Energy Reports 7 (2021) 1962–1985

Contents lists available at ScienceDirect

Energy Reports

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

Review article

A review of cleaner alternative fuels for maritime transportation

Ahad Al-Enazi [a], Eric C. Okonkwo [a,b], Yusuf Bicer [a], Tareq Al-Ansari [a,b,*]

[a] *Division of Engineering Management and Decision Sciences, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Education City, Doha, Qatar*

[b] *Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Education City, Doha, Qatar*

ARTICLE INFO

Article history:
Received 27 December 2020
Received in revised form 19 March 2021
Accepted 28 March 2021
Available online 15 April 2021

Keywords:
Liquified natural gas
Maritime transportation
Hydrogen
Clean bunker fuels
Environmental impact assessment

ABSTRACT

Environmental regulations have always been an essential component in the natural gas supply chain, with recent and greater emphasis on shipping operations. Recently more stringent regulations have been imposed by the International Maritime Organization on global maritime shipping operations. This review explores the challenges and opportunities associated with substituting heavy fuel oils used for maritime transportation with relatively cleaner fuels. First, the review considers the feasibility and environmental dimensions of different bunker fuels, including liquefied natural gas, hydrogen, and ammonia. Also, the operational viability and optimal conditions for these fuels are examined. Secondly, the review considers the entire supply chain, with an emphasis on how liquefied natural gas exporters can establish synergies across the supply chain to also deliver the end-product required by customers instead of delivering only liquefied natural gas. Finally, measures that can support ship operators to comply with environmental regulations are suggested. The outcomes of this review supports the notion that the demand for alternative fuels will continue to increase as the transportation sector moves towards integrating cleaner fuels to comply with increasing environmental regulations.

© 2021 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Contents

* Corresponding author at: Division of Engineering Management and Decision Sciences, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Education City, Doha, Qatar.
E-mail address: talansari@hbku.edu.qa (T. Al-Ansari).

https://doi.org/10.1016/j.egyr.2021.03.036
2352-4847/© 2021 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

The transportation sector is one of the main contributors to greenhouse gas (GHG) emissions worldwide. Approximately, 2% of human-induced CO_2 emissions are generated by the global aviation industry (Bicer and Dincer, 2018d). According to the International Energy Agency (IEA), CO_2 emissions from the transportation sector represented 24% of global CO_2 emissions during the year 2016. These emissions have been dominated by the Asian continent since early 2000 (International Energy Agency, 2018). According to the United Nations Conference on Trade and Development, 80%–90% of transported products is transported through maritime transportation (Baldi et al., 2015). The contribution of the shipping industry amounts to 2.1% of global GHG emissions (Baldi et al., 2014), which is expected to increase further in the upcoming years as new trade links and routes are expanded (Baldi et al., 2016). The need to justify the sourcing strategies and adopt green policies across the supply chain is crucial to global organizations (Bicer and Dincer, 2018a).

The shipping of hydrocarbons constitutes approximately 30% of the world's growing seaborne trade (United Nations Conference on Trade and Development, 2018). Traded natural gas is expected to increase from a recorded 25% in 2017 to 28% of the global gas mix by 2022. Between the period 2017 and 2022, natural gas trades are expected to experience a 1.6% compound yearly growth rate, where natural gas demand is expected to grow to about 300 BCM. Approximately 50% of this growth is expected to be driven by the Asian market, which is expected to increase its liquefaction capacity with an additional 132 BCM annually between 2017 and 2022 (McKinsey, 2018). Moreover, bunker fuel prices have demonstrated growing trends over time, which raises concerns for companies operating large fleets (Baldi et al., 2014). Approximately 56% of the global liquid fuels (such as petroleum) consumption is driven by the transportation sector and is expected to reach 132 EJ by 2040 (International Energy Outlook, 2018). Hence, efforts to mitigate the adverse environmental impacts of the oil and gas supply chains involve various measures, such as reduced flaring, process optimization, and the utilization of clean fuels, which have been extensively reviewed in fuel-utilizing industries such as the aviation sector for over two decades.

As a result of growing energy security, environmental, and economic concerns, policymakers have begun to shift their attention away from fossil fuels. Today, many policymakers and energy analysts worldwide believe that hydrogen has the potential to transform the world's energy outlook. The United Nations Energy Program is also closely monitoring the advancements in hydrogen-energy technology, as it can potentially provide the transition towards a sustainable energy future in the transport sector. The current demand for pure hydrogen is approximately 70 million tons per year (International Energy Agency IEA, 2019). Hydrogen in its pure form constitutes 60% of global hydrogen demand and is required for specific applications, which are mainly oil refining and ammonia production. The remaining 40% represents the additional 45 million tons of demand for a mixture of gases that contains hydrogen, which is mainly used for methanol and steel production. The future demand profile for hydrogen depends on the downstream products' demand (primarily fuels for transportation, fertilizers for food production, and construction material) (International Energy Agency IEA, 2019). However, the complete transition to hydrogen as a replacement for fossil fuels can only be achieved if the current technical, environmental, and cost challenges associated with hydrogen production, storage, and distribution are overcome (United Nations Environment Program (UNEP), 2006). For instance, ammonia, which is a high-density carbon-free hydrogen carrier, has been considered as a potential energy storage medium, therefore providing a practical and clean alternative to fossil fuels (Valera-Medina et al., 2018).

While some studies highlighted the possibility of employing green supply chain principles in the energy and shipping industries (Caniëls et al., 2016; Redda et al., 2010; Soda et al., 2015; Andersen and Skjoett Larsen, 2009; Al-husain, 2014), other studies considered the ship propulsion system. For instance, Huan et al. (2019) examined the main characteristics of multiple propulsion systems in terms of their consumption of fuel, emissions generation, and boil-off-gas treatment. Also, other studies evaluated the application of operational research models within the energy sector (Press, 2008; Fazlollahi and Maréchal, 2013; Fazlollahi et al., 2012; Hwangbo et al., 2017; Sangaiah, 2020). Furthermore, another set of reviewed studies have focused on assessing the environmental impact of different fuels. Incidentally, when determining the benefits of different fuels from an environmental and cost perspective, an assessment spanning the fuel's life cycle should be considered. In this regard, Life Cycle Assessment (LCA), which addresses environmental facets and potential environmental impacts of a particular production system throughout its life cycle (International Organization for Standardization (ISO), 2006), can be utilized to support a comprehensive and holistic analysis for the whole life benefit of the fuels. The LCA approach has been widely used to assess various vehicles for transportation, i.e., cars, aircraft, and ships (Bicer and Dincer, 2018a,b,c,d; Rose et al., 2013; Bicer and Dincer, 2017a; Koroneos et al., 2005; Michihiro Kameyama and Hiraoka, 2007; Jivén et al., 2004; Nicolae et al., 2014; Bengtsson et al., 2014). In addition to vehicles, LCA is commonly used to evaluate the environmental impact of fuels across their life cycle from the extraction stage up to the consumption stage (Bicer et al., 2016; Valente et al., 2017; Simons and Bauer, 2011; Suleman et al., 2016; Bengtsson et al., 2013, 2011; El-Houjeiri et al., 2019). Based on the reviewed literature, it is evident that ammonia and hydrogen have captured the attention of many scholars. For instance, Bicer and Dincer (2018c) studied the environmental impact of ammonia and hydrogen-fuelled maritime vehicles by conducting a Well-to-Hull analysis encompassing the emissions generated from ship and port manufacturing, maintenance, and operations. Similarly, the LCA conducted by Michihiro Kameyama and Hiraoka (2007) has included shipbuilding, ship operation, dismantling, and recycling in addition to the production of fuels, material, and ship parts. In terms of fuels, Bengtsson et al. (2011) performed a comparative life cycle assessment of several marine fuels, namely HFO, MGO, liquefied natural gas (LNG), and GTL. Their comparison also involved two exhaust abatement technologies for NO_X and SO_X.

1.1. Review motivation, objective, and structure

This review is driven by the fact that the shipping industry is deemed to be a major contributor to global GHG emissions and hence to global warming. Therefore, exploring pathways for emission reduction in maritime transportation is expected to be of significant importance to environmentalists and maritime fleet operators. This review explores the possibility of using several clean fuels for maritime application. This study is divided into two main segments. The first is composed of an environmental, economic, and technical evaluation of multiple possible alternative bunker fuels. The environmental assessment of the fuels is not only limited to the consumption stage; it extends across the entire supply chain of the fuel. Fig. 1 depicts the supply chain of the evaluated fuels. This study compares the emissions generated across the entire life cycle of multiple fuels, such as LNG, hydrogen, and ammonia; adopting such a method can lead to a different conclusion than focusing solely on emissions caused by the fuel consumption. For example, comparing CO_2 emission generated from consuming the previously mentioned fuels will deem LNG as the most pollutant fuel, however, an LCA-based comparison between LNG, grey hydrogen, and grey ammonia will yield a different result. The term grey denotes the use of a carbon-based fuel as a feedstock to a fuel's production process. Fig. 1 provides a graphical representation of the production stages considered while adopting an LCA-based environmental assessment of LNG, grey hydrogen, and grey ammonia.

In the second phase of this review study, the possibilities of establishing synergies between supply and demand are examined as illustrated in Fig. 2. Such synergies can be achieved by exploring the possibility of further processing natural gas into other forms of fuels, which are required by customers. Essentially, the first phase focuses on the shipping stage of the LNG value chain by exploring different options for bunker fuels and comparing the emissions generated throughout the life cycle of the specified fuels. The second phase will mainly focus on the distribution stage of the LNG value chain as the market condition in different LNG importing countries is assessed.

This review will cover the following subtopics:

- *Shipping regulations*: Summarizing efforts exerted by regulatory authorities.
- *Shipping operations*: An overview of the multiple operational and design factors that affect the volume of emissions generated from ships.
- *Clean fuels*: General introduction and brief market analysis of several current and potential clean bunker fuels namely, LNG, hydrogen, ammonia, and biofuels.
- *Bunker fuel production and consumption*: General description of the production and consumption of current and potential bunker fuels.
- *Environmental assessment*: Highlighting the environmental aspects of maritime vessel bunkering where several LCA studies from literature are compared.
- *Market prospects of clean fuels*: Demonstration of the growing interest in clean fuels for many countries worldwide.

1.2. Review contribution and novelty

From an operational perspective, ship operators are obligated to limit the emissions generated from their fleet to comply with emissions limits set by environmental regulatory authorities. Therefore, this study is written to aid ship owners, operators and scholars interested in exploring the various means of reducing the adverse environmental effect of the shipping industry. Furthermore, from a strategic level, this study can be beneficial for decision-makers as it supports the evaluation of current and future options for their fuel export. This study explores the necessity for strategic decision making in terms of national fuel production profile for both the short and long term, which can be addressed by understanding the possibility for the further processing of natural gas into alternative fuels that are required by customers. This can be seen to be more economical than transporting LNG when considering some factors such as boil-off gas generation and the social cost of carbon. According to a study conducted by Al-breiki and Bicer (2020), when considering both boil-off gas cost and social cost of carbon it was found that transporting liquid ammonia (1.11 \$/GJ) was more economical than transporting LNG (1.68 \$/GJ) (Al-breiki and Bicer, 2020). The second phase of this review mainly involves market analysis to understand the current nature of the demand for alternative fuels. Finally, the possibility of creating synergies between the transported product and consumed bunker fuel is examined. To the best of the authors' knowledge, there exists no such literature or similar analysis to those presented in this study.

As is the case with any industry or supply chain, in the early stages of development, the efforts of scholars, as well as operators, are all directed towards the enhancement of the structure and functionality of the value chain to enhance profitability. In the later stages, more attention is directed towards the exploration of better performing technologies that will yield better performance and enhanced efficiency. Unless guided by a certain regulatory entity (either global or local), the least consideration will be given to GHG emissions generated across the supply chain. In the past ten years, as the natural gas industry supply chain has witnessed significant development, and as the stringency of environmental regulators (i.e. IMO in the maritime industry) increases, more publications and studies have emerged in relevant domains such as clean fuels, bunkering emissions, and environmental impact assessment, in addition to studies that explore the effectiveness of the natural gas supply chain. The progression of these studies can be seen in Fig. 3.

Several studies in the literature have addressed the issue of emissions generated by seaborne transportation. However, the scope and the methodology deployed in those studies vary from one another, including this review. For example, Mersin et al. (2019) reviewed CO_2 emissions and reduction methods for maritime transportation, although they address the same issue, they presented a high-level analysis focused on the factors contributing to CO_2 emissions and generally tackles the factors that can regulate the amount of CO_2 emissions generated from the maritime shipping industry. This study presents its novelty in the fact that it addresses several aspects affecting the choice of bunker fuel used and emissions generated as a result of regulatory, operational, and market dynamics. The underlying purpose of this study is to provide a multi-dimensional and holistic view on the challenge of GHG emissions generated by seaborne transportation. Considering that various stakeholders in the shipping value chain might have a different perspective of this particular challenge, a collaboration between all stakeholders involved is the only means of achieving progress regarding climate change issues as far as the shipping industry is concerned.

2. Shipping regulations

It has been reported that the shipping industry should reduce its levels of CO_2 emissions by more than 80% relative to 2010 levels by the year 2050, as part of efforts to achieve the maximum 2 °C temperature increase climate goal (Baldi et al., 2016). As such, regulations to reduce fuel-related emissions have been applied to the shipping industry starting from the year 2011 from different entities, such as the revised version of the international

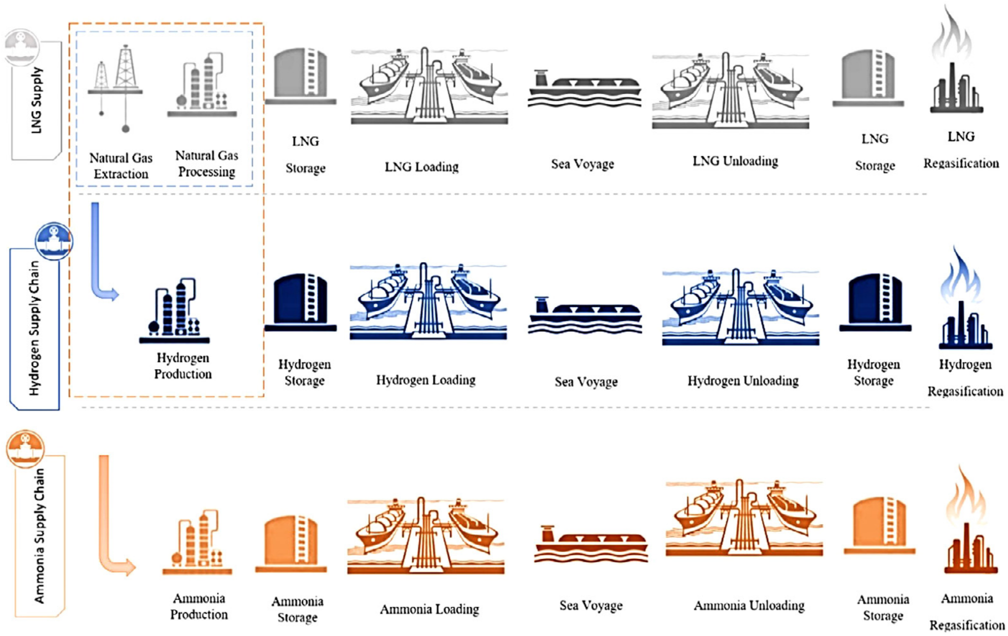

Fig. 1. Supply chains of evaluated fuels.

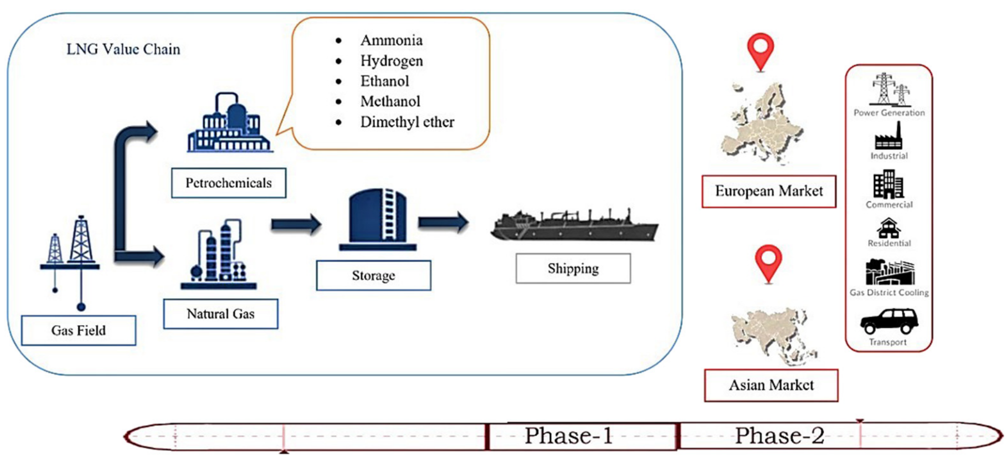

Fig. 2. Graphical representation of the structure of this research.

convention for the preventions of pollution from ships (MARPOL) (Baldi et al., 2016), which is a convention under the Marine Environment Protection Committee (MEPC). It is considered to be the main international convention concerned with the prevention of marine environmental pollution caused by ships due to operational or accidental causes (International Maritime Organization, 2020). MARPOL currently includes six technical Annexes: Annex I cover regulations for the prevention of pollution by oil. Annex II covers regulations for the control of pollution by noxious liquid substances in bulk. Annex III covers the prevention of pollution by harmful substances carried in packaged form. Annex IV covers the prevention of pollution by sewage from ships. Annex V covers the prevention of pollution by garbage from ships. Annex VI covers the prevention of air pollution from ships (Lloyd's Register Group Limited, 2020). MARPOL 2020 restricts the amount of sulphur within marine fuels to 0.5% by the commencement of the year 2020 (Smith et al., 2014), which will lead to a substantial transformation in the landscape of marine fuels. As the demand for alternative transportation fuels increases, a large shift in the global fuel mix is expected to occur. This major shift in demand will pose a challenge for refineries as the demand for Marine Gas Oil (MGO), or Low Sulphur Fuel Oil (LSFO) exceeds their production capacity (Mckinsey & Company, 2020).

