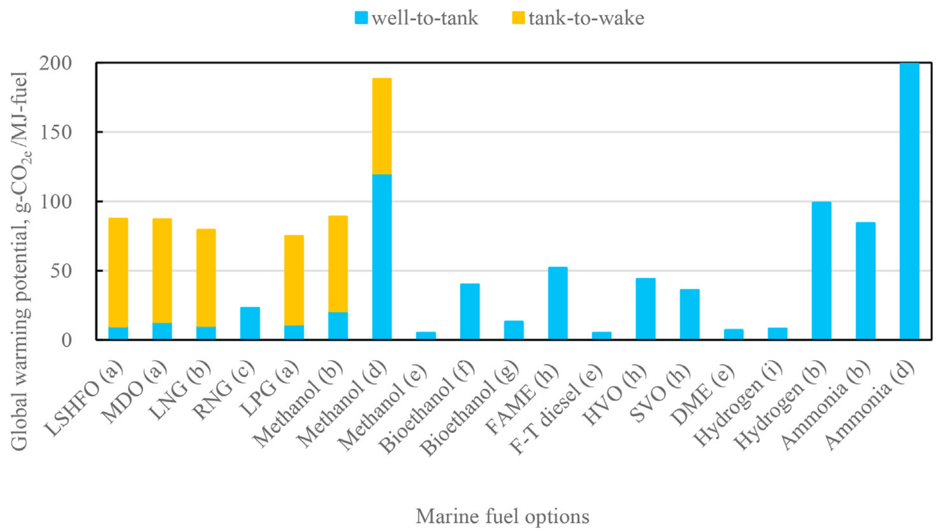

Fig. 5. GWP for different marine fuel options. Data: LSHFO, MDO, LNG, LPG, RNG, methanol, bioethanol, hydrogen (Moirangthem, 2016; DNV GL, 2014; DNV GL, 2015; European Commission, 2009); LNG (Arteconi et al., 2010); hydrogen (Cetinkaya et al., 2012); ammonia (Giddey et al., 2017; IFA, 2009); methanol and biomethanol (Brynolf et al., 2014a). (a)-from crude oil; (b)-from fossil NG; (c)-from municipal solid wastes; (d)-from coal; (e)-from forest residues; (f)-from sugar beets; (g)-from agricultural residues; (h)-from rapeseed; (i)-from water electrolysis via wind energy.

following discussion is to provide the necessary information to facilitate the maritime community to enter into urgent dialogue with the goal of reaching a consensus as quickly as possible.

5.1. Qualitative ranking of potential marine fuels

Comparison and ranking of distinct energy carriers combined with their energy converters were carried out based on the decision-making framework determined in Section 4.2 and the understanding of the characteristics of different alternative marine fuels. The results of the qualitative evaluation are shown in Table 6. The combination of LSHFO/MDO and ICE is taken as a basic reference. The best performance is defined as IV; the worst performance is defined as I; then the relative performances of other combinations are designated as I to IV based on pairwise comparisons with the chosen reference.

Considering technical availability first of all, fully commercial applications, a small number of commercial applications (whether the applications are on board ships or not.), prototype development or few commercial demonstrations, and not fully mature technologies are graded as IV, III, II and I respectively. As for safety, flashpoint, flammability and toxicity are considered. Regarding available infrastructure, fully mature infrastructure, relatively mature or no significant modifications required, relatively immature or large modifications required, and negligible infrastructure are graded as IV, III, II and I respectively. Looking towards the reliable supply of fuel, the feedstocks including fossil fuels (with CCS technologies), biomass and renewable energy are graded as IV; the feedstocks excluding fossil raw materials are graded as III; the feedstocks including biomass only are graded as I. As for investment cost for infrastructure, the existing infrastructure, fuel states, storage, distribution and bunkering requirements are considered and the grades for available infrastructure are referred. In terms of investment cost for propulsion, the same grading system has been applied as for technical availability. As for operational cost, the lifespan and complexity of power systems as well as the fuel storage, distribution and bunkering requirements are considered. Regarding climate change, all alternative fuels theoretically have no CO_2 emissions

Table 6
Qualitative evaluation on different potential marine fuels based on selected decision-making framework.

Criteria	LSHFO/ MDO + ICE	Hydrogen + ICE	Hydrogen + FC	Ammonia + ICE	Ammonia + FC	RNG + ICE	Renewable Methanol + ICE	Renewable methanol + FC	Bioethanol + ICE	BioDME + ICE	Biodiesel + ICE
Technical availability	IV	II	III	II	I	III	III	II	III	II	III
Safety	IV	I	I	I	I	III	II	II	III	III	IV
Available infrastructure	IV	I	I	III	III	II	III	III	III	II	III
Reliable supply of fuel	IV	IV	IV	IV	IV	III	III	III	I	II	I
Investment cost for infrastructure	IV	I	I	II	II	II	III	III	III	II	III
Investment cost for propulsion	IV	II	II	II	I	III	III	I	III	II	III
Operational cost	IV	II	I	III	I	II	III	I	III	III	III
Climate change *	I	IV	IV	III	III	III	III	III	III	III	III
Air pollution	I	II	IV	II	III	III	III	IV	III	III	I
x ± S **	3.3 ± 1.3	2.1 ± 1.2	2.3 ± 1.4	2.4 ± 0.9	2.1 ± 1.2	2.7 ± 0.5	2.9 ± 0.3	2.4 ± 1.0	2.8 ± 0.7	2.4 ± 0.5	2.7 ± 1.0

Notes: I to IV-ranking from the worst to the best; * supposing the world energy mix in 2050 is hybrid fossil energy and non-fossil energy; ** mean value and standard deviation, supposing the scores 1–4 are assigned to the ranking levels I-IV and equal weightings are assigned to each criterion.

supposing renewable feedstocks, renewable energy and CCS technologies are employed for fuel production; however, only hydrogen is graded as IV; other fuels production is based on hydrogen or non-fossil feedstocks and more energy consumption is required. The designations of the grades are regarded as being reasonable because they take into account the expected world energy mix by 2050, which is impossibly composed of 100% renewable energy (IRENA, 2019; DNV GL, 2020); even though the production of alternative marine fuels is all from renewable energy, it will inevitably squeeze the uses of renewable energy in other sectors. Looking towards air pollution, NO_x emissions are taken as the only evaluation indicator. MDO or biodiesel engines have the highest NO_x emissions (and hence are graded as I), followed by hydrogen and ammonia ICE (ranked II), then RNG, renewable methanol, bioethanol and bioDME ICE (ranked III), finally reaching hydrogen and renewable methanol FC which has no NO_x emissions (ranked IV). It is worth noting that an ammonia-fuelled SOFC is the primary option, which is often combined with a GT to increase power. While not considered in this analysis, in such circumstances NO_x emissions are possible due to after combustion of SOFC-GT systems.

Aside from the obvious negative impact upon the climate and local emissions, the option of combining conventional marine fuels and ICE have several positive attributes. However, such systems are excluded due to the incompliant climate performance. Hydrogen has the best climate impact and feedstock security, while there needs to be improvements in the areas of technical preparation, infrastructure and price. Overall, the combination of renewable methanol and ICE exhibits the best comprehensive performance across the different priorities. While other pathways have some indicators with a higher ranking, there are also one or more indicators with bad performance. To illustrate the comparison and ranking intuitively, the scores 1–4 could be assigned to the levels I-IV. Even with equal weighting assigned to each indicator, the combination of renewable methanol and ICE has the highest mean value and the lowest standard deviation, among the evaluated alternative solutions. This clearly demonstrates that this combination offers the best overall performance across all indicators, and is a position that would only be strengthened if the weightings of the different indicators were altered to account for the increased importance of environmental impact and feedstock security.

5.2. Development priority and potential applications

Once multi-dimensional criteria including technical, economic, environmental and sustainable feedstock are considered, there is no clearly ideal alternative fuel for future shipping, even though a wide range of marine fuels have been proposed. Although compromises are often made between benefits and disadvantages of various marine fuel options, some key performance indicators should play a much more significant role. In this paper, the priority levels of the various criteria were ranked in the order of environmental impact, reliability of feedstock, technical viability and then economic factors, which mean these criteria have decreasing weighting factors and further strengthening the ranking orders inferred in Section 5.1. Considering physicochemical properties, low carbon potential, reliability of fuel supply, ease of handling, infrastructure and costs, the priority levels for development and possible applications of different marine fuels are shown in Fig. 6.

Firstly, considering climate impact and the assumption of on board CCS not being available, the continued long-term use of conventional fossil-based marine fuels is not an acceptable option. As a result, LSHFO, MDO and LPG are given the lowest priority level. Fossil NG lacks long-term potential and is given the second lowest priority level, and same level for bioDME due to less competitive advantages than renewable methanol and bioethanol, as discussed in Section 3.6. LNG, CNG and LPG are included in Fig. 6 as comparisons because they are regarded as near-term and mid-term fuel options. Renewable methanol, hydrogen and ammonia are given the highest priority level due to excellent emissions performance; in addition, the feedstock for hydrogen, ammonia and renewable methanol are sufficient, where conventional fossil fuels, biomass and renewable energy sources are all available. Bioethanol and biodiesels are given the second highest priority level due to lacking of global availability of fuel supply. While the availability of feedstocks for RNG is greater than for biomass, more production processes and insignificant technical and cost advantages weaken their competitiveness compared to hydrogen, ammonia and renewable methanol. Therefore, RNG has relatively good emissions performance but is given the second highest priority level.

Secondly, limited by their volumetric energy densities, hydrogen, ammonia and compressed NG are recommended for

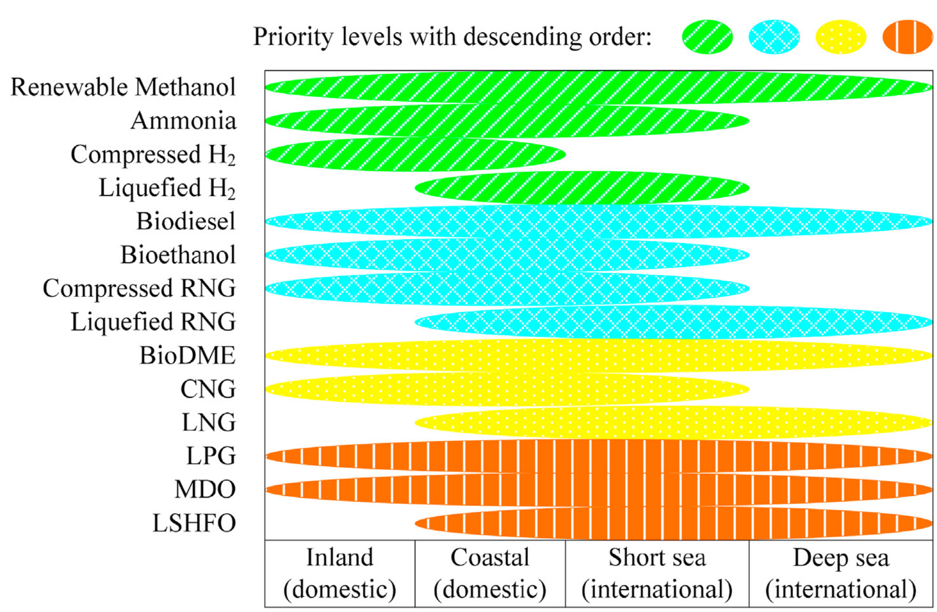

Fig. 6. Priority levels and potential applications of different marine fuels.

domestic and short sea shipping only; liquefied NG is recommended for long-distance shipping for economic considerations. Considering the security of feedstock, the potential of bioethanol and biodiesel for international shipping is restricted due to the uncertainties and the imbalance of biomass production as well as the competition from other fuel-consuming sectors. However, they are viable for local and regional shipping if local feedstock for biofuels production is sufficient.