Emission control areas (ECA) impose stricter restrictions on the emissions of SO_x, particulate matter (PM), NO_x, and other emissions from ships within the prescribed area in comparison to the restriction in other parts of the world. The International Maritime Organization (IMO) was founded in the year 1948 under the name of the Inter-Governmental Maritime Consultative Organization (IMCO), which was later renamed IMO in 1982. It is responsible for ensuring the safety and security of shipping in addition to preventing marine and atmospheric pollution caused by maritime transport. This is achieved by setting measures and regulations that cover all facets of international shipping, such as ship design, construction, equipment, manning, operation, and disposal (International Maritime Organization, 2020). The IMO has introduced the Emissions Control Areas (ECAs) to moderate the damaging impact of emissions on local air quality (Bengtsson et al., 2011). The presence of large harbours and intensive vessel traffic is identified as a common characteristic of these areas (Bengtsson et al., 2013). Sulphur Emissions Control Areas (SECA) with an allowable limit of 0.1% sulphur to be contained

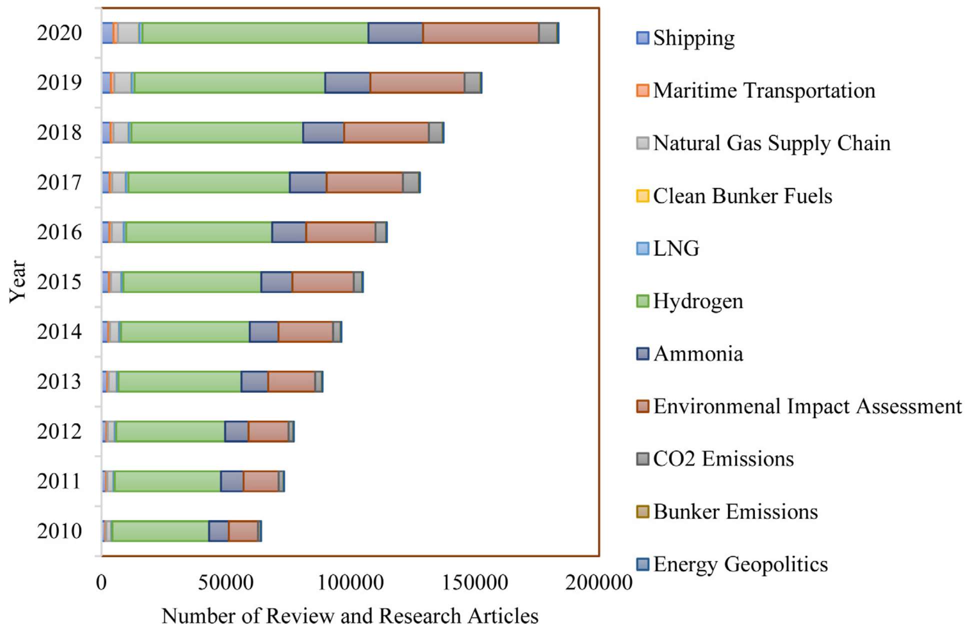

Fig. 3. A statistical view of the progression of studies (number of review and research articles) made available in the ScienceDirect database from the year 2010 until the year 2020.

in marine fuels beginning from 2015 has increased the demand for fuel with low sulphur content. As such, ships that operate outside and within these ECAs are compelled to switch fuel to comply with the variable limits and regulations (Bengtsson et al., 2013). The sulphur emission restriction has been increasing in stringency throughout the years for both ECAs and non-ECAs, reaching a 0.1% restriction as opposed to the 1% limit in 2015 for ECAs. The sulphur emission restriction for the rest of the world has also changed from its 2015 level of 3.5% to 0.5% (Bengtsson et al., 2013). Such restrictions impose additional pressures on ship owners and operators as they are forced to comply and can do so by considering several alternatives to comply with the sulphur content limitations that are imposed by IMO (Mckinsey & Company, 2020):

- Option 1: Switching to Low-sulphur fuel oil (LSFO)
- Option 2: Switching to Marine Gasoil (MGO)
- Option 3: Continue burning HSFO while using Scrubbers
- Option 4: Switching to Liquified Natural Gas (LNG)

As part of its efforts to limit the volume of GHG emissions, the IMO uses projection models to monitor the projected future emissions rate. The model considers several inputs such as transportation demand forecasts, development in fleet productivity, regulatory or independent improvements in the efficiencies. Emissions are then presented in aggregate and per ship type and in the size category (Smith et al., 2014). In recent years, the IMO has developed a set of technical and operational measures for ships. Both the Energy Efficiency Design Index (EEDI), and the Ship Energy Efficiency Management Plan (SEEMP) have gained the attention of governments, industry associations, and organizations that supports the interests of civil society. All of the aforementioned entities are aligned in terms of purpose, which is to ensure that environmental effectiveness is overseen by the EEDI and SEEMP through improved energy efficiency procedures to ensure a substantial decrease in the level of GHG emissions generated as a by-product of the international shipping industry (International Maritime Organization, 2011). The European Union is considering certain protocols to achieve a 40%–50% reduction in CO_2 emissions from ships accessing European harbours by the year 2050. Moreover, in Sweden, the fairway fees might be calculated against the clean shipping index in the near future, which includes CO_2 emissions (Baldi et al., 2016).

3. Shipping operations

According to LCA studies, the main source of the adverse environmental outcome during the life cycle of a ship is the operating stage (Michihiro Kameyama and Hiraoka, 2007). From an operational perspective, there are many factors to be considered that could reduce a vessel's fuel consumption. These categorized into two main categories: (i) Operational measures, such as introducing improvement in voyage execution, monitoring the performance of an engine, reducing auxiliary power consumption, and optimization of the level of draft/trim; (ii) Design measures, such as the use of more efficient engines and propellers, the introduction of an improvement in the hull design, the introduction of cold ironing, and the introduction of waste heat recovery systems (Baldi et al., 2015). Operational measures include efforts that involve no new equipment installation in the ship and include measures such as voyage planning optimization. The optimal route and speed for each ship are determined through the application of complex optimization algorithms which incorporate numerous considerations, such as customer's demand (i.e., time and magnitude of each cargo), maintenance plan of the available fleet, and the available supplies of the transported fuel. Mersin et al. (2019) have highlighted the fact that a reduction in ship navigation speed is becoming a common practice to reduce the amount of fuel consumption per voyage and thereby reducing emissions. When a ship operates at a higher speed, the ship water resistance increases as well, which results in less fuel demand. Given the fact that fuel economy is directly proportional to emissions, this leads to a lower environmental impact. Also, higher emissions are generated during manoeuvring conditions as opposed to ocean-going conditions (Chu-van et al., 2019). However, operating a ship below the optimum speed will lead to increased fuel consumption. Moreover, some other adverse effects can be incurred while operating a ship at a low speed, such as vibration and accumulations in combustion chambers and exhaust systems (Mersin et al., 2019). Al-haidous and Al-ansari (2020), conducted a review study focused on the application of

Table 1
Energy contents of common fuels (Marcellus Community Science, 2020).

Fuel	Amount	Heat content (BTUs)
Oil	1 gallon	138,095
Natural gas	1 cubic foot	1026
Coal	1 lb	9241
Gasoline	1 gallon	124,000
Electricity	1 kWh	3412
Diesel or heating oil	1 gallon	139,000
White oak (20% moisture content)	1 cord	27,000,000

quantitative models to manage the LNG supply chain sustainably. It was highlighted that several studies have been employing mixed-integer linear programming as an optimization tool mainly aimed towards increasing profitability rather than sustainability (Al-haidous and Al-ansari, 2020). Similarly, Chu-van et al. (2019), have highlighted that a classic scheduling problem in the industrial-maritime application is aimed at minimizing the total cost of a fleet while ensuring that all demand is satisfied (i.e, all cargos are delivered) (Halvorsen-weare and Fagerholt, 2010; Christiansen and Ronen, 2004). The joint use of optimization tools along with LCA was discussed by Guille et al. (2020), such an approach will be of high importance for the chemical industry in the near future given the increased stringency of environmental restrictions (Guille et al., 2020).

On the other hand, in terms of design considerations, the age profile of the existing fleet is considered a major contributor to CO_2 emission reduction. The majority of the existing ships in the global fleet have been constructed within the last 14 years, whilst the typical ship decommissioning age ranges between 25 and 30 years (Speirs et al., 2020). The age profile of the existing global fleet determines the pace at which the newly built ships, including natural gas-powered ships, are expected to penetrate the market (Speirs et al., 2020).

To achieve further reductions in emissions, an analysis of the design aspects is required, considering a typical engine, which consists of the main engine, auxiliary engine, boiler each having a demand for a different form of energy: mechanical energy to drive the main engine propulsion, electrical energy to run the auxiliary engine(s), thermal energy generated by the boiler to satisfy various onboard machinery and services (Baldi et al., 2016). Moreover, energy demand varies according to the operational profile of the ship. This operational profile is dictated by many factors, such as weather conditions, time, and scheduling restrictions. This variation is accompanied by a variation in fuel consumption and the magnitude of emissions. There is virtually zero mechanical power demand for propulsion when a ship resides at the port (Baldi et al., 2014). However, the energy demand can vary throughout the voyage depending on factors, such as the amount of LNG transported during the delivery voyage, the amount of heel volume remaining in the container after loading, and the amount of ballast water loaded into the empty vessel to help maintain its balance through the return voyage. The speed of the ship is varied throughout the voyage, and this affects fuel consumption. The heat content of a fuel (measured in BTUs) determines how much useful energy can be obtained by burning this fuel. The heat content of common fuels is provided in Table 1.

Most ships within existing fleets around the globe are equipped with engines that burn heavy fuel oil. Therefore, to facilitate the shift to liquified natural gas as shipping fuel, the engines of these ships require retrofitting. Currently, several ship engine types are capable of burning liquified natural gas, where emissions and costs are correlated with the characteristics of these engines. The four main engine types are Medium Speed 4-Stroke Lean Burn Spark Ignition (LBSI) engines, Medium Speed 4-Stroke Low-Pressure Dual-Fuel (MS-LPDF) engines, Low-Speed 2-Stroke Low-Pressure Dual-Fuel (LS-LPDF) engines, and Low-Speed 2-Stroke High-Pressure Dual-Fuel (LS-HPDF) engines (Speirs et al., 2020).

From an operational perspective, switching from residue fuel to low sulphur distillate fuel jeopardizes the engine life in cases where they are not done properly. Moreover, switching to a different fuel can impose some technical difficulties while operating the engine. During the period from 2009 to 2011, the State of California witnessed an increase of over 100% in the reported loss of propulsion incidents. Half of which was due to fuel switching difficulties (Krzyżanowski and Nowak, 2014). Ship operators can choose to continue burning high sulphur fuel oil while controlling the emissions generated by installing exhaust gas cleaning systems. These systems commonly referred to as scrubbers are comprised of a technology that allows the vessel to continue burning high sulphur fuel oil while complying with the limits imposed by IMO in terms of sulphur emissions. This is achieved by employing alkaline water into the vessel's exhaust, which then traps sulphur and other harmful emissions in that water (S. & P. Global Platts, 2019). Aside from low sulphur fuel oil and LNG, hydrogen, ammonia, and biofuels can result in a significant drop in GHG emissions caused by fuel combustion and production. This mainly depends on the production process of these fuels in addition to the feedstock used to produce these fuels. In summary, the increased stringency of environmental regulations imposed on maritime transportation by regulatory authorities acts as a catalyst for the evolution of existing ship operations management practices. Ship operators will have to explore all possible enhancements leading to less GHG emissions caused by shipping, such as enhancing fuel efficiency, optimization of shipping routes, enhanced inventory management, and the utilization of alternative clean fuels.

4. Clean fuels

In the past few years, several developed countries have been interested in clean fuels as a potential replacement for conventional fossil fuels. Some countries were driven by their obligation to global agencies to reduce their emissions to decrease global warming. During the 2015 United Nations Climate Change Conference (COP 21), an agreement was developed and signed by several countries worldwide. The purpose of this agreement was to maintain the rise in the global average temperature below 2 °C above pre-industrial levels (UNFCCC, 2016). Incidentally, countries that are self-sufficient in terms of hydrocarbon fuels lag with the developed world in the transition towards wider adoption of 'clean fuels'.

4.1. Liquified natural gas

The continent of Asia is considered to be the biggest LNG consumer worldwide as it is responsible for a trading magnitude that is equivalent to three-quarters of global LNG trades and one-third of total global natural gas trade (The Maritime Executive, 2020). The demand for natural gas in the five years to come will certainly be driven by demand from the Asian market (International Energy Agency, 2019). The global gas demand is mainly being met by the Middle East, Russia, Australia, and the United States (A joint study of the International Energy Agency and Korea Energy Economics Institute, 2019). The major share of the probable upsurge in global energy consumption is attributed to non-OECD Asian countries, a group that includes China and India. Energy demand observed in 2018 for this category was found to be larger than any other region. This demand is projected to reach almost double the observed demand in 2018 by the year 2050. Therefore, it is considered the largest and fastest-growing region in the world in terms of energy consumption. The rapid increase in population growth rate in addition to access to an abundance of domestic resources acts as the main determinant of energy demand in Africa and the Middle East (EIA, 2019a). China is likely to continue to be the main driver for the future growth in gas demand even though this increase in demand is expected to be slower than in the recent past due to a slowdown in economic growth. Currently, natural gas accounts for 10% of China's primary energy consumption and this share is expected to grow to 15% by the year 2030 (Zhongyuan et al., 2018). Moreover, China's partial switch from coal to gas plays a major role in the growth in demand (International Energy Agency, 2019). Meanwhile, the emergence of a rapidly growing LNG importer such as China and India has resulted in substantial growth in the Asian LNG market coinciding with more diversification from LNG suppliers. Thus, shorter, and more flexible LNG contracts started to emerge causing a significant impact on the price structure (International Energy Agency IEA, 2019).

The convergence of gas prices in different gas markets was more observable in the year 2019, where a sharp decline in differences in regional prices have been witnessed (especially between Asia and Europe). However, price volatility still exists to a high degree in the Asian spot market. This price convergence is likely to be further encouraged by the expansion of LNG trades. However, the debottlenecking of pipeline capacity within the Permian Basin is expected to keep the US gas prices at a low level in the future (International Energy Agency IEA, 2019). The Asian region does not have a benchmark in terms of pricing that reliably reflects the supply–demand dynamics in the Asian market. The Energy Information Administration (EIA) has initiated a study to explore the potential for the establishment of an Asian hub. Presently, the Asian region lacks the required physical infrastructure and regulatory frameworks to accommodate the creation of a natural gas trading hub. However, Japanese, Chinese, and Singaporean officials have been exploring the possibility of establishing such a trading hub. In the year 2016, Japan developed a comprehensive strategy liberating its domestic market while launching key initiatives encouraging the participation of the private sector in the development of an LNG trading hub and a pricing index. Also, a benchmark of LNG pricing indexes was established by Japan, China, and Singapore (El-Houjeiri et al., 2019).

4.2. Hydrogen

Hydrogen fuel has the potential to serve multiple sectors such as transportation, construction, and industrial sectors (IEA Hydrogen Technology Collaboration Program, 2017). Hydrogen can serve as a storage medium for solar and wind electricity technologies due to their intermittent nature (IEA Hydrogen Technology Collaboration Program, 2017). Nevertheless, a considerable amount of research and development efforts must be invested in overcoming the current technical and economic considerations that hinder the emergence of a hydrogen-based economy (United Nations Environment Program (UNEP), 2006). A practical solution for the issue of economic hydrogen cryogenic storage requirements, especially onboard vessels, is yet to be developed. Moreover, for hydrogen to gain a competitive economic advantage over other fuels, unit cost has to endure large reductions, especially in bulk transportation and storage utilizing economies of scale (United Nations Environment Program (UNEP), 2006).

Moreover, hydrogen-powered fuel cells have the potential to replace conventional oil-based fuels in road vehicles. Fuel cells act as a means to convert the intrinsic energy normally stored within a given fuel into another form of energy (O'Hayre et al., 2016). Hydrogen–Oxygen Fuel Cell is an electrochemical device that utilizes the energy released from the chemical reaction of hydrogen and oxygen in generating electricity. This energy conversion is conducted in an environmentally-sound manner as it is only associated with the generation of water and heat (IEA Hydrogen Technology Collaboration Program, 2017). The huge capacity needed to replace existing hydrocarbon systems in addition to meeting growing global energy demand indicates that fossil fuels will continue to be the mainstay of the global energy system for a while. Likely, the initial stage of the transition to a hydrogen-based economy will mainly involve hydrogen that is produced from fossil fuels generated by the existing energy systems. Liquified natural gas specifically can bridge the gap between the existing fossil fuel-based economy and the future hydrogen-based economy. Furthermore, it can be economically viable to create a blend of hydrogen and natural gas and allow it to be transmitted through the existing pipeline systems (United Nations Environment Program (UNEP), 2006).