Finally, considering technical and economic aspects, renewable methanol used in conjunction with an ICE represents the strongest opportunity for future global shipping. Aside from this, hydrogen and ammonia are promising fuels for short sea shipping. However, the technology pathways combining hydrogen with low temperature FC and ammonia with ICE are better than the combinations of hydrogen and ICE or ammonia and high temperature FC. The development of distinct technology pathways combining fuels with propulsion systems is inevitable, and ship types and shipping routes are the decisive factors in the most suitable fuel and technology combinations. Therefore, the recommendations in Fig. 6 are just general profiles, the best technological solutions are both ship-specific and area-specific.

6. Conclusions and implications

Primary alternative marine fuel options were reviewed and clarified in this paper with the goal of achieving low carbon maritime transportation by 2050. Integrated abatements of SO_x, NO_x and CO_2 emissions were considered together. Hydrogen, ammonia, RNG, renewable methanol, bioethanol, bioDME and biodiesel were analyzed in terms of key physicochemical properties, feedstock, production processes, transportation, storage, end use, combustion characteristics and emissions performance. A qualitative ranking of the potential of different marine fuel options was conducted based on a decision-making framework incorporating the total life-cycle stages and the multi-dimensional evaluation criteria. Based on the analysis, development priorities and applicable types of shipping were determined for potential alternative marine fuel options. The following conclusions and implications from the analysis are intended to inform maritime stakeholders.

(1) It is difficult to achieve low carbon shipping through technological and operational measures. Nuclear-powered ships are probably unacceptable (Schøyen and Steger-Jensen, 2017) and wind or solar assistance could only be used as auxiliary power sources. Therefore, the adoption of alternative marine fuels is inevitable. Direct fossil fuels as primary marine fuels, e.g., LSHFO and MDO, should be changed gradually and the substitution of marine fuels will inevitably be a long process. Choosing the most promising pathway is especially important prior to entering a new era of alternative marine fuels. The selection of LNG or LPG as future marine fuel should be treated with caution due to the low potential for carbon saving and the high infrastructure investment.

(2) Hydrogen and ammonia as zero carbon fuels, which are expected to have robust prospects in road transportation, are also ideal fuels for inland and coastal shipping in certain regions. However, current costs are high and existing infrastructure is insufficient. Therefore, the introduction of national or regional incentives could be encouraged depending on local low carbon development strategies. Renewable energy and CCS technology need to be employed in parallel for clean hydrogen production. Earlier and wider deployment of zero carbon fuels in shipping will reduce the pressure on future shipping emissions. However, hydrogen and ammonia have limited potential for deep-sea applications and they are not recommended due to their low volumetric energy densities.

(3) Biofuels as so-called carbon-neutral fuels, such as RNG, biogenic methanol, bioethanol, bioDME and biodiesels, are limited by the reliability of fuel supply due to the uneven geographical distribution of land and water resources and the competition from other energy-consuming sectors. Hence, the prospects for biofuels in global shipping are not optimistic. But the potentials in local or regional shipping are worth investigating further. In particular, increased electrification of road transport may allocate more liquid biofuels to shipping and aviation sectors. RNG, methanol and DME could be derived from biomass, fossil raw materials, renewable energy as well as fossil energy combined with CCS. A broad range of suitable feedstocks ensures their global availability, and their short-term and long-term potential should both be simultaneously taken into account. Therefore, RNG, methanol and DME are more competitive than bioethanol and biogenic diesels. Considering the fuel characteristics, methanol (current fossil methanol and future renewable methanol) is the most promising alternative fuel for global shipping. Therefore, considering the long timescales associated with marine fuel substitution, the international maritime community needs to build consensus and adopt a unified plan of action as soon as possible. The sooner that specific plans are made to switch to an alternative marine fuel and invest in infrastructure, the sooner the goal of low carbon maritime transportation can be realized.

(4) The combination of alternative marine fuel proposed in this study is methanol for global shipping, and hydrogen, ammonia, bioethanol and biodiesels from renewable energy sources for domestic and short sea shipping, depending on local practices. LSHFO and MDO need to be phased out gradually, and it is suggested that the development of ships fuelled by LNG, LPG and DME should be cautious. Consequently, FC power systems fuelled by hydrogen, ammonia and methanol could be taken as key priorities for future research and development, which are supposed as the priority power solutions for domestic and short-sea shipping in this paper. Dual fuel compression ignition engines should be widely developed to use hydrogen, ammonia, methanol, bioethanol or biodiesels as secondary and then primary fuel. However, blended fuels may not be the main application modes. NO_x emissions control cannot be avoided through the use of alternative marine fuels. Therefore, low NO_x combustion and exhaust gas aftertreatment technologies need to be improved continuously. However, with more use of renewable energy in land-based industries and with the use of renewable fuels with relatively low NO_x emissions in the shipping sector, the pressure upon shipping NO_x emissions might be significantly reduced and the abatement of NO_x emissions will likely not be the highest priority.

(5) The life-cycle emissions and well-to-wake costs of alternative fuels strongly depends on the type of feedstock, the country the feedstock originated from, the production processes and the primary energy sources employed. Accordingly, the understanding of alternative marine fuels in this paper is still fragmentary and not all-inclusive. More complete life-cycle assessments for more alternative fuels need to be undertaken as soon as possible in specific flag states, coastal states and fuel producing countries.

(6) The construction of infrastructure should take account of the integral utilization of feedstock and the recycling utilization of intermediate products for the production of alternative

marine fuels and byproducts as well as the cogeneration of cooling, heating and power. This is an important way to reduce the production cost, which is one of the primary factors restricting the broad deployment of alternative marine fuels. The development of fuels from biomass depends on local situations; integral policies on food, energy, waste, land and water resources are required. The increase of fossil-free energy (mainly wind, solar and nuclear) in the world energy mix and the expansion of carbon capture, utilization and storage in land-based industrial sectors will reduce not only the global carbon emissions directly, but also the life-cycle emissions and the costs of alternative fuels. Therefore, the extent of utilizing alternative marine fuels strongly depends on the change of the world energy mix, which means the individual effort of the maritime sector is less important and the actions of upstream sectors are even more important when considering the transition to alternative marine fuels. However, global and national policy programs on the changes of energy and fuels could dramatically advance the world's clean energy transition. For the maritime community, consensus is stronger than divergence and decisive actions on the most promising pathways as early as possible are more necessary than hesitation and waiting. Correspondingly, local or global legal frameworks and economic incentives should go ahead of other actions, and national or regional policies and pilot projects could take the lead.

Funding agencies

China Scholarship Council.
The Fundamental Research Funds for the Central Universities.

CRediT authorship contribution statement

Hui Xing: Methodology, Formal analysis, Investigation, Writing – original draft. **Charles Stuart:** Formal analysis, Investigation, Writing – original draft. **Stephen Spence:** Resources, Writing – review & editing, Supervision. **Hua Chen:** Conceptualization, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was financially supported by the China Scholarship Council [grant number, 2019-44] and the Fundamental Research Funds for the Central Universities [grant number, 3132019330]. The authors would also like to express their appreciation to the anonymous reviewers for their valuable comments.

Abbreviations, Nomenclature list

AHP	Analytic Hierarchy Process
BtL	Biomass-to-Liquid
CCS	Carbon Capture and Storage
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
DME	Dimethyl Ether
EGCS	Exhaust Gas Cleaning Systems
FAME	Fatty Acid Methyl Esters
FC	Fuel Cells
F-T	Fischer-Tropsch
GHG	Greenhouse Gas
GT	Gas Turbine
GWP	Global Warming Potential
HDRD	Hydrogenation-Derived Renewable Diesel
HFO	Heavy Fuel Oil
HVO	Hydrotreated Vegetable Oils
ICE	Internal Combustion Engines
IMO	International Maritime Organization
LBG	Liquefied Biogas
LH_2	Liquefied Hydrogen
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LSHFO	Low Sulphur Heavy Fuel Oil
MARPOL	International Convention for the Prevention of Pollution from Ships
MCDA	Multi-Criteria Decision Analysis
MCFC	Molten Carbonate Fuel Cell
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
NG	Natural Gas
NO_x	Nitrogen Oxides
PEMFC	Proton Exchange Membrane Fuel Cells
PM	Particulate Matters
PtL	Power-to-Liquid
RNG	Renewable Natural Gas
SCR	Selective Catalytic Reduction
SNG	Synthetic Natural Gas
SOFC	Solid Oxide Fuel Cells
SO_x	Sulphur Oxides
SVO	Straight Vegetable Oil

References

Afif, A., Radenahmad, N., Cheok, Q., Shams, S., Kim, J.H., Azad, A.K., 2016. Ammonia-fed fuel cells: a comprehensive review. Renew. Sustain. Energy Rev. 60, 822–835.
Ahmad, A.L., Mat Yasin, N.H., Derek, C.J.C., Lim, J.K., 2011. Microalgae as a sustainable energy source for biodiesel production: a review. Renew. Sustain. Energy Rev. 15, 584–593.
Ali, O.M., Mamat, R., Abdullah, N.R., Abdullah, A.A., 2016. Analysis of blended fuel properties and engine performance with palm biodiesel-diesel blended fuel. Renew. Energy 86, 59–67.
Alonso, D.M., Bond, J.Q., Dumesic, J.A., 2010. Catalytic conversion of biomass to biofuels. Green Chem. 12, 1493–1513.
Amar, I.A., Lan, R., Petit, C.T.G., Tao, S., 2011. Solid-state electrochemical synthesis of ammonia: a review. J. Solid State Electrochem. 15, 1845–1860.
Andersson, K., Salazar, C.M., 2015. Methanol as a Marine Fuel Report. Prepared for Methanol Institute by FCBI Energy.
Appels, L., Baeyens, J., Degrève, J., Dewil, R., 2008. Principles and potential of the anaerobic digestion of waste-activated sludge. Prog. Energ. Combust. 34, 755–781.
Arcoumanis, C., Bae, C., Crookes, R., Kinoshita, E., 2008. The potential of di-methyl ether (DME) as an alternative fuel for compression-ignition engines: a review. Fuel 87, 1014–1030.
Arteconi, A., Brandoni, C., Evangelista, D., Polonara, F., 2010. Life-cycle greenhouse gas analysis of LNG as a heavy vehicle fuel in Europe. Appl. Energy 87, 2005–2013.
Ashraful, A.M., Masjuki, H.H., Kalam, M.A., Rizwanul Fattah, I.M., Imtenan, S., Shahir, S.A., Mobarak, H.M., 2014. Production and comparison of fuel properties, engine performance, and emission characteristics of biodiesel from various non-edible vegetable oils: a review. Energy Convers. Manag. 80, 202–228.
Atabani, A.E., Silitonga, A.S., Badruddin, I.A., Mahlia, T.M.I., Masjuki, H.H., Mekhilef, S., 2012. A comprehensive review on biodiesel as an alternative energy resource and its characteristics. Renew. Sustain. Energy Rev. 16, 2070–2093.
Atabani, A.E., Silitonga, A.S., Ong, H.C., Mahlia, T.M.I., Masjuki, H.H., Badruddin, I.A., Fayaz, H., 2013. Non-edible vegetable oils: a critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. Renew. Sustain. Energy Rev. 18, 211–245.
Bailera, M., Lisbona, P., Romeo, L.M., Espatolero, S., 2017. Power to Gas projects review: lab, pilot and demo plants for storing renewable energy and CO2. Renew. Sustain. Energy Rev. 69, 292–312.