While a sustainable global energy future can be attained by utilizing hydrogen fuel in addition to other clean fuels. It is important to note that hydrogen can only be considered as a clean fuel if the technologies utilized in its generation and consumption are also clean (United Nations Environment Program (UNEP), 2006). There are three classes of hydrogen: (1) Grey Hydrogen: produced from a hydrocarbon-based fuel, which implies that CO_2 emissions were associated with its production; (2) Blue hydrogen, where grey hydrogen is accompanied by carbon capture technology; (3) Green hydrogen where hydrogen production from renewable energy and with zero emissions. Currently, the major share of the produced hydrogen is from methane reforming, where methane is normally obtained from natural gas, and in some cases, oil and coal are also used to generate hydrogen (IEA Hydrogen Technology Collaboration Program, 2017). However, minimal emissions associated with hydrogen production from natural gas can be attained by the implementation of carbon capture and storage technology. Progressively renewable and nuclear energy sources will replace fossil fuels as a primary energy source for the production of hydrogen and electricity as the production routes are illustrated in Fig. 4 (United Nations Environment Program (UNEP), 2006).

The current worldwide public spending directed towards low carbon energy technologies (technologies including Carbon Capture and Storage (CCS), renewables, nuclear, hydrogen, and fuel cells) research and development amounts to $18.5 billion per year as estimated by the International Energy Agency (IEA) (IEA, 2019). Japan is currently intensifying its efforts in developing technologies to facilitate its transition to a hydrogen-fuelled economy. The Fukushima Daiichi incident compelled the Japanese government to conduct a full review in an attempt to attain the optimal energy portfolio mix for the year 2030 (Tanaka, 2013). In the year 2018, Kawasaki, Iwatani, J-Power, and Marubeni Corporation formed an association with the Australian company AGL Loy Yang. Financial provision was provided by Australian and Victorian governments to facilitate the construction of a gas refining facility in addition to a hydrogen liquefaction and loading terminal. Excluding the Australian ally, AGL Loy Yang, the Japanese consortium joined with Shell Japan, and Electric Power Development has focused their efforts on developing an energy supply chain that is free of carbon dioxide emissions. As a result, the Hydrogen Energy Supply-Chain Technology Research Association (HYSTRA) was founded in the year 2016 (Maritime Executive, 2019). Japan's project "New Hydrogen Project (NEP)" was initiated in 2003 with a focus on commercialization. Funding for this project has been raised on an annual basis and has reached $320 million during the financial year 2005. The NEP resulted in setting ambitious targets for fuel-cell vehicle introduction, fuelling stations, and stationary fuel cell power systems for the years 2010 and 2020 as demonstrated in

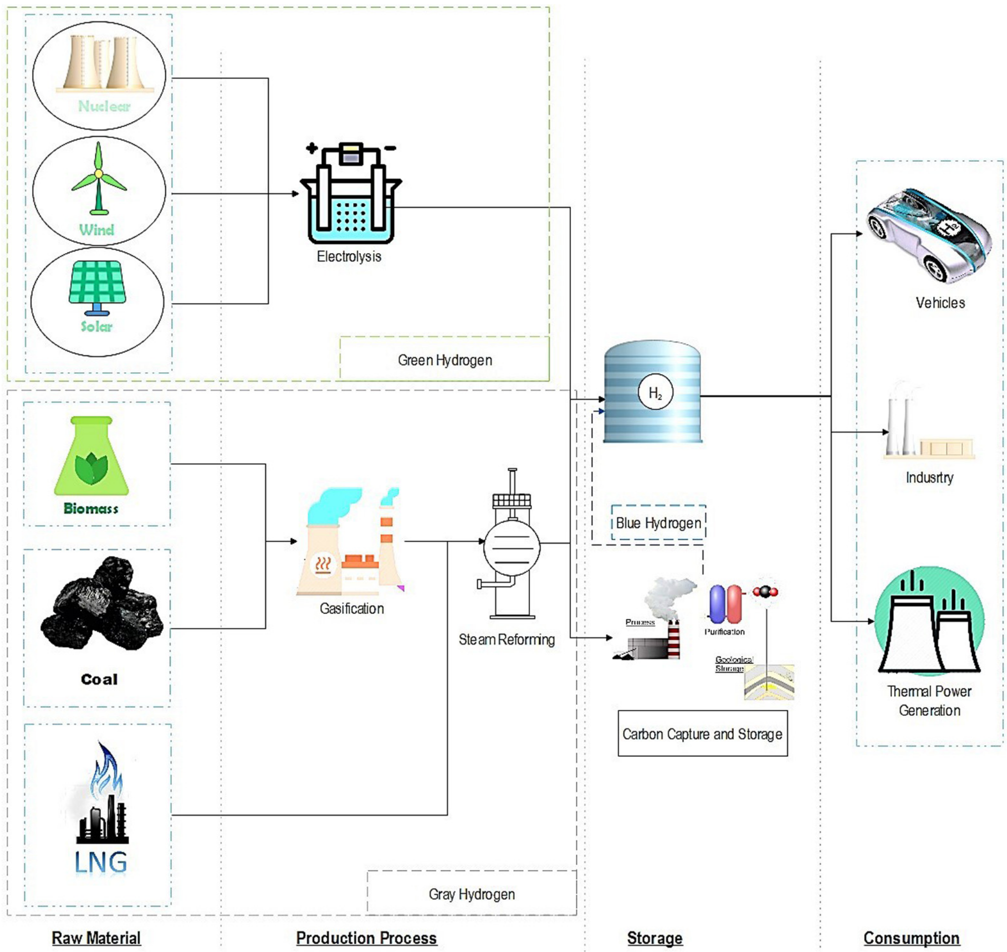

Fig. 4. Hydrogen production routes from different energy resources and application areas (United Nations Environment Program (UNEP), 2006).

Table 2
Hydrogen commercialization targets in Japan (United Nations Environment Program (UNEP), 2006).

Application	2010	2020
Fuel-cell vehicles on the road (number)	50,000	5,000,000
Hydrogen refuelling stations (number)	–	4,000
Stationary fuel-cell co-generation systems (MW)	2,200	10,000

Table 2. According to the International Energy Agency, a total of 470 hydrogen refuelling stations have existed worldwide by the end of 2019. Even though this number is very far from the Japanese optimistic target mentioned in Table 2, most of the hydrogen fuelling stations in the world are located in Japan (113 Stations) (IEA, 2020).

A national collaboration with the State of Qatar is currently under exploration by Japan as Japanese authorities highlighted Qatar's capability of producing hydrogen at a competitive price (Gulf Times, 2018). Moreover, China's motivation towards funding hydrogen research and development projects is mainly motivated by the magnitude of its population in addition to its raising concerns about energy security. The UNDP/GEF demonstration project has facilitated the operation of Beijing's first hydrogen-fuelled buses. Moreover, the Republic of India budgeted 2.5 billion rupees ($58 million) for funding hydrogen and fuel cell projects over three years until the year 2007. One of India's projects involves fuelling about 50 buses in New Delhi with a blend of hydrogen and diesel fuel. The republic of India plans to introduce 1000 hydrogen-powered vehicles by the end of this decade (United Nations Environment Program (UNEP), 2006). Moreover, the Korean government has started funding hydrogen-related research and development since the year 1998. Another program was launched in the year 2004 with a budget of $586 million. The program's objectives included renewable-based electrolysis as a means of producing hydrogen, the commercialization of stationary 370 MW fuel cells, in addition to introducing a total of 10,000 vehicles that utilizes fuel cell technology. The Korean Government has also made several subsidies available for hydrogen and fuel cell investments (United Nations Environment Program (UNEP), 2006). Australia has set another example of national efforts exerted to advocate the transition to hydrogen fuels. It is expected to become the leader in this domain due to its efforts in forming collaborations with local and international companies. Thus far, cooperation agreements have been signed with Japan, and the way was paved to initiate agreements with the Republic of Korea. During the period between 2015 to 2019, the total investment from the Australian government in hydrogen projects across the supply chain have amounted to $146 million (COAG Energy Council Hydrogen Working Group, 2019). The European Union is accelerating the commercialization of hydrogen-related technologies. Production related projects target the advancement of research conducted to construct a large-scale plant for demonstration. This plant is capable of producing hydrogen fuel in addition to electricity on an industrial scale while separating and storing CO_2 generated as a side product of the process. End-use projects are focused on exploring the economic and technical feasibility of managing what is known as "Hydrogen villages". This will help achieve: (i) centralized and decentralized hydrogen infrastructure for both production and distribution; (ii) hydrogen-power systems that are autonomous or connected to a distribution grid; (iii) a large number of vehicles that run on hydrogen; and (iv) fuel-supplying infrastructure (United Nations Environment Program (UNEP), 2006).

4.3. Ammonia

Although ammonia is a fuel that does not contain carbon in its chemical composition. Around 80% of the world's ammonia production in the year 2018 was used as feedstock for the production of fertilizers (Business Wire, 2019). The USA is the biggest importer of ammonia with a share that amounts to approximately 35% to 40% of the world's trade, whereas 25% of global trade is accounted to Europe. A major share of the imports' development is anticipated to occur in Asia due to its industrial demand (Bicer et al., 2016). Ammonia can also be utilized to contribute to power generation along with other fuels. The Wobbe index of the ammonia blends is in proximity to that of hydrogen in comparison to hydrocarbon-based fuels and has a similar volumetric high heating value. This simplifies the conversion process of equipment fuelled by hydrogen to ammonia or vice versa (Valera-Medina et al., 2018). The US National Fire Protection Association (NFPA) has categorized ammonia as a toxic substance, although the hazards associated with its unintended ignition or explosion are much lower than other fuels due to its low level of reactivity (Valera-Medina et al., 2018). Furthermore, ammonia can be supplied via pipeline to residential areas to serve as fuel for vehicles, boilers and furnaces, and stationary generators (Bicer et al., 2016). The Fukushima Renewable Energy Institute (FREI) has developed fuel-flexible platforms to burn liquid ammonia generated from renewable sources in combination with kerosene. It proved that the equipment can be operated using blends of ammonia–kerosene at various concentrations, where the gas turbine was started by kerosene which was later replaced by ammonia (Valera-Medina et al., 2018). Several companies have initiated programs to enhance their understanding of ammonia-fired systems. The most notable program is the "Power-to-Ammonia" program developed by NUON in collaboration with TU Delft, OCI Nitrogen, Proton Ventures, ISPT, AkzoNobel, and the University of Twente. In this project, ammonia is perceived as a "super battery" that reserves excess renewable power at a large-scale over prolonged periods (Valera-Medina et al., 2018).

Green ammonia is another option being explored for its potential to serve as an emission-free fuel. Fig. 5 outlines the stages involved in the production of green ammonia and its potential uses. The NUON-Magnum gas-fired combined-cycle power plant located in Eemshaven, Netherlands, is planned to be transformed into a green ammonia-fuelled plant. The facility's power generation capacity is sufficient to meet the demand of approximately two million Dutch households. A project to convert one of its units to run on hydrogen is currently in progress and is due to be completed by 2023. Upon completion, this advancement will be the first of its kind as the facility will be the world's first 100% carbon-free power generation facility fuelled by hydrogen (Valera-Medina et al., 2018; NS Energy, 2020). The AmVeh ammonia fuelled engine technology provides a new concept, which is to convert existing vehicles to operate with 70% ammonia and 30% gasoline. The Korean Institute for Energy Research (KIER) has converted an LPG gasoline unit by adding a control system and removing the corrodible metals. The KIER claims that this system can yield an annual CO_2 emissions reduction of 10 million tons if installed in 20% of vehicles in Korea (Valera-Medina et al., 2018).

4.4. Biofuels

Vegetable oils represent a promising replacement to diesel due to their renewable nature and the fact that they can be easily produced in rural areas. Several engine issues are encountered as a result of burning raw vegetable oils, such as the accretion of carbon particles on the piston and head of the engine and excessive engine wear. Therefore, many researchers recommended the transesterification of vegetable oils to reduce their viscosity (Hassan and Kalam, 2013). Transesterification is a process by which monohydric alcohol is reacted with vegetable oil or animal fat to generate the corresponding Mono Alkyl Esters with the aid of a catalyst (Keera et al., 2011). Transesterified vegetable oils are called biodiesel, which can be considered an alternative to conventional diesel fuel within the transportation sector. Biodiesel refers to a variety of ester-based oxygenated fuels that are produced from biological sources, such as sunflower, soya bean, palm, and corn. Switching to biodiesel does not require a lot of modifications to the engine and results in a reduction in the amount of GHG emissions generated. This makes it a more favourable option for decision-makers, in terms of achieving multiple objectives of energy security and environmental sustainability in addition to contributing to rural development.

In addition to biodiesel, another commonly used biofuel is bioethanol, which is mostly produced from the fermentation or hydrolysis of sugarcane, corn, wheat, maize, and potatoes (Hassan and Kalam, 2013). The production of ethanol was established by utilizing molasses generated from the sugar industry, and in association with the market growth of ethanol in the 1980s, autonomous ethanol plants started to emerge in the industry (Bergmann et al., 2018). An additional emerging biofuel is known as Bio-Synthetic Natural Gas. This fuel is produced by converting synthetic gas into methane, where the feedstock for this process is biomass. A feasibility study reviewing the use of Bio-Synthetic Natural Gas delivered via the gas grid as a way to decarbonize road transport and heat generation was conducted in the North East of England Process Industry Cluster, National Grid, and Centrica (Bioenergy Insight, 2010). The study concluded that the amount of CO_2 emissions generated from burning Bio-Synthetic Natural Gas is 90% less than the fossil fuel alternatives (Bioenergy Insight, 2010).

Evidently, there is a global transition towards the utilization of clean fuels. This is confirmed by the enormous investments made by many developed nations to facilitate the transition to cleaner energy supply chains. Given the fact that the world has not yet entirely adapted to the use of such fuels, an enormous technological advancement needs to take place to enhance the robustness and maturity of the supply chain of these fuels, in addition to ensuring that a satisfactory level of performance is expected from the engines designed to utilize these fuels. In the years to come, the results of these national-level efforts will start to emerge and will result in the expansion of integrated sustainable energy supply chains for various energy systems.

5. Maritime propulsion systems

The propulsion of a maritime vehicle is a major energy demand source onboard a ship. Baldi et al. (2014) have highlighted that propulsion energy demand constitutes 68% of annual ship energy demand (Baldi et al., 2014). In the past, ship-energy systems have been adopting a relatively simple setup consisting of a single main engine for propulsion, two or more auxiliary engines for auxiliary electric power generation, and a single boiler to facilitate onboard thermal power generation, which means that the three main types of power demand of a ship (mechanical, electrical, and thermal) are fulfilled using three separate

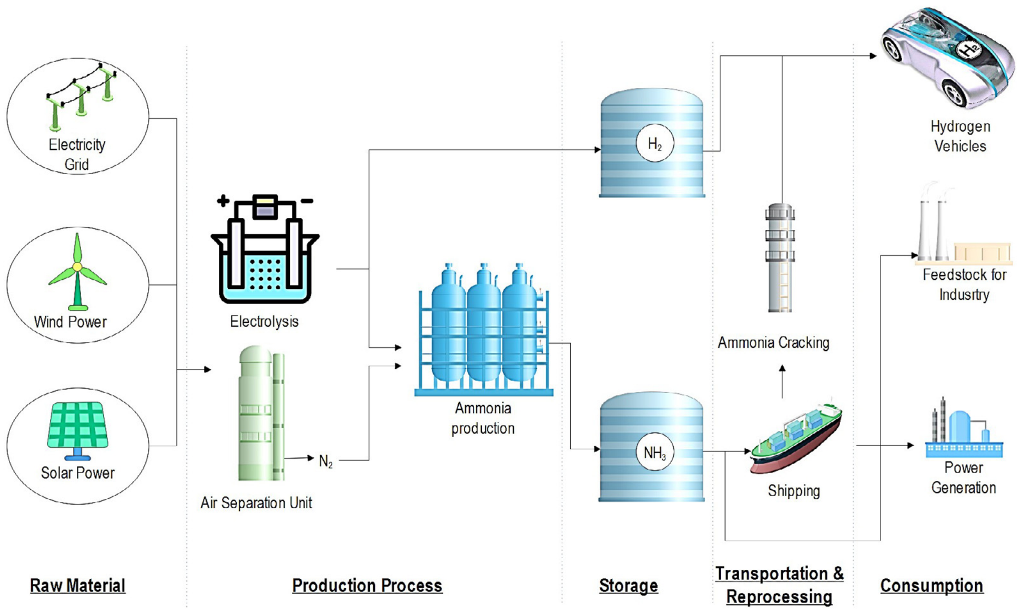

Fig. 5. Green ammonia production and potential uses (Valera-Medina et al., 2018).

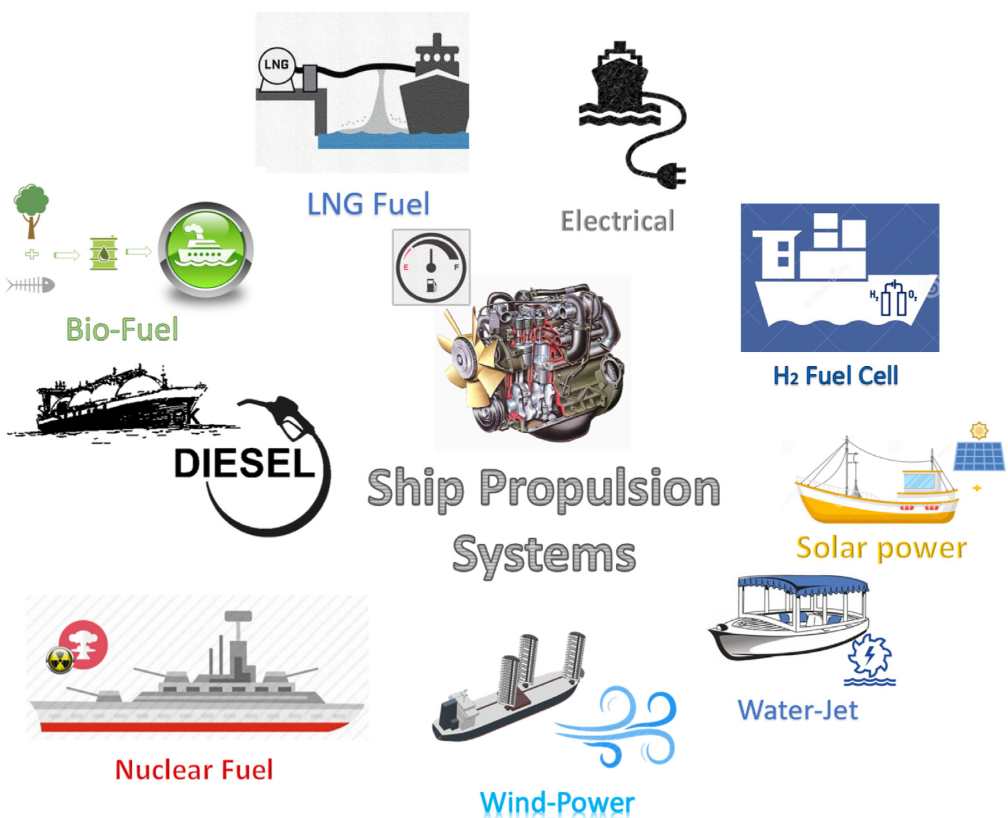

Fig. 6. A pictorial representation of various ship propulsion options.

systems. However, growing energy efficiency requirements fostered the integration of onboard energy systems. Various types of integrations between the aforementioned three systems have been introduced recently to enhance efficiency and simultaneously provide flexibility in fulfilling different types of energy demand. Facilitating such integration have proven to result in up to 2% of fuel savings (Baldi et al., 2016). In terms of satisfying a ship's propulsion energy demand, multiple pathways are available in the literature, such as single fuel/propulsion engines (like a diesel engine or engines fuelled by other fuels like LNG), gas turbine propulsion, biodiesel propulsion, fuel cell propulsion, steam turbine propulsion, wind propulsion, water-jet propulsion, solar propulsion, nuclear propulsion. Also, dual-fuel engines such as diesel-electric propulsion are available. In such hybrid-electric propulsion systems a battery with a large capacity is utilized to store electricity for later onboard fuel consumption. When electricity is used the quantity of emission generated throughout a particular voyage is reduced as the amount of fossil fuel required is reduced. This has recently attracted the attention of scholars and industry officials as a means to reduce emissions generated from bunker fuel consumption (Jianyun et al., 2019). Fig. 6 shows a representation of various kinds of propulsion systems used in a ship.

5.1. Emission abatement technologies

Exhaust gas emissions are an inevitable by-product of the combustion process of any conventional bunker fuel consumed. There are three main categories of emissions NO_x, SO_x, and CO_2 emissions. NO_x is a term used to refer to nitrogenous oxide gases such as NO, NO_2, and other oxides of nitrogen. Nitrogen dioxide is considered to be the most common NO_x form. NO_2 is a highly reactive gas that is created by the oxidation of nitric oxide (NO) in ambient air. On the other hand, NO_x is formed through a complex process that involves the nitrogen found within the combustion air and nitrogen within the fuel. The main source of human-induced NO_x emissions is from combustion at high temperatures. The biggest contributor to global emissions generated from shipping is NO_x, followed by SO_x and CO_2 emissions (Bengtsson et al., 2011). Both local and international impacts are perceived as a result of the previously mentioned exhaust gas generation. Local air quality is mainly affected by pollutants such as NO_x and SO_x, whilst CO_2 emissions, have an adverse global impact affecting the climate in the long term (Bengtsson et al., 2011).

Zincir and Deniz (2014), mentioned several emissions abatement systems and methods. For NO_x emissions, the following are considered; exhaust gas recirculation, selective catalytic reduction, scavenger air humidification method, water injection; for SO_x emissions, the emphasis is on SO_x scrubbers; and for CO_2 emissions, special anti-fouling paint, and production of extra-long stroke main engines are considered (Zincir and Deniz, 2014). Elgohary et al. (2015) highlighted that amongst the aforementioned methods, the highest NO_x reduction can be attained by the selective catalytic reduction method, which can lead to a 95% reduction. As SO_x emissions, the most effective way (excluding the fuel-switching approach) was reported as seawater scrubbing, leading to up to a 95% reduction in SO_x emissions. Finally, Elgohary et al. (2015) highlighted that PM emissions using electrostatic filters could achieve a reduction of up to 85% of PM emissions (Elgohary et al., 2015). Moreover, Zincir and Deniz (2014) have highlighted that some of these methods can adversely affect other types of emissions while reducing the targeted type and increase fuel consumption. For example, while the exhaust gas recirculation method reduces NO_x emissions, it increases CO_2 and PM emissions, and it adversely affects fuel combustion. Moreover, cost and ship compatibility challenges can hinder the use of some of these methods (Zincir and Deniz, 2014). Furthermore, Goldsworthy (Goldsworthy, 2015), discussed different methods of reducing NO_x emissions generated from ship engines, such as simultaneously increasing compression pressure and delaying the fuel injection time, optimizing the patterns at which fuel is sprayed, and optimizing the shape of the combustion chamber. The study also highlighted that further reductions could be attained by other measures such as water injection (Goldsworthy, 2015). Also, a promising technology that utilizes a hybrid electron beam technology in combination with a wet scrubber was studied by Zwolińska et al. (2020). The reported SO_2 removal efficiency was 100%, while the achieved NO_x removal efficiency was 89.6% (Zwolińska et al., 2020).

6. Bunker fuel production and consumption

Hydrocarbon fuels are more favourable and commercially viable because they are considered mature products in the market with established infrastructure and handling requirements. Therefore, these fuels are intensively consumed within the transportation sector to fuel various transportation means, including air, road, and sea transportation. However, the focus of authorities in the transportation sector is shifting towards alternative fuels due to price fluctuations, limited proven reserves, and end-user emissions from hydrocarbons (Bicer and Dincer, 2017b). Moreover, it has been demonstrated that the addition of hydrogen or ammonia to conventional bunker fuels can further improve flame stability and mitigate NO_x production, which encourages the use of hydrogen or ammonia for power generation whilst limiting the amount of NO_x emissions associated with the process. Nevertheless, the severity of ammonia combustion hazards is moderated by its relatively slow reaction characteristic (Valera-Medina et al., 2018). Although hydrogen has the potential to be an energy carrier, issues concerning its special storage and distribution requirements have hindered its implementation. Therefore, both ammonia and methanol have emerged as potential indirect energy storage mediums.

6.1. Fuel oil

Fuel oil is one of the by-products of the refining process of petroleum, which yields different types of fuel oil depending on their intended use. Fuel oil is a flammable yellowish to light brown liquid that possesses the odder of kerosene. In terms of composition, the exact composition of fuel oil varies depending on several factors such as the source of raw material used as feed to the refinery, the refinery which is processing the raw material, and the existence of additives to name a few (Laffon, 2014). There are multiple classes of fuel oil. These classes are differentiated based on their characteristics, such as composition, boiling point, in addition to other physical properties. According to the classification set by the American Society for Testing and Materials (ASTM) standard (ASTM-D396), fuel oil is divided into six main classes (Laffon, 2014). There are mainly two types of fuel oil, distillate and residual fuel oil (Krzyżanowski and Nowak, 2014). Distillate fuel oils do not contain high boiling elements, and they normally have a specific boiling range as they undergo vaporization and condensation as part of the distillation process. There are two distinct grades of distillate fuel: Marine Gas Oil (MGO) and Marine Diesel Oil (consisting of a blend of HFO and MGO) (Bengtsson et al., 2011). Sulphur residual fuel oils contain more impurities and residues from the crude distillation of thermal cracking (Laffon, 2014). The amount of sulphur contained in the refined fuel correlates to that in the crude oil in addition to the type of processing it undergoes. Typically sulphur content is the heaviest fractions from the distillation column. Some refineries can produce low sulphur Heavy Fuel Oil (HFO) (with approximately 1% sulphur content) and Marine Gas Oil (MGO) (with less than 0.5% sulphur content). Generally, low sulphur marine fuels are produced by employing technical measures in the refinery, such as catalytic cracking and hydro skimming (Bengtsson et al., 2011).

6.2. Liquefied natural gas

Liquefied natural gas is a fossil fuel typically extracted from an underground reservoir consisting of a mixture of hydrocarbons, 90%–95% of which is methane (CH_4), in addition to other components such as ethane, propane, butanes, pentanes, water, hydrogen, nitrogen, carbon dioxide, and other gases. Liquified natural gas is natural gas that has been cooled to a temperature below its boiling point (i.e., −163 °C). Once refrigerated, natural gas shrinks to a volume that is 600 times smaller than its volume in a gaseous state. Natural gas is a non-toxic, non-corrosive colourless, and odourless substance. The concentration of these compounds varies depending on the reservoir. It is then refined through several processing stages to yield a product that contains more than 90% methane gas (Wikinson and Hudson, 2004). The existence of competitive LNG prices can result in incentivizing alternative fuel investment strategies set by companies (Merk et al., 2018). Therefore, LNG is expected to constitute around 80% of the marine fuels in the market by the year 2050 (Bengtsson et al., 2011). However, one adverse environmental outcome that results from using natural gas (which mainly consists of methane) as a bunker fuel is that methane slippage can occur. The release of uncombusted methane to the atmosphere has a GHG impact, which is between 28 and 34 times the amount of GHG emissions per gram of CO_2 over a 100-year prospect. In 20 years, the warming effect per grams of methane is 85 times that of CO_2 (Lindstad et al., 2020). Moreover, the global warming potential of natural gas is an aspect that could reduce the attractiveness of natural gas as a fuel. According to Bicer and Dincer (2018d), 97% of the global warming potential associated with natural gas-driven electricity production takes place within the fuel-combustion stage (Bicer and Dincer, 2018d). Manouchehrinia et al. (2020) have conducted a well-to-propeller environmental assessment of natural gas and concluded that about 82% of emissions are generated from the downstream operation and when natural gas is being consumed as fuel. LNG is therefore taken to be a more favourable option as opposed to marine diesel as it generates 50% fewer emissions when upstream operations are considered. Since the majority of emissions is generated from fuel consumption the studies addressing the development of cleaner propulsion technologies for natural gas driven engines is pivotal for making LNG a more favourable fuel for ship operators and thereby achieving a further reduction of the environmental impact of maritime transportation. However, it is important to highlight that aspects other than emissions need to be considered in future research while assessing new technologies for natural gas propulsion systems such as, methane slippage in addition to water consumption and wastewater treatment during the hydraulic fracturing process for the case of shale gas (Manouchehrinia et al., 2020).

The supply chain of natural resources is unique and complex. A typical LNG supply chain comprises several main stages: Exploration and production, conditioning and processing, storage, shipping, and distribution (WARTSILA, 2017). The nature of distribution might vary from one region to another. In some developed countries, natural gas is distributed to end-users via distribution grids, this grid forms a trading hub across countries such as Henry Hub in the US and Title Transfer Facility (TTF) in the Netherlands. However, in the Middle East, more specifically the Gulf Cooperation Council (GCC) countries, the existence of such trading hubs is not considered to be economically viable. Building such infrastructure would require an unjustifiable huge investment cost. Since most of the countries in the region are self-sufficient in terms of energy supply, exporting to external markets is more favourable. Due to geographical remoteness, shipping liquified natural gas is seen as the only feasible means of transportation.

The first instance of an LNG-fuelled ship (not an LNG carrier) was witnessed in the year 2000. This ship was operated by a Norwegian car/passenger ferry shipowner. The number of LNG-fuelled ships has grown since then. According to Rozmarynowska-mrozek (2015), as of July 2015, a total of 64 LNG-powered ships have existed. Fig. 7 illustrates the distribution of these ships according to the application and region of operation (Rozmarynowska-mrozek, 2015).

The world fleet consisted of 118 LNG-fuelled vessels in the year 2018 and this is predicted to double by the year 2020 based on the ship order data. A major portion of these ships are expected to operate in Europe, and approximately a third of ordered ships are expected to have global routes. Thereby, creating growing prospects for bunkering of LNG-Fuelled ships. Currently, LNG is transported in vessels using two main types of tanks; Self-supportive Moss type (Spherical aluminium tanks) and the Membrane type. In recent years, Membrane tanks are becoming more favourable as they require less space and a small vessel per volume capacity compared to the Moss type. The advantage of a spherical tank is that it reduces the severity of the sloshing of LNG throughout the voyage. Whereas in the membrane tank, if the tank is not filled, the sloshing of LNG can affect the stability of the entire ship (Bengtsson et al., 2013). The majority of LNG produced is consumed as fuel for electricity generation. The electricity generation sector is expected to continue to be the leading consumer of LNG in the years ahead, accounting for a total of 36% of global gas demand in the year 2024 (Gas Exporting Countries Forum (GECF), 2019). The costs incurred throughout the value chain of LNG dictates a major portion of the cost of electricity generation. Therefore, optimizing the value chain of LNG is not merely an interest of the LNG producers. A major portion of the cost across the LNG value chain is associated with shipping unless shipping operations are planned properly. The logistics LNG chain incorporates large, medium, and small-scale chains. Due to economies of scale, the cost associated with shipping in a large-scale chain is significantly lower than the shipping cost of a small-scale value chain. Shipping costs for large, medium, and small value chains are approximately 0.8, 1.3, and 1.5 $/MMBTU, respectively (WARTSILA, 2017). The shipping of LNG from the production facility to the point of sale can be handled in three different ways; LNG producers operating their fleet, chartering a vessel from the market, or arranging transport through an LNG provider (WARTSILA, 2017).

The average LNG carrier in the 1970s has grown from about 80,000 m^3 to about 130,000 m^3 in 2006. After 2006, the average size has further increased due to the commissioning of larger Q-series ships. In the year 2012, the average capacity of an LNG carrier amounted to 148,000 m^3 (Smith et al., 2014). Due to the restrictions on the sulphur content of marine fuel imposed by the International Maritime Organization, the market for LNG as bunker fuel has been growing. However, the IMO is the only entity imposing pressure on ship operators to consider adopting cleaner fuels. Thus, the ship operators' decision to either use LNG or any other type of fuel depends on other sets of metrics. Besides, a decision from one or two operators to use LNG as bunker fuel can have a significant influence on the LNG market as ship operators normally own or operate a large fleet.

From a ship operator's perspective, the cost of consumed fuel is a major consideration as it constitutes 60% to 80% of operational cost. Current fuel prices have tripled in comparison to the 1980s. Furthermore, the imposed regulations on SO_X emissions are expected to augment fuel prices. In the case of LNG, the use of proxies is imperative as prices are not made available in the public domain. Proximations are led by the associated trading hub. When compared to gas oil, natural gas has a smaller commodity price in both Europe and the United States. Natural gas is at least $5/MMBTU cheaper than gas oil. Over the long term, the use of clean fuel such as LNG is bound to result in lengthening a carrier's maintenance cycle. However, the costs expected to be incurred for retrofitting are immense (Le Fevre, 2018). Moreover, the cryogenic nature of LNG poses a challenge to the use of LNG as fuel. The fact that it is a super-cooled fuel indicates that its evaporation is unavoidable while stored. Special logistical arrangements must be set in place to mitigate the effect of the aforementioned issue. The establishment of a comprehensive cryogenic supply chain must supersede the use of LNG as vessel fuel (Le Fevre, 2018).

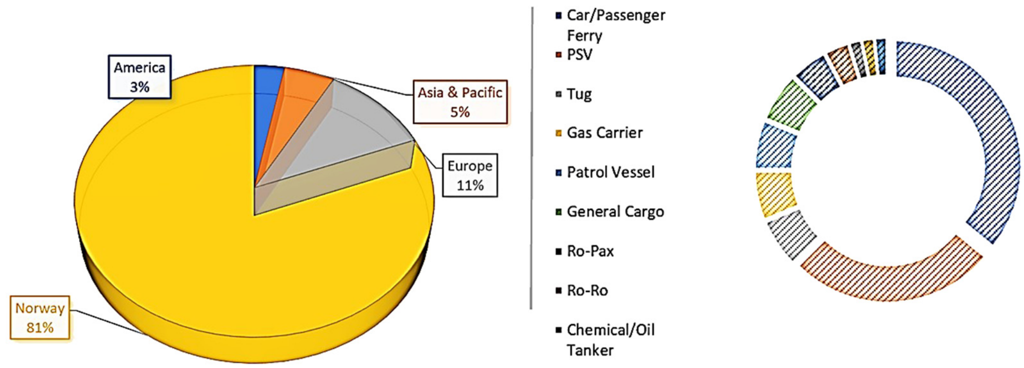

Fig. 7. Distribution of LNG-powered ships according to application and region of operation (Rozmarynowska-mrozek, 2015).

Table 3
Energy sources and methods for hydrogen production (Simons and Bauer, 2011).