Bajpai, S., Sahoo, P.K., Das, L.M., 2009. Feasibility of blending Karanja vegetable oil in petro-diesel and utilization in a direct injection diesel engine. Fuel 88, 705–711.
Balat, M., 2008. Possible methods for hydrogen production. Energy Sources Part A 31, 39–50.
Balat, M., Balat, H., 2009. Recent trends in global production and utilization of bio-ethanol fuel. Appl. Energy 86, 2273–2282.
Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., Staffell, I., 2019. How to decarbonise international shipping: options for fuels, technologies and policies. Energy Convers. Manag. 182, 72–88.
Bengtsson, S.K., Fridell, E., Andersson, K.E., 2014. Fuels for short sea shipping: a comparative assessment with focus on environmental impact. Proc. IMechE Part M: J. Eng. Marit. Environ. 228, 44–54.
Bhandari, R., Trudewind, C.A., Zapp, P., 2014. Life cycle assessment of hydrogen production via electrolysis-a review. J. Clean. Prod. 85, 151–163.
Boretti, A., 2011. Advances in hydrogen compression ignition internal combustion engines. Int. J. Hydrogen Energy 36, 12601–12606.
Bouman, E.A., Lindstad, E., Rialland, A.I., Strømman, A.H., 2017. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping-a review. Transport. Res. Transport Environ. 52, 408–421.
Brahim, T., Wiese, F., Münster, M., 2019. Pathways to climate-neutral shipping: a Danish case study. Energy 188, 116009.
Brynolf, S., Fridell, E., Andersson, K., 2014a. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and biomethanol. J. Clean. Prod. 74, 86–95.
Brynolf, S., Magnusson, M., Fridell, E., Andersson, K., 2014b. Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels. Transport. Res. Transport Environ. 28, 6–18.
Brynolf, S., Taljegard, M., Grahn, M., Hansson, J., 2018. Electrofuels for the transport sector: a review of production costs. Renew. Sustain. Energy Rev. 81, 1887–1905.
Ce Delft, UMAS, 2019. Study on Methods and Considerations for the Determination of Greenhouse Gas Emission Reduction for International Shipping. Final report prepared for the European Commission.
Cetinkaya, E., Dincer, I., Naterer, G.F., 2012. Life cycle assessment of various hydrogen production methods. Int. J. Hydrogen Energy 37, 2071–2080.
Chaubey, R., Sahu, S., James, O.O., Maity, S., 2013. A review on development of industrial processes and emerging techniques for production of hydrogen from renewable and sustainable sources. Renew. Sustain. Energy Rev. 23, 443–462.
Chauhan, B.S., Kumar, N., Cho, H.M., Lim, H.C., 2013. A study on the performance and emission of a diesel engine fuelled with Karanja biodiesel and its blends. Energy 56, 1–7.
Cinti, G., Discepoli, G., Sisani, E., Desideri, U., 2016. SOFC operating with ammonia: stack test and system analysis. Int. J. Hydrogen Energy 41, 13583–13590.
Corbett, J.J., Winebrake, J.J., 2018. Life Cycle Analysis of the Use of Methanol for Marine Transportation. Prepared for Maritime Administration, U.S. Department of Transportation, 10 August 2018.
Demirbas, A., 2009. Progress and recent trends in biodiesel fuels. Energy Convers. Manag. 50, 14–34.
Deniz, C., Zincir, B., 2016. Environmental and economical assessment of alternative marine fuels. J. Clean. Prod. 113, 438–449.
Dimitriou, P., Tsujimura, T., 2017. A review of hydrogen as a compression ignition engine fuel. Int. J. Hydrogen Energy 42, 24470–24486.
DNV GL, 2014. Alternative Fuels for Shipping. Position paper 17-2014.
DNV GL, 2015. LNG as Ship Fuel: Latest Developments and Projects in the LNG Industry, 2015, No. 01.
DNV GL, 2019. Comparison of Alternative Marine Fuels. Report No. 2019-0567, Rev. 3.
DNV GL, 2020. Energy Transition Outlook 2020: A Global and Regional Forecast to 2050. https://eto.dnvgl.com/2020/index.html.
dos Santos Prucole, E., da Cunha Pinto, R.R., Valle, M.L.M., 2014. Use of biodiesel in marine fuel formulation: a study of combustion quality. Fuel Process. Technol. 122, 91–97.
Douvartzides, S.L., Charisiou, N.D., Papageridis, K.N., Goula, M.A., 2019. Green diesel: biomass feedstock, production technologies, catalytic research, fuel properties and performance in compression ignition internal combustion engines. Energies 12, 809.
Eide, M.S., Chryssakis, C., Endresen, Ø., 2013. CO_2 abatement potential towards 2050 for shipping, including alternative fuels. Carbon Manag. 4, 275–289.
Ellis, J., Tanneberger, K., 2015. Study on the Use of Ethyl and Methyl Alcohol as Alternative Fuels in Shipping. Final Report prepared for the European Maritime Safety Agency (EMSA). Version 20151204.5.
EMSA, 2019. The World Merchant Fleet: Statistics from Equasis. http://www.emsa.europa.eu/equasis-statistics/items.html?cid=95&id=472. (Accessed 2 February 2020).
European Commission, 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union L140, 16–62.
FACTFISH, 2019. Topics for Crop. http://www.factfish.com/catalog/crop. (Accessed 2 February 2020).
FAOSTAT, 2019a. Crops. http://www.fao.org/faostat/en/#data/QC/visualize. (Accessed 2 February 2020).
FAOSTAT, 2019b. Food and Agriculture Data. http://www.fao.org/faostat/en/?#home. (Accessed 2 February 2020).
Fazal, M.A., Haseeb, A.S.M.A., Masjuki, H.H., 2011. Biodiesel feasibility study: an evaluation of material compatibility, performance, emission and engine durability. Renew. Sustain. Energy Rev. 15, 1314–1324.
Fernández, I.A., Gómez, M.R., Gómez, J.R., Insua, A.Á.B., 2017. Review of propulsion systems on LNG carriers. Renew. Sustain. Energy Rev. 67, 1395–1411.
Fleisch, T.H., Basu, A., Sills, R.A., 2012. Introduction and advancement of a new clean global fuel: the status of DME developments in China and beyond. J. Nat. Gas Sci. Eng. 9, 94–107.
Freire, L.O., de Andrade, D.A., 2015. Historic survey on nuclear merchant ships. Nucl. Eng. Des. 293, 176–186.
Ganesh, I., 2014. Conversion of carbon dioxide into methanol-a potential liquid fuel: fundamental challenges and opportunities (a review). Renew. Sustain. Energy Rev. 31, 221–257.
Geng, P., Cao, E., Tan, Q., Wei, L., 2017a. Effects of alternative fuels on the combustion characteristics and emission products from diesel engines: a review. Renew. Sustain. Energy Rev. 71, 523–534.
Geng, P., Mao, H., Zhang, Y., Wei, L., You, K., Ju, J., Chen, T., 2017b. Combustion characteristics and NO_x emissions of a waste cooking oil biodiesel blend in a marine auxiliary diesel engine. Appl. Therm. Eng. 115, 947–954.
Giddey, S., Badwal, S.P.S., Munnings, C., Dolan, M., 2017. Ammonia as a renewable energy transportation media. ACS Sustain. Chem. Eng. 5, 10231–10239.
Gilbert, P., Bows-Larkin, A., Mander, S., Walsh, C., 2014. Technologies for the high seas: meeting the climate challenge. Carbon Manag. 5, 447–461.
Gilbert, P., Walsh, C., Traut, M., Kesieme, U., Pazouki, K., Murphy, A., 2018. Assessment of full life-cycle air emissions of alternative shipping fuels. J. Clean. Prod. 172, 855–866.
Götz, M., Lefebvre, J., Mörs, F., Koch, A.M., Graf, F., Bajohr, S., Reimert, R., Kolb, T., 2016. Renewable Power-to-Gas: a technological and economic review. Renew. Energy 85, 1371–1390.
Guerra, A., Jenssen, M.M., 2014. Multi Criteria Decision Analysis (MCDA) in the Norwegian Maritime Sector: Adding Environmental Criteria in Maritime Decision Support Systems. MSc thesis: Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, Trondheim.
Halim, R.A., Kirstein, L., Merk, O., Martinez, L.M., 2018. Decarbonization pathways for international maritime transport: a model-based policy impact assessment. Sustainability 10, 2243.
Hansson, J., Mansson, S., Brynolf, S., Grahn, M., 2019. Alternative marine fuels: prospects based on multi-criteria decision analysis involving Swedish stakeholders. Biomass Bioenergy 126, 159–173.
Haq, F., Ali, H., Shuaib, M., Badshah, M., Hassan, S.W., Munis, M.F.H., Chaudhary, H.J., 2016. Recent progress in bioethanol production from lignocellulosic materials: a review. Int. J. Green Energy 13, 1413–1441.
Hirdaris, S.E., Cheng, Y.F., Shallcross, P., Bonafoux, J., Carlson, D., Prince, B., Sarris, G.A., 2014. Considerations on the potential use of nuclear small modular reactor (SMR) technology for merchant marine propulsion. Ocean. Eng. 79, 101–130.
Holladay, J.D., Hu, J., King, D.L., Wang, Y., 2009. An overview of hydrogen production technologies. Catal. Today 139, 244–260.
Hua, J., Wu, Y., Chen, H.L., 2017. Alternative fuel for sustainable shipping across the Taiwan Strait. Transport. Res. Transport Environ. 52, 254–276.
Hwang, S., Jeong, B., Jung, K., Kim, M., Zhou, P., 2019. Life cycle assessment of LNG fueled vessel in domestic services. J. Mar. Sci. Eng. 7, 359.
IEA, 2018. Data and Statistics. https://www.iea.org/data-and-statistics/data-tables?country=WORLD&energy=Balances&year=2017. (Accessed 2 February 2020).
IFA, 2009. Energy Efficiency and CO_2 Emissions in Ammonia Production. https://www.fertilizer.org//images/Library_Downloads/2009_IFA_energy_efficiency.pdf. (Accessed 2 February 2020).
IMO, 2015. Third IMO GHG Study 2014. Technical report. Published by the International Maritime Organization.
IMO, 2018. Initial IMO strategy on reduction of GHG emissions from ships. Resolution MEPC 304 (72) adopted on 13 April 2018.
Inal, O.B., Deniz, C., 2020. Assessment of fuel cell types for ships: based on multi-criteria decision analysis. J. Clean. Prod. 265, 121734.
IRENA, 2019. Global Energy Transformation: A Roadmap to 2050, 2019 edition. International Renewable Energy Agency, Abu Dhabi.
Jamrozik, A., 2017. The effect of the alcohol content in the fuel mixture on the performance and emissions of a direct injection diesel engine fueled with diesel-methanol and diesel-ethanol blends. Energy Convers. Manag. 148, 461–476.
Janaun, J., Ellis, N., 2010. Perspectives on biodiesel as a sustainable fuel. Renew. Sustain. Energy Rev. 14, 1312–1320.
Jiao, Y., Liu, R., Zhang, Z., Yang, C., Zhou, G., Dong, S., Liu, W., 2019. Comparison of combustion and emission characteristics of a diesel engine fueled with diesel and methanol-Fischer-Tropsch diesel-biodiesel-diesel blends at various altitudes. Fuel 243, 52–59.
Kalligeros, S., Zannikos, F., Stournas, S., Lois, E., Anastopoulos, G., Teas, C., Sakellaropoulos, F., 2003. An investigation of using biodiesel/marine diesel blends on the performance of a stationary diesel engine. Biomass Bioenergy 24, 141–149.
Kim, Y.-D., Yang, C.-W., Kim, B.-J., Moon, J.-H., Jeong, J.-Y., Jeong, S.-H., Lee, S.-H., Kim, J.-H., Seo, M.-W., Lee, S.-B., Kim, J.-K., Lee, U.-D., 2016. Fischer-Tropsch diesel production and evaluation as alternative automotive fuel in pilot-scale integrated biomass-to-liquid process. Appl. Energy 180, 301–312.
Klerke, A., Christensen, C.H., Nørskov, J.K., Vegge, T., 2008. Ammonia for hydrogen