Source	Method
Fossil fuels as direct feedstock	Natural gas steam methane reforming (SMR) Natural gas SMR with carbon capture and storage (CCS) Coal gasification and reforming (CGR) Coal gasification and reforming with CCS
Biomass as direct feedstock	Wood gasification and reforming (WGR) Wood gasification and reforming (WGR) with CCS
Electrolysis	Hydro, river-based electrolysis Nuclear based electrolysis Coal-based electrolysis Natural gas-based electrolysis Photovoltaics (PV) based electrolysis Wind-based electrolysis Solar thermal-based electrolysis Nuclear, European Pressurized Reactor (EPR) Coal, Integrated Gasification Combined Cycle (IGCC) Natural gas combined cycle (CC)
Concentrating solar	Thermochemical Dissociation of ZnO (STD) & hydrolysis Carbothermic reduction of ZnO (SCR) & hydrolysis

6.3. Hydrogen fuel

Hydrogen fuel can be a substitute for conventional transportation fuels. There are multiple methods for hydrogen production utilizing different sources. It can be produced from natural gas through steam methane reforming. This is a process where compressed methane is mixed with water after being subjected to heat (Boyano et al., 2011). Biomass or coal through gasification can also be used for hydrogen generation (AlNouss et al., 2020, 2019b). Biomass gasification is the process of converting biomass into value-added products such as biofuels. This method can reduce the ratio between the generated carbon and hydrogen, which results in a higher calorific value. The generated syngas consists of hydrogen, methane, carbon monoxide, and carbon dioxide. Some contaminants are generated as a by-product of biomass gasification, the amount and type of contaminants depends on several factors such as feedstock material, type of reactor, and catalyst (AlNouss et al., 2019a). The synthesized gas is then subjected to an exothermic reaction, known as the water shift reaction, which results in carbon dioxide and hydrogen (Lin et al., 2002). Water electrolysis is also a mature method of hydrogen production. The electricity required to perform electrolysis can be generated using renewables sources, which are capable of lowering emissions (Bicer et al., 2016). Table 3 details different hydrogen production methods available in the literature.

Hydrogen can be transported using road tankers or via pipelines. When hydrogen is cooled to −253 °C, it occupies 1/800 of its gas-state volume (Simons and Bauer, 2011). Japan has recently launched the world's first liquified hydrogen carrier (Maritime Executive, 2019). The Suiso Frontier is designed to be a cryogenic means of transportation for liquified natural gas. The construction phase of this vessel is expected to be completed by late 2020 (Maritime Executive, 2019). Hydrogen is considered to be more advantageous in comparison to other fuels due to its high energy content per unit of mass in addition to the availability of its primary source (when produced from water) (Contreras et al., 1997). In terms of flammability for hydrogen, hydrogen is relatively easy to ignite in the presence of air (Deniz and Zincir, 2016). However, due to its relatively low heating value and density, using hydrogen as fuel will require a special engine design. For maritime application using hydrogen as an engine fuel to mobilize a vessel instead of conventional diesel fuel with the same performance will require larger engine dimensions (El-gohary, 2009). Moreover, the special storage requirements of hydrogen, such as high pressure does hinder its favourability as a maritime fuel as it raises safety concerns (Zincir and Deniz, 2014). However, it is predicted that hydrogen production cost will be reduced in the future as more technological advancements are made in the field of renewable energy harvesting and hydrogen production. Also, as more studies focus on the use of hydrogen as bunkering fuel, more research will be required to address the special onboard storage requirements of hydrogen (Atilhan et al., 2019).

6.4. Ammonia fuel

Another substitute for fuel oil can be anhydrous ammonia (ammonia without water) (Klerke et al., 2008). Over 90% of the world's production of ammonia is generated by the Haber–Bosch synthesis process. This process was developed in the year 1913 (Bicer et al., 2016). In this process, an iron-based catalyst is utilized to combine hydrogen and nitrogen atoms by subjecting them to high pressure and temperature. The ammonia molecule with a chemical composition of NH_3 and has a calorific value of 22.5 MJ/kg. Ammonia is utilized as feedstock for the production process of liquid fertilizer solutions. Currently, the unit price per ton of ammonia ranges between $250 and $300 (Klerke et al., 2008). The contribution of the production process of ammonia to the world's GHG emissions amounts to about 1%, whereas its consumption of the world's total primary energy is around 1.2% (Bicer et al., 2016). In association with the production of 1 tonne of ammonia, about 1.5–2.5 tonnes of carbon dioxide are released into the environment using the existing technology (Bicer et al., 2016). Natural gas is converted to hydrogen through steam reforming and then further processed to yield ammonia using the Haber–Bosch process. Ammonia can be produced from renewable electricity, using electrolysis to extract hydrogen from water and combine it with nitrogen extracted from the air (Valera-Medina et al., 2018). Ammonia is known to have numerous desirable characteristics as a fuel, which makes it potentially attractive as a medium for hydrogen storage. Ammonia has a 45% higher volumetric hydrogen density than that of liquid hydrogen. This implies that the amount of hydrogen contained in a litre of liquid ammonia is greater than that in a litre of liquid hydrogen (Le Fevre, 2018). When hydrogen is required as fuel by the end-user for specific applications, ammonia can be reformed to hydrogen utilizing a very small amount of energy for the reforming process. However, the type of catalyst dictates the temperature required for efficient cracking (Bicer et al., 2016).

6.5. Marine biofuels

A growing number of countries are exploring options that can facilitate the shift from linear economies towards circular economies, where waste reduction and recycling is promoted rather than traditional disposal methods. There is a desire to develop fuels motivated by the circular economy as an alternative to conventional hydrocarbons, such as the production of chemicals made from municipal waste (Biofuels International, 2019). In addition to replacing currently used fuels, biofuels can be blended with hydrocarbon-based fuels, thus impacting the fuel economy. The extent of which depends on the energy difference in the created blend (EIA, 2019b). For instance, ethanol fuels are extracted from crops containing significant amounts of sugar such as corn, wheat, and barley. The energy content of ethanol is small in comparison to gasoline, as its calorific value is approximately 33% less than the calorific value of pure gasoline. Notably, ethanol is flammable at 13 °C as it releases vapour into the atmosphere at this temperature. Therefore, it requires specific storage conditions (PubChem, 2020). They can be blended with gasoline to generate blended fuels such as E85, E87, and E10 blends (EIA, 2019b). The production of ethanol was established by utilizing molasses generated from the sugar industry. Today, the use of ethanol is omnipresent, were above 98% of gasoline traded within the US contains some amount of ethanol (US Department of Energy - Eneregy Efficiency and Renewable Energy, 2020).

Despite the environmental favourability of biofuels, technical and financial obstacles might hinder the utilization of biofuels for maritime transportation. Depending on the type of biofuel consumed, some form of modification of onboard engines and storage tanks is required. The relatively high viscosity of vegetable oils results in unfavourable pumping and spry characteristics, which results in serious engine fouling. This necessitates corrective measures such as blending with diesel, microemulsions, thermal cracking, and transesterification (Keera et al., 2011). Logistical challenges in terms of bunkering requirements are also imposed as these fuels do not have a mature supply chain at this stage. Moreover, biofuels are costly in comparison to other marine fuels, which undermines their favourability by ship operators (Biofuels International, 2019; ETIP, 2018).

In conclusion, both LNG and hydrogen are good candidates for replacing currently used bunker fuels since they are both free of sulphur; therefore, their consumption as fuels will have a positive impact on the amount of SO_x and PM emissions (Deniz and Zincir, 2016). Although hydrogen has several obstacles that hinder its development as a bunker fuel, a pathway to its utilization still exists. This can be attained by mixing the currently used bunker fuels with hydrogen to create a fuel blend that generates fewer emissions at an acceptable efficiency level (Zincir and Deniz, 2014).

6.6. Other renewable energy sources

The electrification of ship propulsion systems and onboard power demand has been extensively addressed in many studies in the literature as a means to increase the efficiency of a ship's power system. Several technologies and operational measures have been suggested as a means of improving overall efficiency. For example, the integration of energy storage in parallel to the introduction of smart power management systems to achieve an optimal power split between different power generation sources (Nuchturee et al., 2018). On the other hand, wind energy is known to be an abundant and renewable energy source that can facilitate ship propulsion. Currently, wind energy has not been extensively utilized within the shipping industry. The utilization of wind energy for maritime transportation is thought to be more suitable than on-land utilization given the fact that a lower reduction in velocity is expected to take place due to friction. Therefore, wind maritime propulsion can result in the achievement of significant fuel and emissions reductions as opposed to conventional ship fuelling options (Talluri et al., 2016). Due to the growing prices of fossil fuels, several studies have considered the utilization of wind energy as an additional source of power to support conventional ship propulsion systems. This approach has been referred to as "wind-assisted" ship propulsion systems (Maria et al., 2020). According to Maria et al. (2020), maximum propeller thrust reduction (approximately 10% when the ship sails at 10 knots in 13 knots of wind) is made possible by the wind sails. Also, a decrease in the ship's speed was found to have a positive impact as it allows for a decrease in ship resistance and an increase in the contribution of the wind sails to the thrust (Maria et al., 2020). Moreover, the development of a combined thermal-wind-photovoltaic power system with an optimal generation plan can also lead to desired cost reductions (Li et al., 2021). Nevertheless, the use of renewable energy sources such as solar and wind power is normally associated with several challenges, one of which is the uncertainty of supply as the amount of energy generated is dependent on variable weather conditions (Qadir et al., 2021). Qadir et al. (2021), have addressed this issue in their study where they have explored several machine learning models that are used to estimate the output of hybrid photovoltaic-wind renewable energy systems. Seven factors affecting the weather condition and their individual or combined impact on photovoltaic and wind energy systems were found to be; solar irradiation, wind speed, ambient temperature, humidity, precipitation, atmospheric pressure, and wind direction (Qadir et al., 2021). According to Qadir et al. (2021), the results imply that a sustainable scheme of computation has the potential to provide accurate energy output predictions.

7. Environmental assessment

Various factors can impact the decision of which type of fuel is to be used for a particular means of transportation to achieve sustainability targets. These factors encompass distance, fuel cost, efficiency, emissions, end-user requirement, and production capability. From an environmental perspective, the amount of emissions generated from utilizing a particular fuel signifies the level of environmental favourability. However, the emissions associated with each fuel is not constrained to the emissions generated from the fuel consumption process. A major portion of the emissions generated throughout a given fuel's value chain is generated during the transportation phase. For a given vessel, the amount of CO_2 emitted is reliant on several factors such as the type of vessel, size of the vessel, and the type of voyage it undertakes. The amount of CO_2 emissions generated from a ship varies over a wide spectrum depending on the type of ship utilized for a given voyage. Lloyds register of ships, which was first published in the year 1974, is considered to be the official source of information about the world fleet (IHS Markit, 2020). The amount of emissions depends also on the weight of the vessel which in turn depends on the quantity of fuel and ballast water loaded into the ship. Psaraftis and Kontovas (2009) have analysed the emissions of the world fleet database. A sensitivity analysis was made to further understand the effect of capacity utilization on the amount of emissions generated. It was found that the increase in capacity utilization results in a uniform reduction of CO_2 emissions, while the relative standing amongst ship categories remains unchanged (Psaraftis and Kontovas, 2009). Moreover, it was concluded that the emissions rate and speed are directly correlated, where faster ships such as containerships generate more CO_2 emissions than slower ships.

7.1. Life cycle assessment comparison

There are five different approaches of LCA analysis: (i) Cradle-To-Grave covering the linear life cycle of the product system, (ii) Cradle-To-Cradle covering the entire circular life cycle of the product system, (iii) Gate-To-Gate covering selected stages of the life cycle of the product system, (iv) Cradle-To-Gate covering selected stages of the life cycle of the product system life cycle with the addition of upstream environmental impacts, and (v) Gate-To-Grave covering selected stages of product system life cycle in addition to downstream environmental impacts (Rybaczewska-Błażejowska and Palekhov, 2018).

Fig. 8 provides a graphical representation of all stages of LCA for maritime applications from the wells to the hull and finally to the wake (Rybaczewska-Błażejowska and Palekhov, 2018). It demonstrates the main stages involved in a Well-to-Wake life cycle assessment of a particular fuel used for maritime transportation. This LCA can be segregated into three main stages:

- Well-to-Pump: It is concerned with evaluating the emissions associated with fuel extraction, production, storage, and transportation.
- Pump-to-Hull: It is concerned with evaluating the emissions associated with the consumption of the fuel.
- Hull-to-Wake: It is concerned with evaluating the emissions associated with the manufacturing, maintenance, and disposal of the ship which is burning the fuel.

Table 4 provides a summary of the examined LCAs for different types of fuels and vehicles.

For the case of maritime transportation, the tank-to-propeller phase is responsible for the most significant influence on the total life cycle performance. This phase accounts for 50%–90% of total life cycle performance depending on the impact category and the fuel alternative. Bengtsson et al. (2011) quantified this emission to be 4 g CO_2 equivalent per functional unit for natural gas-based fuels as opposed to 1 g or less for crude-oil-based fuels. As for hydrogen, it was concluded that hydrogen can be deemed an environmentally friendly fuel (Bicer and Dincer, 2018a). Moreover, Simons and Bauer (2011), highlighted that steam methane reforming is the most widely used hydrogen production method. As for ammonia fuel, Bicer et al. (2016) conducted a comparative life cycle assessment for various ammonia production methods. As the efficiency of renewable sources increases, the overall environmental footprint of ammonia fuel produced from renewable sources can be further reduced (Bicer et al., 2016).

7.2. Fuel comparison

The amount of emissions generated across the value chain of a given fuel varies across each segment. Emissions generated during the production and processing stage can be reduced by controlling the amount of flaring throughout the process. However, this is not always possible as some operational requirements oblige plant operators to resort to flaring. Alternatively, emissions generated from the utilization of bunker fuels can be controlled by utilizing exhaust gas abatement techniques, such as installing a ship exhaust scrubber. Scrubbers utilize a medium that absorbs particulate matters associated with the exhaust gas. The type of scrubber used determines the type of particles or pollutants that are trapped in the medium (Sciencing, 2020; World Maritime Affairs, 2020). Table 5 illustrates the percentage of emissions generated from each segment across the LNG and HFO value chain.

Table 6 summarizes the different types of emissions generated from various types of fuels while consumed as bunker fuel in two conditions: (i) baseline condition, and (ii) ship exhaust scrubber.

Table 7 illustrates the different price ranges for several fuels that are either currently used or have the potential to be utilized as bunker fuel.

Based on the given information, LNG is deemed to be more favourable than HFO as it emits less CO_2 throughout its lifecycle and has a similar price range. However, the exhaust gas generated from burning LNG carries more methane than HFO exhaust gas. From an overall LCA perspective LNG has proven to be more environmentally friendly than HFO. Alternatively, hydrogen fuel appears to be a promising fuel that can significantly reduce the emissions generated upon utilization. This is at an additional cost associated with the production of hydrogen, which in turn results in a higher unit price for hydrogen. Understanding the market portfolio of clean fuels is also an important factor in determining the optimal bunker fuel to be consumed. As market dynamics and nationwide strategic directions can influence the potential of one source of energy against other sources.

8. Market prospects of clean fuels

Energy security continues to feature at the top of the agenda for global leaders as it is fundamental to economic growth. Today, many nations rely on imports of hydrocarbons to meet their energy demand and will continue to do so for the foreseeable future. Due to growing supply chain uncertainties, climate change, and volatility in energy prices, there is a growing trend to satisfy integrated requirements for both security and sustainability, enhancing self-sufficiency and maintaining diversified energy portfolios. Essentially, this is a function of available resources, geospatial characteristics, political climate, and participation in the global market. Today energy security entails maintaining a balance between the diversification of sources of electricity supply, ensuring energy sustainability, and climate change mitigation. In the past century, combustion-propelled engines were commonly used in automobiles due to the availability of oil at low prices, while this century, the attention has shifted to electric-powered vehicles (Tanaka, 2013). Many countries have made renewable sources of energy a major part of their energy mix to ensure self-sufficiency and reduce their reliance on external energy suppliers. New Zealand for example, has managed to utilize renewables for satisfying approximately 40% of its energy demand. However, other countries such as China and India rely heavily on their imports of natural gas in meeting their internal energy demand, whilst others such as France and Korea have made nuclear energy their main source of energy generation. Such decisions are mainly driven by a country's interest

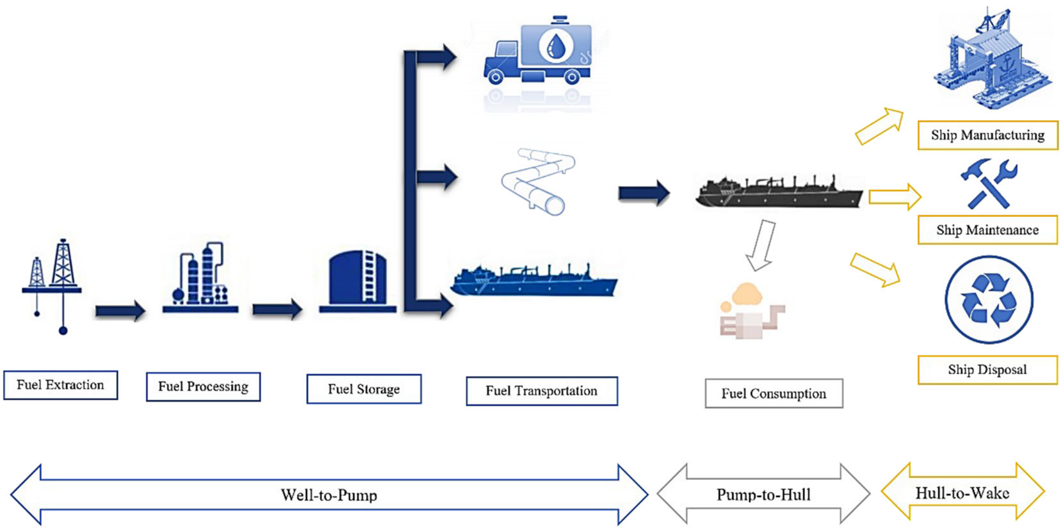

Fig. 8. Stages of life cycle assessment for maritime transportation.