storage: challenges and opportunities. J. Mater. Chem. 18, 2304–2310.
Kumar, N., Varun, Chauhan, S.R., 2013. Performance and emission characteristics of biodiesel from different origins: a review. Renew. Sustain. Energy Rev. 21, 633–658.
Lan, R., Irvine, J.T.S., Tao, S., 2012. Ammonia and related chemicals as potential indirect hydrogen storage materials. Int. J. Hydrogen Energy 37, 1482–1494.
Liu, J., Liu, S., Li, Y., Wei, Y., Li, G., Zhu, Z., 2010. Regulated and nonregulated emissions from a Dimethyl Ether powered compression ignition engine. Energy Fuel. 24, 2465–2469.
Mahmudul, H.M., Hagos, F.Y., Mamat, R., Adam, A.A., Ishak, W.F.W., Alenezi, R., 2017. Production, characterization and performance of biodiesel as an alternative fuel in diesel engines-A review. Renew. Sustain. Energy Rev. 72, 497–509.
Malmgren, E., Brynolf, S., Borgh, M., Ellis, J., Grahn, M., Wermuth, N., 2020. The HyMethShip Concept: an investigation of system design choices and vessel operation characteristics influence on life cycle performance. Helsinki, Finland. In: Proceedings of 8th Transport Research Arena (TRA 2020), pp. 27–30 (April).
Mat Yasin, M.H., Yusaf, T., Mamat, R., Fitri Yusop, A., 2014. Characterization of a diesel engine operating with a small proportion of methanol as a fuel additive in biodiesel blend. Appl. Energy 114, 865–873.
Mazloomi, K., Gomes, C., 2012. Hydrogen as an energy carrier: prospects and challenges. Renew. Sustain. Energy Rev. 16, 3024–3033.
Mofijur, M., Atabani, A.E., Masjuki, H.H., Kalam, M.A., Masum, B.M., 2013. A study on the effects of promising edible and non-edible biodiesel feedstock on engine performance and emissions production: a comparative evaluation. Renew. Sustain. Energy Rev. 23, 391–404.
Moirangthem, K., 2016. Alternative Fuels for Marine and Inland Waterways-An Exploratory Study. Technical report by the Joint Research Centre of European Commission.
Mojović, L., Pejin, D., Grujić, O., Markov, S., Pejin, J., Rakin, M., Vukašinović, M., Nikolić, S., Savić, D., 2009. Progress in the production of bioethanol on starch-based feedstock. Chem. Ind. Chem. Eng. Q. 15, 211–226.
Ni, M., Leung, M.K.H., Leung, D.Y.C., 2009. Ammonia-fed solid oxide fuel cells for power generation-A review. Int. J. Energy Res. 33, 943–959.
Noor, C.W.M., Noor, M.M., Mamat, R., 2018. Biodiesel as alternative fuel for marine diesel engine applications: a review. Renew. Sustain. Energy Rev. 94, 127–142.
Ölçer, A., Ballini, F., 2015. The development of a decision making framework for evaluating the trade-off solutions of cleaner seaborne transportation. Transport. Res. Transport Environ. 37, 150–170.
Paulauskiene, T., Bucas, M., Laukinaite, A., 2019. Alternative fuels for marine applications: biomethanol-biodiesel-diesel blends. Fuel 248, 161–167.
Peral, E., Martín, M., 2015. Optimal production of dimethyl ether from switchgrass-based syngas via direct synthesis. Ind. Eng. Chem. Res. 54, 7465–7475.
Popp, J., Lakner, Z., Harangi-Rákos, M., Fári, M., 2014. The effect of bioenergy expansion: food, energy, and environment. Renew. Sustain. Energy Rev. 32, 559–578.
Qi, D.H., Chen, H., Geng, L.M., Bian, Y.Z., 2010a. Experimental studies on the combustion characteristics and performance of a direct injection engine fueled with biodiesel/diesel blends. Energy Convers. Manag. 51, 2985–2992.
Qi, D.H., Chen, H., Geng, L.M., Bian, Y.Z., Ren, X.C., 2010b. Performance and combustion characteristics of biodiesel-diesel-methanol blend fuelled engine. Appl. Energy 87, 1679–1686.
Rakopoulos, D.C., Rakopoulos, C.D., Kakaras, E.C., Giakoumis, E.G., 2008. Effects of ethanol-diesel fuel blends on the performance and exhaust emissions of heavy duty DI diesel engine. Energy Convers. Manag. 49, 3155–3162.
Ramachandra, T.V., Hebbale, D., 2020. Bioethanol from macroalgae: prospects and challenges. Renew. Sustain. Energy Rev. 117, 109479.
Rehbein, M.C., Meier, C., Eilts, P., Scholl, S., 2019. Mixtures of ammonia and organic solvents as alternative fuel for internal combustion engines. Energy Fuel. 33, 10331–10342.
Reiter, A.J., Kong, S.-C., 2011. Combustion and emissions characteristics of compression-ignition engine using dual ammonia-diesel fuel. Fuel 90, 87–97.
Ren, J., Liang, H., 2017. Measuring the sustainability of marine fuels: a fuzzy group multi-criteria decision making approach. Transport. Res. Transport Environ. 54, 12–29.
Ren, J., Lützen, M., 2017. Selection of sustainable alternative energy source for shipping: multi-criteria decision making under incomplete information. Renew. Sustain. Energy Rev. 74, 1003–1019.
RFA, 2019. Annual World Fuel Ethanol Production. https://ethanolrfa.org/statistics/annual-ethanol-production/. (Accessed 2 February 2020).
Riaz, A., Zahedi, G., Klemeš, J.J., 2013. A review of cleaner production methods for the manufacture of methanol. J. Clean. Prod. 57, 19–37.
Sadeghinezhad, E., Kazi, S.N., Badarudin, A., Oon, C.S., Zubir, M.N.M., Mehrali, M., 2013. A comprehensive review of bio-diesel as alternative fuel for compression ignition engines. Renew. Sustain. Energy Rev. 28, 410–424.
Sakthivel, R., Ramesh, K., Purnachandran, R., Mohamed Shameer, P., 2018. A review on the properties, performance and emission aspects of the third generation biodiesels. Renew. Sustain. Energy Rev. 82, 2970–2992.