Table 4
LCAs for different fuels and vehicles.

Author(s)	Vehicle	Fuel(s)	LCA type	Main contribution	Tool
Michihiro Kameyama and Hiraoka (2007)	Maritime vehicle	N/A	Life cycle impact assessment includes: – Shipbuilding. – Ship operation. – Ship dismantling. – Recycling stages. – Production of fuels, materials, and ship parts.	– The operation stage is the main contributor to the total ship life cycle emission. – Primary environmental impact categories: acidification, global warming, resource consumption, and urban air pollution.	– Proprietary LCA software developed by authors employing LIME (Life-cycle Impact assessment method based on endpoint modelling).
Bicer and Dincer (2018d)	Passenger Cars	– Ammonia – Gasoline – Diesel	– Vehicle manufacturing. – Vehicle operation. – Vehicle maintenance. – Vehicle disposal.	– Carbon-free fuels such as ammonia can lead to reduced GHG emissions in city transportation and power generation. – Evaluated environmental impact categories: acidification, abiotic depletion, ozone layer depletion, and global warming potential. – Ammonia fuel produced from wind energy-based water electrolysis (using molten salt electrolyte) has a significantly lower environmental impact. – Ammonia-fuelled vehicles can reduce GHG emissions by approximately 63% in comparison to gasoline-fuelled vehicles. – The main source of GHG emissions throughout its life cycle is due to the ammonia production process (93%).	– Simapro software & Eco-invent database – GREET: Greenhouse gases regulated emissions and energy use in transportation
Bicer and Dincer (2018a)	Passenger car	– Gasoline – Diesel – Methanol – Hydrogen – LPG – CNG – Electricity (Electric vehicles) – 50% of electricity & 50% gasoline (Parallel Hybrid Electric Vehicle)	– CML 2001 environmental impact assessment method by the centre of environmental science of Leiden university. – Eco-Indicator 99 impact assessment method. – Vehicle manufacturing. – Vehicle operation. – Vehicle maintenance. – Vehicle disposal.	– Environmentally friendliness and cost-effectiveness are the main criteria for sustainable fuel. – Evaluated environmental impact categories: acidification, abiotic depletion, eutrophication, global warming, human toxicity, terrestrial ecotoxicity, and ozone layer depletion steady state – Hydrogen fuel is an environmentally friendly fuel based on all environmental impact categories evaluated – Electric vehicles do not have a harmful environmental impact during the consumption stage, but both electricity production and disposal have a harmful effect in terms of acidification, eutrophication, and human toxicity.	– Simapro software – GREET 2015 software

(*continued on next page*)

in reducing its reliance on external suppliers of fossil fuels, in addition to the environmental gains attained by the reduction in CO_2 emissions as compared to those generated when fossil fuels are consumed. For instance, in Japan, the focus is to offset the scarcity of domestic resources by diversifying their supply, trades, and investments. For countries with large populations such as China and India, the main concern lays in their ability to adjust to the fact that they are now dependent on global markets and have shifted away from their former self-sufficiency commitments (Yergin, 2006). For Europe, the main concern is to manage dependence on natural gas imports in most EU countries aside from France and Finland (Yergin, 2006). On another aspect a nation's supply/demand dynamics can be greatly influenced by the need to meet international targets for greenhouse gas

Table 4 (*continued*).

Author(s)	Vehicle	Fuel(s)	LCA type	Main contribution	Tool
Bicer and Dincer (2018c)	Maritime vehicle	– Hydrogen – Ammonia	– CML 2001 environmental impact assessment method by the centre of environmental science of Leiden university. – Well-to-Haul: 1. Exploration and recovery activities from the well to fuel production and subsequent transportation to pump. 2. Combustion of fuel during ocean vehicle operation.	– Hydrogen and ammonia have the potential of reducing GHG emissions when used as fuels as they are carbon-free fuels. – Hydrogen and ammonia-fuelled tankers and ships recorded lower global warming impact in the operation stage. – Conventional heavy fuel oil recorded the highest global warming potential. – CO_2 equivalent emissions per tonne-kilometre while using conventional heavy fuel oil was 0.01 kg for a transoceanic freight ship and 0.005 kg for a tanker. – CO_2 equivalent emissions per tonne-kilometre while using conventional hydrogen (produced from geothermal energy) was 0.0017 kg for freight ship and 0.0010 kg for a tanker. – A 33.5% reduction in total GHG emissions per tonne-kilometre is expected when ammonia (produced from geothermal energy) is used as dual fuel for maritime engines.	– Simapro software – GREET 2016 software
Bicer and Dincer (2017b)	Aircraft	– Kerosene – Ethanol – LNG – Liquid Hydrogen – Liquid Ammonia – Methanol	Well-to-Wake: 1. Well-to-Pump: exploration and recovery activities from well to fuel production and subsequent transportation to the dispensing pumps. 2. Pump-to-Wake: combustion of fuel during aircraft operations.	— Hydrogen, ammonia, LNG, and methanol are more environmentally benign than kerosene when used as aviation fuels. – GHG emissions associated with hydrogen and ammonia fuel is mainly generated during the fuel production stage. – The lowest GHG emissions release observed was associated with the use of hydrogen (produced from geothermal energy) as aviation fuel. – Looking at the total life cycle emissions of aviation fuels, hydrogen recorded an emission of 0.014 kg of CO_2 equivalent per tonne-kilometre while kerosene recorded emissions of 1.05 kg CO_2 equivalent per tonne-kilometre. – In terms of global warming potential LNG is more favourable than currently used aviation fuel (kerosene-based fuels). – The cost of flight is lower when kerosene jet fuels are used, and further development in technology is required for hydrogen, ammonia, and methanol to compete economically with existing fuel.	– Simapro software & Eco-invent database
Bicer et al. (2016)	N/A	– Ammonia	– Cradle-to-Grave.	– Ammonia produced from municipal waste-based water electrolysis recorded the lowest abiotic depletion, global warming, and human toxicity relative to other ammonia production methods. – Hydropower-based ammonia production has the largest sustainability index and recorded the highest exergy and energy efficiency relative to other ammonia production methods. – Nuclear-based ammonia production recorded the second-highest exergy and energy efficiency after hydropower-based production. – Energy efficiencies of various ammonia production methods are calculated as follows: hydropower (42.7%), nuclear (23.8%), biomass (15.4%), municipal waste (11.7%). – Exergy efficiencies of various ammonia production methods are calculated as follows: hydropower (46.4%), nuclear (20.4%), biomass (15.5%), municipal waste (10.3%). – Sustainability index values of various ammonia production methods are calculated as follows: hydropower (1.866), nuclear (1.257), biomass (1.183), municipal waste (1.115).	– Simapro software
Nicolae et al. (2014)	Maritime vehicle	– Not mentioned	Life cycle assessment: – Shipbuilding. – Ship operation. – Ship recycling.	– The results are based on a life cycle of a ship, including construction, operation stages over 20 years, dismantling, and recycling stages.	– Solid works

(*continued on next page*)

emission reductions, as well as the reduction in particulate matter pollution, including NO_X and SO_X. This can be currently observed in the shipping industry where a growing number of stringent environmental regulations means that an eventual transition to

Table 4 (*continued*).

Author(s)	Vehicle	Fuel(s)	LCA type	Main contribution	Tool
Bengtsson et al. (2013)	N/A	Natural gas and HFO	–	– LNG was observed to be more environmentally friendly than HFO with overall life cycle emission for a passenger ferry of 127 g of CO_2 equivalent per tonne-kilometre compared to 130.13 g CO_2 equivalent per tonne-kilometre. – Combustion of fuel is found to be the main contributor to the overall environmental impact of evaluated fuels. – LNG was observed to have better acidification potential. – LNG can result in a 92% reduction of SO_2 equivalent emissions in comparison to HFO. – Environmental preferability of LNG can be further increased if methane slip throughout the supply chain is reduced. – The results attained show that LNG recorded a very low potential contribution to acidification and is expected to fulfil the regulatory requirements for Sulphur content in maritime fuels as well as Tire III regulations.	–
Bengtsson et al. (2011)	N/A	LNG, GTL, HFO, and MGO	Well-to-Propeller: – Stage1: Well-to-Tank. – Stage 2: Tank-to-Propeller.	– LNG proves to be more environmentally friendly than HFO while being evaluated from a life cycle perspective. – LNG recorded approximately 90% reduction in both acidification potential and eutrophication in comparison to HFO. – In terms of global warming potential, LNG use will only achieve a minor decrease in global warming potential, the magnitude of which is dependent on the amount of methane slippage from the maritime gas engine. – Assuming zero methane slippage is achieved, the overall life cycle global warming reduction of LNG fuel versus HFO is expected to be around 20%. – A 2% methane slippage throughout the LNG life cycle will result in hindering the preferability of LNG over HFO in terms of global warming potential.	–
Simons and Bauer (2011)	N/A	– Hydrogen	– Well-to-Tank.	– Assessing various pathways of hydrogen production using LCA shows a wide variation in terms of environmental impact. – Steam Methane reforming is the most widely used hydrogen production method is proved to be more energy-intensive than the fuels used for an internal combustion engine, and almost equal GHG emissions are released from both fuels. – Steam methane reforming results in higher particulate matter emissions throughout the life cycle. – Applying carbon capture and storage to steam methane reforming can positively transform its position in terms of environmental viability.	– Simapro software
Jivén et al. (2004)	Maritime vehicle	– Diesel – Heavy fuel oil – Hydrogen	Life cycle inventory analysis includes: – Construction. – Operation. – Maintenance. – Scrapping.	– Design of a computerized life cycle assessment tool designed to enhance energy efficiency on board ships, and track and control the environmental impact of maritime transportation.	– LCA-Ship a software developed by authors

Table 5
CO_2 emissions generated across the fuel value chain.

	Production & Processing	Transmission & Storage	Liquefaction	Utilization as fuel for transportation
HFO	1416 g CO_2 eq/ton km (Bengtsson et al., 2013)	1720 g CO_2 eq/ton km (Bengtsson et al., 2013)	0 g CO_2 eq/ton km (Bengtsson et al., 2013)	13 013 g CO_2 eq/ton km (Bengtsson et al., 2013)
LNG	7–14 g/MJ (LHV) (Speirs et al., 2020) 192 g CO_2 eq/ton km (Bengtsson et al., 2013)	0.5–1.5 g/MJ (LHV) (Speirs et al., 2020) 748 g CO_2 eq/ton km (Bengtsson et al., 2013)	4.5–8 g/MJ (LHV) (Speirs et al., 2020) 3039 g CO_2 eq/ton km (Bengtsson et al., 2013)	1.5–2 g/MJ (LHV) (Speirs et al., 2020) 8722 g CO_2 eq/ton km (Bengtsson et al., 2013)

zero-emission shipping is required. External drivers (i.e., the regulation imposed by international/national regulatory authorities) to initiate such a transition are of great importance in reshaping the energy mix demand of the shipping industry and the energy industry as a whole. Therefore, as suggested by Elshurafa et al. (2019), adequate assessment of the effect of newly introduced local policy on both the domestic and global energy markets is important for a particular nation as it can have a significant effect on their energy security. Moreover, the importance of assessing the risks and uncertainties associated with the introduction of a new policy is of high importance, especially with regards to other self-imposed targets that have been set by other nations. Bruno

Table 6
Emissions generated from utilizing several fuels for two scenarios (baseline and scrubber).

Emissions	HFO		MGO		LNG		Hydrogen	
	Baseline g/MJ	Scrubber g/MJ	Baseline g/MJ	Scrubber g/MJ	Baseline g/MJ	Scrubber g/MJ	Baseline g/MJ	Scrubber g/MJ
CO_2	78 (Bengtsson et al., 2011)	–	74 (Bengtsson et al., 2011)	–	54.56 (LEVON Group, 2015)	–	–	–
CO	0.13 (Bengtsson et al., 2011)	–	0.13 (Bengtsson et al., 2011)	–	–	–	–	–
CH_4	0.0005 (Bengtsson et al., 2011)	–	0.0005 (Bengtsson et al., 2011)	–	0.08684 (LEVON Group, 2015)	–	–	–
NO_x	1.6 (Bengtsson et al., 2011)	–	1.5 (Bengtsson et al., 2011)	–	–	–	–	–
NMVOC	0.06 (Bengtsson et al., 2011)	–	0.06 (Bengtsson et al., 2011)	–	–	–	–	–
N_2O	0.004 (Bengtsson et al., 2011)	–	0.004 (Bengtsson et al., 2011)	–	–	–	–	–
NH_3	0.0003 (Bengtsson et al., 2011)	–	0.0003 (Bengtsson et al., 2011)	0.0029 (Bengtsson et al., 2011)	–	–	0.0003 (Bengtsson et al., 2011)	0.0029 (Bengtsson et al., 2011)
PM10	0.093 (Bengtsson et al., 2011)	0.071 (Bengtsson et al., 2011)	0.034 (Bengtsson et al., 2011)	–	–	–	0.034 (Bengtsson et al., 2011)	–
SO_2	0.5 (Bengtsson et al., 2011)	0.05 (Bengtsson et al., 2011)	0.05 (Bengtsson et al., 2011)	–	–	–	0 (Bengtsson et al., 2011)	–

Table 7
Price comparison of multiple fuels.

Fuel	Price $/GJ
HFO	9.41–14.11 (Bengtsson et al., 2014)
MGO	14.11–22.35 (Bengtsson et al., 2014)
LNG	8.23–14.11 (Bengtsson et al., 2014)
Hydrogen	12 (Al-breiki and Bicer, 2020)
Ammonia	28.2 (Al-breiki and Bicer, 2020)
Methanol	16.3 (Al-breiki and Bicer, 2020)
Dimethyl Ether	15.06 (Al-breiki and Bicer, 2020)

et al. (2016), have addressed this point by introducing a stochastic dual dynamic programming model. Moreover, Grau et al. (2012), suggests that targets can be achieved more adequately by the employment of a global policy coordination scheme. Recently, scholars from several disciplines such as law, economics, urban planning, political science have been collaborating to study nationwide policy tools and their interrelationships (Cheng and Yi, 2017). Environmental policies within the shipping industry are expected to result in some significant transitions in the energy demand for ship propulsion. The relationship that exists between a range of technologies and fuels that have significant potentials to play a role in the global transition to 50% emission reduction by 2050 in the deep-sea shipping sector is summarized in Fig. 9, it is obvious that LNG and hydrogen are major drivers in this transition.

Some of the important characteristic properties for future alternative fuels for deep-sea shipping are that the fuel should have a good energy density, be readily available, have the security of supply, and should be free of GHG emissions from the well to the propulsion supply chain. The energy density, which is the energy per unit volume of the fuel should be comparable to current marine fuels. If the value is smaller than that of the existing marine fuels, more space would be needed on-board the vessel for fuel storage, and this might decrease the space allotted to the loaded fuel.

There are currently several candidates for clean bunker fuels such as ammonia, methanol, liquified petroleum gas, ethanol, dimethyl ether (DME), biogas, synthetic fuels, etc. Hydrogen fuel is also an option when combined with fuel cells. Amongst these fuels, ammonia, and methanol appears to be the two dominant choices as future fuels for deep-sea shipping mainly due to their cost, ability to integrate with existing ship engine technology and resource availability. The choice of ammonia and methanol is also driven by the fact that both products are already widely carried as cargos in vessels due to their global demand. This would make it relatively easier to retrofit existing ships and engines; while methanol can suitably burn-in adapted marine diesel engines and can also be used as an alternative fuel with pure hydrogen in fuel cells, research on ammonia as diesel cycle fuel is currently ongoing.

Ammonia already has an increasing global demand, especially in the United States and Europe, where it is used largely in fertilizer production and is seen as a possible carrier for hydrogen. Hydrogen remains the prime source of energy in all fuels and is seen as a player in the future energy system. Currently, the global demand for hydrogen is driven by Japan who aims to increase its share of hydrogen fuel cell vehicle deployment, thanks to auto manufacturers Toyota and Honda. Hydrogen refuelling stations are also being set up around Japan, China, and Europe as these cars are rolled out commercially. The production of hydrogen is a very carbon-intensive process, and hence the demand for blue and green hydrogen is growing globally. 96% of global demand for hydrogen is met by fossil fuel using either steam methane reformation or through the gasification of coal, and these currently present a cheaper way to produce hydrogen as compared to water electrolysis.