Santasalo-Aarnio, A., Nyari, J., Wojcieszyk, M., Kaario, O., Kroyan, Y., Magdeldin, M., Larmi, M., Järvinen, M., 2020. Application of Synthetic Renewable Methanol to Power the Future Propulsion. https://doi.org/10.4271/2020-01-2151. SAE Technical Paper 2020-01-2151.
Sayin, C., 2010. Engine performance and exhaust gas emissions of methanol and ethanol-diesel blends. Fuel 89, 3410–3415.
Schøyen, H., Steger-Jensen, K., 2017. Nuclear propulsion in ocean merchant shipping: the role of historical experiments to gain insight into possible future applications. J. Clean. Prod. 169, 152–160.
Semelsberger, T.A., Borup, R.L., Greene, H.L., 2006. Dimethyl ether (DME) as an alternative fuel. J. Power Sources 156, 497–511.
Serov, A., Kwak, C., 2009. Progress in development of direct dimethyl ether fuel cells. Appl. Catal. B Environ. 91, 1–10.
Shahid, E.M., Jamal, J., 2011. Production of biodiesel: a technical review. Renew. Sustain. Energy Rev. 15, 4732–4745.
Singh, S.P., Singh, D., 2010. Biodiesel production through the use of different sources and characterization of oils and their esters as the substitute of diesel: a review. Renew. Sustain. Energy Rev. 14, 200–216.
Sorate, K.A., Bhale, P.V., 2015. Biodiesel properties and automotive system compatibility issues. Renew. Sustain. Energy Rev. 41, 777–798.
Svanberg, M., Ellis, J., Lundgren, J., Landälv, I., 2018. Renewable methanol as a fuel for the shipping industry. Renew. Sustain. Energy Rev. 94, 1217–1228.
Taljegard, M., Brynolf, S., Grahn, M., Andersson, K., Johnson, H., 2014. Cost-effective choices of marine fuels in a carbon-constrained world: results from a Global Energy Model. Environ. Sci. Technol. 48, 12986–12993.
Torres-Jimenez, E., Jerman, M.S., Gregorc, A., Lisec, I., Dorado, M.P., Kegl, B., 2011. Physical and chemical properties of ethanol-diesel fuel blends. Fuel 90, 795–802.
Tronstad, T., Åstrand, H.H., Haugom, G.P., Langfeldt, L., 2017. Study on the Use of Fuel Cells in Shipping. Report to European Maritime Safety Agency by DNV GL. http://www.emsa.europa.eu/component/flexicontent/items.html?cid=96&id=2921&Itemid=.
Ushakov, S., Stenersen, D., Einang, P.M., 2019. Methane slip from gas fuelled ships: a comprehensive summary based on measurement data. J. Mar. Sci. Technol. 24, 1308–1325.
van Vliet, O.P.R., Faaij, A.P.C., Turkenburg, W.C., 2009. Fischer-Tropsch diesel production in a well-to-wheel perspective: a carbon, energy flow and cost analysis. Energy Convers. Manag. 50, 855–876.
Varone, A., Ferrari, M., 2015. Power to liquid and power to gas: an option for the German Energiewende. Renew. Sustain. Energy Rev. 45, 207–218.
Vassiliev, A., Reumert, A.K., Jensen, J.O., Aili, D., 2019. Durability and degradation of vapor-fed direct dimethyl ether high temperature polymer electrolyte membrane fuel cells. J. Power Sources 432, 30–37.
Walsh, C., Mander, S., Larkin, A., 2017. Charting a low carbon future for shipping: a UK perspective. Mar. Pol. 82, 32–40.
Wang, H., Xu, J., Sheng, L., Liu, X., Lu, Y., Li, W., 2018. A review on bio-hydrogen production technology. Int. J. Energy Res. 42, 3442–3453.
WBA, 2019. Global Bioenergy Statistics 2019. https://worldbioenergy.org/uploads/191129%20WBA%20GBS%202019_LQ.pdf. (Accessed 2 February 2020).
Weiland, P., 2010. Biogas production: current state and perspectives. Appl. Microbiol. Biotechnol. 85, 849–860.
White, C.M., Steeper, R.R., Lutz, A.E., 2006. The hydrogen-fueled internal combustion engine: a technical review. Int. J. Hydrogen Energy 31, 1292–1305.
Wong, A., Zhang, H., Kumar, A., 2016. Life cycle assessment of renewable diesel production from lignocellulosic biomass. Int. J. Life Cycle Assess. 21, 1404–1424.
Xing, H., Spence, S., Chen, H., 2020. A comprehensive review on countermeasures for CO_2 emissions from ships. Renew. Sustain. Energy Rev. 134, 110222. https://doi.org/10.1016/j.rser.2020.110222.
Xing, H., Stuart, C., Spence, S., Chen, H., 2021. Fuel cell power systems for maritime applications: progress and perspectives. Sustainability 13, 1213. https://doi.org/10.3390/su13031213.
Xue, J., Grift, T.E., Hansen, A.C., 2011. Effect of biodiesel on engine performances and emissions. Renew. Sustain. Energy Rev. 15, 1098–1116.
Yan, F., Xu, L., Wang, Y., 2018. Application of hydrogen enriched natural gas in spark ignition IC engines: from fundamental fuel properties to engine performances and emissions. Renew. Sustain. Energy Rev. 82, 1457–1488.
Yilmaz, N., 2012. Comparative analysis of biodiesel-ethanol-diesel and biodiesel-methanol-diesel blends in a diesel engine. Energy 40, 210–213.
Yusri, I.M., Mamat, R., Najafi, G., Razman, A., Awad, O.I., Azmi, W.H., Ishak, W.F.W., Shaiful, A.I.M., 2017. Alcohol based automotive fuels from first four alcohol family in compression and spark ignition engine: a review on engine performance and exhaust emissions. Renew. Sustain. Energy Rev. 77, 169–181.
Zamfirescu, C., Dincer, I., 2008. Using ammonia as a sustainable fuel. J. Power Sources 185, 459–465.
Zheng, Y., Zhao, J., Xu, F., Li, Y., 2014. Pretreatment of lignocellulosic biomass for enhanced biogas production. Prog. Energ. Combust. 42, 35–53.
Zhu, Z., Li, D.K., Liu, J., Wei, Y.J., Liu, S.H., 2012. Investigation on the regulated and unregulated emissions of a DME engine under different injection timing. Appl. Therm. Eng. 35, 9–14.