While the goal remains a carbon-free maritime industry, LNG can be seen as a transition alternative to deep-sea shipping, as it remains the best immediate available alternative to reducing the carbon footprints from shipping activities. When compared to oil-powered ships, the use of LNG can result in a reduction of 99% in sulphur emissions, 99% in fine particle emission, 85% in

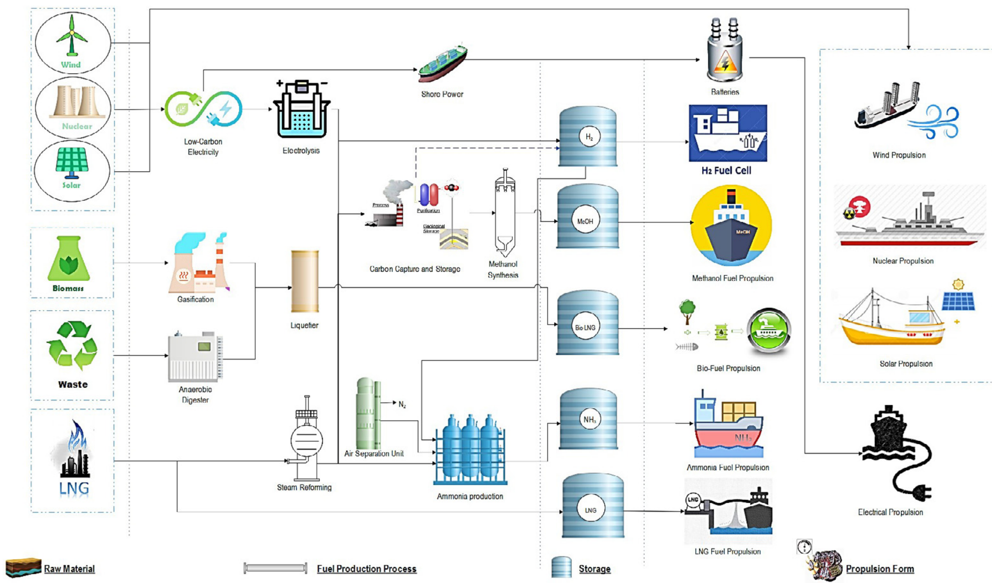

Fig. 9. Technologies and fuels on a pathway to zero-emission shipping (Department for Transport, 2019).

nitrogen oxide emission, and a 20% decrease in GHG emission. The demand for LNG is already driven by nations seeking low carbon emission fuels. Japan, China, and India need LNG for electricity generating plants, and in Europe, the demand for LNG is driven by the demand for heating. Currently, LNG powered propulsion vessels already constitute a small number of global shipping fleets, and this is expected to increase in the coming years. The major challenge faced with the use of LNG is the cost associated with building new or converting existing ships. This can be an obstacle, as the capital cost of investments in ships is expected to be repaid within their life span (average 25 years). For the conversion of existing ships, only a very small number of ship owners believe that they could reach a positive return on investment should they move to LNG powered propulsion. Another challenge faced by this fuel is the availability of LNG bunkering ports, however, ports that make this available can take advantage of the significant commercial opportunities brought about by the increasing number of LNG propelled ships arriving in them which will also increase the trade volume in these ports. According to Lindstad et al. (2020), as LNG prices drop below HFO prices in some regions, it is expected that the number of dual-fuel Otto engines that meet the EEDI requirements will increase (Lindstad et al., 2020). Moreover, since the global demand for many of the alternative clean fuels is high, the incentive for ship owners to modify their vessels to operate with cleaner hydrogen-based fuels will get greater in the coming years. The current and projected shift in the LNG market will justify the use of natural gas as feedstock to the hydrogen and ammonia production process as supply is expected to supersede the demand. It is also necessary for strategic decision-making that the future expansion of product offerings from LNG exporters are in line with the global demand trend for cleaner fuels. According to the international energy agency (IEA) future hydrogen report (International Energy Agency IEA, 2019), the production costs of hydrogen from natural gas in selected regions, show that the middle east has the potential for producing hydrogen at a cheaper rate as compared to other regions in the world. This is mainly due to the low cost of natural gas in the region. Expanding the fuel exports from LNG exporting countries such as Qatar and Russia to include hydrogen fuels can result in great economic gains and aid in the global transition to clean fuels. It will also present opportunities for these countries to sustain economic gains in a post-fossil-fuel based global economy. An estimated ∼5% compound annual growth rate (CAGR) for hydrogen is anticipated between 2016 and 2025. This growth will be driven by the increased demand for hydrogen fuel cells and refineries (petrochemical) and ammonia industries. Fig. 10 indicates that the North American market currently driven by the United States and Canada dominates the global hydrogen market due to its growing adaptation of novel technologies and government regulations that promote the use of alternative clean fuels in that region. Other key global markets for hydrogen are Japan, China, India, and South Korea in the Asia Pacific and the European Union, with countries such as Germany, France, the United Kingdom, and Denmark considered possible destinations for hydrogen exporters. The emerging markets for hydrogen fuels also include Saudi Arabia, Brazil, South Africa, and Argentina (Mordor Intelligence, 2019). The hydrogen generation market is expected to reach $199.1 billion by 2023 from $135.5 billion in 2018 with an expected global CAGR of ∼8%. The Asia Pacific is estimated to be the largest market for hydrogen generation driven by the refinery operations in Japan, South Korea, India, and China who is already building a hydrogen city to foster research and development into fuel cells and has ramped up its number of hydrogen stations, to achieve the mass production of fuel cell vehicle.

9. Challenges and opportunities

Some of the challenges that can hinder conducting accurate assessment studies in addition to the attainment of an environmentally friendly maritime transportation sector are listed below:

- The limitations for the assessment of alternative fuels from an environmental perspective lay in the fact that the use of clean fuels such as hydrogen or ammonia for maritime applications is either limited to certain ship categories or non-existent. This deters the reliability of the results attained as emissions data acquisition for such an application becomes extremely challenging.

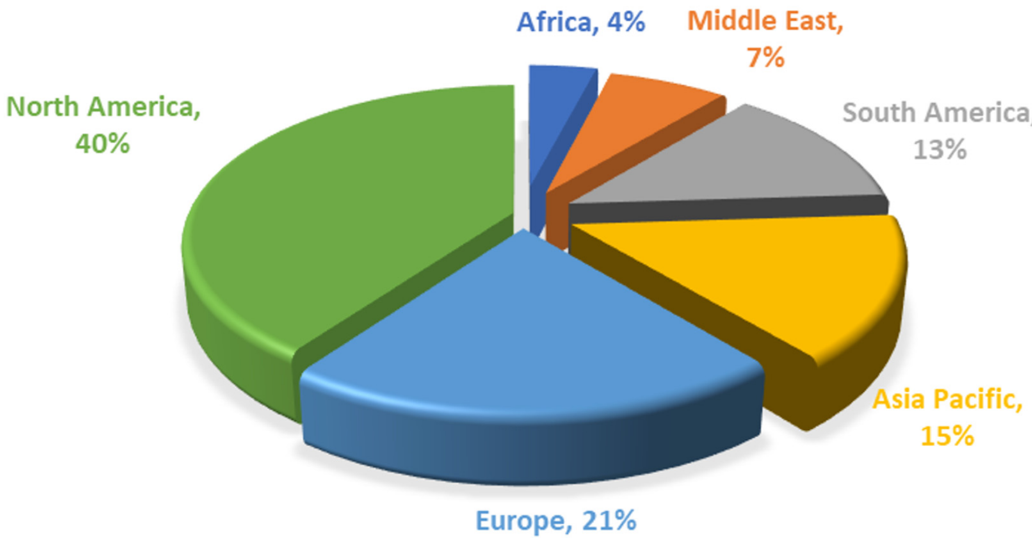

Fig. 10. Global hydrogen market by region (Markets and Markets, 2018).

- Widespread utilization of clean fuels such as hydrogen and ammonia can be obstructed or delayed due to issues related to the underdeveloped infrastructure and supply chains of these relatively new fuels especially in the maritime industry such as the high cost of production, special cryogenic storage requirements, high transportation cost of fuel.
- Given the cryogenic nature of the suggested bunker fuel alternatives, the high boil-off generation rate of these fuels can create an issue in terms of space requirements and special cryogenic storage requirements.
- Uncertainty of supply is a major concern when renewable energies such as solar and wind power are considered as a source of energy due to their dependence on varying weather conditions.

However, several general recommendations can be inferred from this extensive review:

- Decision-makers need to acknowledge the importance of the contribution and collaboration of all stakeholders involved (including research scientists, universities, industry associations, ship designers, shipyard operators, technical support teams, manufacturers, port management authorities, fuel producers/suppliers, banks, insurance companies, funding entities, regulatory authorities, etc.) to enable clean fuels to be deemed technologically and economically viable as a sustainable alternative to current carbon-based fuels.
- Implementation of an even risk-allocation mechanism amongst stakeholders is necessary to avoid the withdrawal or lack of motivation from any of the involved parties, which can be driven by uneven risk-allocation.
- Future studies evaluating renewable energy sources such as solar and wind can help in creating further technological advancements to combat the current challenges that hinder the intense use of these energy sources such as energy storage solutions. This can lead to a further reduction of maritime transportation induced GHG emissions.

10. Summary and conclusions

This research explores the possibility of reducing the environmental impact of maritime transportation by exploring the opportunities for the integration, production, transportation, and utilization of alternative clean fuels such as liquified natural gas, hydrogen, and ammonia as bunker fuels in ships. The study evaluates the amount of NO_x, SO_x, and CO_2 emissions generated across the entire value chain of the current heavy fuel oils used in this sector as they have a long-term global impact on climate and human health. As a result of increased environmental concerns, the International Maritime Organization has imposed a cap on the amount of sulphur emission generated as a result of burning bunker fuel. For ship operators/owners to comply with the IMO sulphur restriction, they have to implement one of the following available solutions; (i) switching to Low-sulphur fuel oil (LSFO), (ii) switching to Marine Gasoil (MGO), (iii) continue burning HSFO while using Scrubbers, (iv) switching to Liquefied Natural Gas (LNG) or other cleaner alternative fuels. Hydrogen remains a favourable option as a future bunker fuel because it yields more energy per unit mass when compared to conventional maritime fuel and generates less GHG emissions. However, certain obstacles inhibit the widespread utilization of hydrogen fuel, such as the cost of production and the special handling requirements for storage and transportation. Incidentally, Ammonia is considered to be a good storage medium for hydrogen as it has a higher volumetric hydrogen density than that of liquid hydrogen. However, the amount of GHG emissions associated with the existing ammonia production process (i.e., Haber–Bosch technology) is considerably high, while, other novel technologies such as solid-state synthesis and thermochemical processes are still in the research and development phase. One of the advantages of using ammonia fuel is that it can easily become compatible with engines, turbines, and burners with minor modifications. Both hydrogen and ammonia have promising potential to completely replace hydrocarbon fuels. This is projected to occur in the future due to the growing global energy demand and the time required to develop the infrastructure and supply chain of these relatively new fuels. While the use of LNG presents a readily available transition fuel for the maritime industry, it is anticipated that the initial stage of the transition to a hydrogen-based economy will involve hydrogen produced from natural gas, which would serve as a bridge between the current fossil fuel economy and the future hydrogen-based economy. Emissions generated by this process can be minimized using carbon capture and storage technology. Many governments worldwide have heavily invested in the development of hydrogen and ammonia fuel production and utilization technologies. Nevertheless, these amounts are relatively modest when compared to spending directed towards research and development of other energy sources. Many of the main LNG importers are intensifying their efforts towards the transition to a hydrogen-based economy. Currently, Asia is considered to be the world's largest consumer of LNG, and gas demand in the next five years will certainly be driven by demand from the Asian market. As more LNG suppliers enter the market, shorter and more flexible LNG contracts have emerged causing a significant impact on the price structure. The current and projected shift in the LNG market justifies the use of natural gas as feedstock to the hydrogen and ammonia production process. Since the demand for many of the alternative clean fuels will increase in the coming years, the demand for shipping companies and ports operators to modify their vessels to operate with cleaner fuels will not only increase with time, but this would yield great commercial benefits for those willing to make an early transition. It is also necessary for strategic decision-making that the future expansion of product offerings from LNG exporters are diversified in line with the global demand trends for cleaner fuels. Future work should involve the application of an interdisciplinary approach to address the multi-dimensional issues related to the transition towards supply chains that are comprised of clean fuels.

Nomenclature

ASTM	American Society for Testing and Materials
BCM	Billion Cubic Metres
BTU	British Thermal Units
CAGR	Compound Annual Growth Rate
CCS	Carbon Capture and Storage
CGR	Coal gasification and reforming
CH_4	Methane
CNG	Compressed Natural Gas
COP	United Nations Climate Change Conference
CO_2	Carbon Dioxide
ECA	Emissions Controlled Area
EEDI	Energy Efficiency Design Index
EIA	Energy Information Administration
EJ	The SI prefix "exa" represents a factor of 10^{18}
EPR	European Pressurized Reactor
EU	European Union
FREI	Fukushima Renewable Energy Institute
GEF	Global Environment Facility
GCC	Gulf Cooperation Council
GHG	Green House Gases
GTL	Gas to Liquids
HFO	Heavy Fuel Oil
HHV	Higher Heating Value
HYSTRA	Hydrogen Energy Supply-Chain Technology Research Association
lb	Pound
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IMCO	Inter-Governmental Maritime Consultative Organization
IMO	International Maritime Organization
ISO	International Organization for Standardization
kg	Kilogramme
KIER	Korean Institute for Energy Research
kWh	Kilowatt-hour
LBSI	Lean Burn Spark Ignition
LCA	Life Cycle Assessment
LIME	Life-cycle Impact assessment Method based on Endpoint Modelling
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
LSFO	Low Sulphur Fuel Oil
LS-HPDF	Low-Speed 2-Stroke High-Pressure Dual-Fuel
MARPOL	International convention for the preventions of pollution from ships
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MJ	Megajoule
MMBTU	Million British Thermal Unit
MMSCM	Million Metric Standard Cubic Metres
MMTPA	Million Metric Tons Per Annum
MS-LPDF	Medium Speed 4-Stroke Low-Pressure Dual-Fuel
MW	Megawatt
NEP	New Hydrogen Project
NFPA	National Fire Protection Association
NH_3	Ammonia
NO	Nitric Oxide
NOx	Nitrogen Oxides
OECD	Organization for Economic Co-operation and Development
PM	Particulate Matter
PV	Photovoltaic
R&D	Research and Development
SECA	Sulphur Emissions Control Areas
SEEMP	Ship Energy Efficiency Management Plan
SMR	Steam Methane Reforming
SOx	Sulphur Oxides
TCF	Trillion Cubic Feet
TTF	Title Transfer Facility
UAE	United Arab Emirates
UNDP	United Nations Development Program
US/USA	United States of America
VLSFO	Very Low Sulphur Fuel Oil
WGR	Wood Gasification and Reforming

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.

Data availability statement

All the data, models, and codes that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgements

This publication was made possible by GSRA grant, ID# GSRA6-2-0615-19090, from the Qatar National Research Fund (a member of Qatar Foundation). The authors also acknowledge the support provided by Hamad Bin Khalifa University, Qatar Foundation, Qatar.

References

Al-breiki, M., Bicer, Y., 2020. Comparative cost assessment of sustainable energy carriers produced from natural gas accounting for boil-off gas and social cost of carbon. Energy Rep. 6, 1897–1909.

Al-haidous, S., Al-ansari, T., 2020. Sustainable Liquefied Natural Gas Supply Chain Management : A Review of Quantitative Models. pp. 1–23.

Al-husain, R., 2014. Supply Chain Management in the Petroleum Industry : Challenges and Supply Chain Management in the Petroleum Industry : Challenges and Opportunities, No. April.

AlNouss, A., McKay, G., Al-Ansari, T., 2019a. Superstructure optimization for the production of fuels. In: Fertilizers and Power using Biomass Gasification, Vol. 46. Elsevier Masson SAS.

AlNouss, A., McKay, G., Al-Ansari, T., 2019b. A techno-economic-environmental study evaluating the potential of oxygen-steam biomass gasification for the generation of value-added products. Energy Convers. Manage. 196, 664–676.

AlNouss, A., McKay, G., Al-Ansari, T., 2020. Production of syngas via gasification using optimum blends of biomass. J. Clean. Prod. 242, 118499.
Andersen, M., Skjoett Larsen, T., 2009. Corporate social responsibility in global supply chains. Supply Chain Manage. Int. J. 14 (2), 75–86.
Atilhan, S., Park, S., El-halwagi, M.M., Moore, M., Nielsen, R.B., 2019. Green hydrogen as an alternative fuel for the shipping industry. Curr. Opin. Chem. Eng. 31, 100668.
Baldi, F., Ahlgren, F., Melino, F., Gabrielii, C., Andersson, K., 2016. Optimal load allocation of complex ship power plants. Energy Convers. Manage. 124, 344–356.
Baldi, F., Johnson, H., Gabrielii, C., Andersson, K., 2014. Energy and exergy analysis of ship energy systems - The case study of a chemical tanker, Proc. 27th Int. Conf. Effic. Cost, Optim. Simul. Environ. Impact Energy Syst. ECOS 2014, 18, (2) pp. 82–93.
Baldi, F., Larsen, U., Gabrielii, C., 2015. Comparison of different procedures for the optimisation of a combined diesel engine and organic Rankine cycle system based on ship operational profile. Ocean Eng. 110, 85–93.
Bengtsson, S., Andersson, K., Fridell, E., 2011. A comparative life cycle assessment of marine fuels: Liquefied natural gas and three other fossil fuels. Proc. Inst. Mech. Eng. M 225 (2), 97–110.
Bengtsson, S., Andersson, K., Fridell, E., 2013. An environmental life cycle assessment of LNG and HFO as Marine Fuels, An Environ. Life Cycle Assess. LNG HFO as Mar. Fuels 225 (2), 97–110.
Bengtsson, S.K., Fridell, E., Andersson, K.E., 2014. Fuels for short sea shipping: A comparative assessment with focus on environmental impact. Proc. Inst. Mech. Eng. M 228 (1), 44–54.
Bergmann, J.C., Trichez, D., Sallet, L.P., de Paula e Silva, F.C., Almeida, J.R.M., 2018. Technological Advancements in 1G Ethanol Production and Recovery of By-Products Based on the Biorefinery Concept.
Bicer, Y., Dincer, I., 2017a. Life cycle assessment of nuclear-based hydrogen and ammonia production options: A comparative evaluation. Int. J. Hydrog. Energy 42 (33), 21559–21570.
Bicer, Y., Dincer, I., 2017b. Life cycle evaluation of hydrogen and other potential fuels for aircrafts. Int. J. Hydrog. Energy 42 (16), 10722–10738.
Bicer, Y., Dincer, I., 2018a. Life cycle environmental impact assessments and comparisons of alternative fuels for clean vehicles. Resourc. Conservation Recycling 132, 141–157.
Bicer, Y., Dincer, I., 2018b. Clean fuel options with hydrogen for sea transportation: A life cycle approach. Int. J. Hydrog. Energy 43 (2), 1179–1193.
Bicer, Y., Dincer, I., 2018c. Environmental impact categories of hydrogen and ammonia driven transoceanic maritime vehicles: A comparative evaluation. Int. J. Hydrog. Energy 43 (9), 4583–4596.
Bicer, Y., Dincer, I., 2018d. Life cycle assessment of ammonia utilization in city transportation and power generation. J. Clean. Prod. 170, 1594–1601.
Bicer, Y., Dincer, I., Zamfirescu, C., Vezina, G., Raso, F., 2016. Comparative life cycle assessment of various ammonia production methods. J. Clean. Prod. 135 (July), 1379–1395.
Bio-SNG feasibility study published. [Online]. Available: https://www.bioenergy-news.com/news/bio-sng-feasibility-study-published/.
Biofuels International, 2019. Fuelling a circular economy.
Boyano, A., Blanco-Marigorta, A.M., Morosuk, T., Tsatsaronis, G., 2011. Exergoenvironmental analysis of a steam methane reforming process for hydrogen production. Energy 36 (4), 2202–2214.
Bruno, S., Ahmed, S., Shapiro, A., Street, A., 2016. Risk Neutral and Risk Averse Approaches to Multistage Renewable Investment Planning under Uncertainty, Vol. 250. pp. 979–989.
2019. Business Wire, Global Ammonia Market Growth, Trends, and Forecasts 2019-2024 - Agriculture Industry Dominates the Market. [Online]. Available: https://www.businesswire.com/news/home/20190731005611/en/Global-Ammonia-Market-Growth-Trends-Forecasts-2019-2024.
Caniëls, M.C.J., Cleophas, E., Semeijn, J., 2016. Implementing green supply chain practices : an empirical investigation in the shipbuilding industry. Marit. Policy Manage. 43 (8), 1005–1020.
Cheng, Q., Yi, H., 2017. Complementarity and substitutability : A review of state level renewable energy policy instrument interactions. Renew. Sustain. Energy Rev. 67, 683–691.
Christiansen, M., Ronen, D., 2004. Ship Routing and Scheduling: Status and Perspectives, No. February.
Chu-van, T., et al., 2019. A comparison of particulate matter and gaseous emission factors from two large cargo vessels during manoeuvring conditions. Energy Rep. 5, 1390–1398.
COAG Energy Council Hydrogen Working Group, 2019. Australias National Hydrogen Strategy.
Contreras, A., Yiğit, S., Özay, K., Veziroğlu, T.N., 1997. Hydrogen as aviation fuel: A comparison with hydrocarbon fuels. Int. J. Hydrog. Energy 22 (1053), 10–11–1060.
Deniz, C., Zincir, B., 2016. Environmental and economical assessment of alternative marine fuels. J. Clean. Prod. 113 (X), 438–449.
2019. Department for Transport, Clean Maritime Plan, London.
U. E. I. A. (EIA), 2019a. International Energy Outlook 2019 with Projections To 2050, Vol. 85.
U. E. I. A. (EIA), 2019b. How much ethanol is in gasoline, and how does it affect fuel economy?. [Online]. Available: https://www.eia.gov/tools/faqs/faq.php?id=27&t=10.
El-gohary, M.M., 2009. Design of marine hydrogen internal combustion engine.
El-Houjeiri, H., Monfort, J.C., Bouchard, J., Przesmitzki, S., 2019. Life cycle assessment of greenhouse gas emissions from marine fuels: A case study of saudi crude oil versus natural gas in different global regions. J. Ind. Ecol. 23 (2), 374–388.
Elgohary, M.M., Seddiek, I.S., Salem, A.M., 2015. Overview of alternative fuels with emphasis on the potential of liquefied natural gas as future marine fuel, 229 (4) 365–375.
Elshurafa, A.M., Farag, H.M., Hobbs, D.A., 2019. Blind spots in energy transition policy : Case studies from Germany and USA. Energy Rep. 5, 20–28.
ETIP, 2018. Factsheet Marine Biofuels (ETIP Bioenergy).
Fazlollahi, S., Mandel, P., Becker, G., Maréchal, F., 2012. Methods for multi-objective investment and operating optimization of complex energy systems. Energy 45 (1), 12–22.
Fazlollahi, S., Maréchal, F., 2013. Multi-objective , multi-period optimization of biomass conversion technologies using evolutionary algorithms and mixed integer linear programming (MILP). Appl. Therm. Eng. 50 (2), 1504–1513.
Gas Exporting Countries Forum (GECF), 2019. Global Natural Gas Demand Set to Exceed 4.3 Tcm By 2024. [Online]. Available: https://www.gecf.org/events/global-natural-gas-dem{and}-set-to-exceed-43-tcm-by-2024.
Goldsworthy, L., 2015. DESIGN OF SHIP ENGINES FOR REDUCED EMISSIONS OF OXIDES OF Reproduced with the permission of the Australian Maritime College, no. March.
Grau, T., Huo, M., Neuhoff, K., 2012. Survey of photovoltaic industry and policy in Germany and China. Energy Policy 51, 20–37.
Guille, G., Pozo, C., Limleamthong, P., 2020. Systematic MultiObjective Life Cycle Optimization Tools Applied To the Design of Sustainable Chemical Processes. pp. 435–449.
Gulf Times, 2018. Japan eyes hydrogen exploration with Qatar. [Online]. Available: https://www.gulf-times.com/story/615077/Japan-eyes-hydrogen-exploration-with-Qatar.
Halvorsen-weare, E., Fagerholt, K., 2010. Routing and scheduling in a liquefied natural gas shipping problem with inventory and berth constraints, no. March.
Hassan, M.H., Kalam, M.A., 2013. An overview of biofuel as a renewable energy source: Development and challenges. Procedia Eng. 56, 39–53.
Huan, T., Hongjun, F.W.L., Guoqiang, Z., 2019. Options and Evaluations on Propulsion Systems of LNG Carriers.
Hwangbo, S., Lee, I., Han, J., 2017. Mathematical model to optimize design of integrated utility supply network and future global hydrogen supply network under demand uncertainty. Appl. Energy 195, 257–267.
I. E. A. and K. E. E. Institute, 2019. LNG Market Trends and their Implications.
IEA, 2019. Energy Technology R & D Budgets.
IEA, 2020. Hydrogen Tracking Report - 2020. [Online]. Available: https://www.iea.org/reports/hydrogen.
IEA Hydrogen Technology Collaboration Program, 2017. Global Trends and Outlook for Hydrogen.
IHS Markit, 2020. Lloyd's Register of Ships. pp. 2020–2021, [Online]. Available: https://ihsmarkit.com/products/maritime-ships-register.html.
International Energy Agency, 2018. CO2 emissions from fuel combustion: Overview. Int. Energy Agency 14.
International Energy Agency, 2019. IEA Market Report Series: Gas 2019.
International Energy Agency IEA, 2019. The Future of Hydrogen, Seizing today's opportunities.
2018. International Energy Outlook 2018. US Government.
International Maritime Organization, 2011. Note By the International Maritime Organization To the Thirty-Fifth Session of the Subsidiary Body for Scientific and Technical Advice.
International Maritime Organization, 2020. International maritime organization. [Online]. Available: http://www.imo.org/en/About/Pages/Structure.aspx.
International Organization for Standardization (ISO), 2006. Environmental management — Life cycle assessment — Principles and framework. In: Iso 14040, Vol. 41, second ed. pp. 1628–1634, (5).
Jianyun, Z., Li, C., Lijuan, X., Bin, W., 2019. Bi-objective optimal design of plug-in hybrid electric propulsion system for ships. Energy 177, 247–261.
Jivén, K., Sjöbris, A., Nilsson, M., Ellis, J., Trägårdh, P., Nordström, M., 2004. LCA-ship, Design Tool for Energy Efficient Ships-a Life Cycle Analysis Program for Ships. Final report: 2004-08-27.
Keera, S.T., El Sabagh, S.M., Taman, A.R., 2011. Transesterification of vegetable oil to biodiesel fuel using alkaline catalyst. Fuel 90 (1), 42–47.
Klerke, A., Christensen, C.H., Nørskov, J.K., Vegge, T., 2008. Ammonia for hydrogen storage: Challenges and opportunities. J. Mater. Chem. 18 (20), 2304–2310.
Koroneos, C., Dompros, A., Roumbas, G., Moussiopoulos, N., 2005. Life cycle assessment of kerosene used in aviation. Int. J. Life Cycle Assess. 10 (6), 417–424.

Krzyżanowski, J., Nowak, P., 2014. A proposal for marine fuel oil system arranged to burn heavy fuel oil and low sulphur distillate grade. J. KONES. Powertrain Transp. 21 (2), 161–168.
Laffon, B., 2014. Fuel Oils B.
Le Fevre, C., 2018. A review of demand prospects for LNG as a marine transport fuel, no. June.
LEVON Group, 2015. Consistent Methodology for Estimating Greenhouse Gas Emissions.
Li, Y., et al., 2021. Optimal generation expansion planning model of a combined thermal – wind – PV power system considering multiple boundary conditions : A case study in Xinjiang. China 7, 515–522.
Lin, S., Harada, M., Suzuki, Y., Hatano, H., 2002. Hydrogen production from coal by separating carbon dioxide during gasification. Fuel 81 (16), 2079–2085.
Lindstad, E., Eskeland, G.S., Rialland, A., Valland, A., 2020. Decarbonizing maritime transport: The importance of engine technology and regulations for LNG to serve as a transition fuel. Sustain. 12 (21), 1–19.
Lloyd's Register Group Limited, 2020. International Convention for the Prevention of Pollution from Ships (MARPOL). [Online]. Available: https://www.lr.org/en/marpol-international-convention-for-the-prevention-of-pollution/?AspxAutoDetectCookieSupport=1).
Manouchehrinia, B., Dong, Z., Gulliver, T.A., 2020. Well-to-Propeller environmental assessment of natural gas as a marine transportation fuel in British Columbia, Canada. Energy Rep. 6, 802–812.
Marcellus Community Science, 2020. Energy Efficiency and Energy Content of Different Fuels. [Online]. Available: https://www.e-education.psu.edu/marcellus/node/825.
Maria, I., Sacher, M., Xu, J., Wang, F., 2020. A numerical method for the design of ships with wind-assisted propulsion. 105 (2015) 33–42.
Maritime Executive, 2019. World's First Liquefied Hydrogen Carrier Launched.
Markets and Markets, 2018. Hydrogen Generation Market By Generation, Application (Petroleum Refinery, Ammonia Production, Methanol Production, Transportation, Power Generation), Technology (Steam Reforming, Water Electrolysis, & Others), Storage, and Region -Global Forecast to 2023.
McKinsey, 2018. Global gas & LNG outlook to 2035. Energy Insights September (September), 31.
Mckinsey & Company, 2020. MARPOL 2020: An Opportunity for OPEC To Reclaim Market Share.
Merk, O., Kirstein, L., Aronietis, R., Hasegawa, N., 2018. Fuelling Maritime Shipping with Liquied Natural Gas, Vol. 38.
Mersin, Kadir, Bayirhan, Irsad, Gazioglu, Cem, 2019. Review of CO2 emission and reducing methods in maritime transportation. Thermal Sci. 23, 2073–2079.
Michihiro Kameyama, H.T., Hiraoka, Katsuhide, 2007. Study on Life Cycle Impact Assessment for Ships.
Mordor Intelligence, 2019. Hydrogen gas market - growth, trends, and forecast (2020-2025).
Nicolae, F., Popa, C., Beizadea, H., 2014. Applications of life cycle assessment (LCA) in shipping industry. Int. Multidiscip. Sci. GeoConf. Surv. Geol. Min. Ecol. Manage. SGEM 2 (4), 289–296.
NS Energy, Nuon Magnum Power Plant. [Online]. Available: https://www.nsenergybusiness.com/projects/nuon-magnum-power-plant/.
Nuchturee, C., Li, T., Xia, H., 2018. Energy Efficiency of Integrated Electric Propulsion for Ships – a Review, Vol. 134. p. 2020.
O'Hayre, R., Cha, S.-W., Colella, W., Prinz, F.B., 2016. Chapter 2: Fuel cell thermodynamics. In: Fuel Cell Fundamentals. John Wiley & Sons, Inc., Hoboken, NJ.
Press, A.I.N., 2008. Operational research models and methods in the energy sector.
Psaraftis, H.N., Kontovas, C.A., 2009. CO2 emission statistics for the world commercial fleet. WMU J. Marit. Aff. 8 (1), 1–25.
PubChem, Ethanol. [Online]. Available: https://pubchem.ncbi.nlm.nih.gov/compound/702#datasheet=LCSS.
Qadir, Z., Imran, S., Khalaji, E., Suliman, H., 2021. Predicting the energy output of hybrid PV – wind renewable energy system using feature selection technique for smart grids. Energy Rep. (xxxx).
Redda, Y., El-abed, A., Regterschot, J., Scholten, W., Centre, T., 2010. LNG Supply Chain Design and Optimization At Qatargas. pp. 1–13.
Rose, L., Hussain, M., Ahmed, S., Malek, K., Costanzo, R., Kjeang, E., 2013. A comparative life cycle assessment of diesel and compressed natural gas powered refuse collection vehicles in a Canadian city. Energy Policy 52, 453–461.
Rozmarynowska-mrozek, Monika, 2015. THE DEVELOPMENT of the LNG-FUELLED FLEET and the LNG-BUNKERING INFRASTRUCTURE, No. 884.
Rybaczewska-Blażejowska, M., Palekhov, D., 2018. Life Cycle Assessment (LCA) in Environmental Impact Assessment (EIA): principles and practical implications for industrial projects. Management 22 (1), 138–153.
S & P Global Platts, 2019. Turning Tides the Future of Fuel Oil After IMO 2020. p. 2019.
Sangaiah, A.K., 2020. Robust optimization and mixed-integer linear programming model for LNG supply chain planning problem. Soft Comput. 24 (11), 7885–7905.
Sciencing, Types of Scrubbers. [Online]. Available: https://sciencing.com/about-5568843-devices-remove-pollutants-smoke-stacks.html.
Simons, A., Bauer, C., 2011. Life Cycle Assessment of Hydrogen Production, No. January.
Smith, T.W.P., et al., 2014. Third IMO Greenhouse Gas Study 2014, Vol. 327. Int. Marit. Organ..
Soda, S., Anish, S., Garg, R.K., 2015. Green Supply Chain Management in Power Industry of Punjab : Evaluation of Key Drivers By using ISM. p. 2014.
Speirs, J., et al., 2020. Natural gas fuel and greenhouse gas emissions in trucks and ships. Prog. Energy 2 (1), 012002.
Suleman, F., Dincer, I., Agelin-Chaab, M., 2016. Comparative impact assessment study of various hydrogen production methods in terms of emissions. Int. J. Hydrog. Energy 41 (19), 8364–8375.
Talluri, L., Nalianda, D.K., Kyprianidis, K.G., Nikolaidis, T., Pilidis, P., 2016. Techno economic and environmental assessment of wind assisted marine propulsion systems. Ocean Eng. 121, 301–311.
Tanaka, N., 2013. Big Bang in Japan's energy policy. Energy Strateg. Rev. 1 (4), 243–246.
The Maritime Executive, 2020. Asia Ready for LNG Pricing Hub. [Online]. Available: source: https://www.maritime-executive.com/article/asia-ready-for-lng-pricing-hub.
UNFCCC, 2016. Report of the Conference of the Parties on Its Twenty-First Session. held in Paris from 30 November to 13 2015.
2018. United nations conference on trade and development. Rev. Marit. Transp..
2006. United Nations Environment Program (UNEP). Hydrog. Econ..
US Department of Energy - Eneregy Efficiency and Renewable Energy, Alternative Fuels Data Center. [Online]. Available: https://afdc.energy.gov/fuels/ethanol.html.
Valente, A., Iribarren, D., Dufour, J., 2017. Life cycle assessment of hydrogen energy systems: a review of methodological choices. Int. J. Life Cycle Assess. 22 (3), 346–363.
Valera-Medina, A., Xiao, H., Owen-Jones, M., David, W.I.F., Bowen, P.J., 2018. Ammonia for power. Prog. Energy Combust. Sci. 69, 63–102.
WARTSILA, 2017. The LNG Logistics chain.
Wikinson, K.T.C. John D., Hudson, Hank M., 2004. LNG production in CRYOGENIC natural gas production plants.pdf.
World Maritime Affairs, Ship Exhaust Scrubber system : What is all about ? [Online]. Available: https://www.worldmaritimeaffairs.com/ship-exhaust-scrubber-system-what-is-all-about/..
Yergin, D., 2006. Ensuring energy security. Foreign Aff. 85 (2), 69.
Zhongyuan, W., Dongkun, L., Linlin, L., 2018. Natural gas utilization in China : Development trends and prospects. Energy Rep. 4, 351–356.
Zincir, B., Deniz, C., 2014. An Investigation of Hydrogen Blend Fuels Applicability on Ships an Investigation of Hydrogen Blend Fuels Applicability on Ships. p. 2016.
Zwolińska, E., Sun, Y., Chmielewski, A.G., Pawelec, A., 2020. Removal of high concentrations of NOx and SO 2 from diesel off-gases using a hybrid electron beam technology. Energy Rep. 6 (2), 952–964.