Hydrogen Utilization in Ships in Line with EU Green Deal Goals

Egemen Sulukan, Alperen Sari, Musa Cenk Özekinci, Doğuş Özkan, and Tanay Sıdkı Uyar

1 Introduction

Since the dawn of civilization, energy and its utilization have been among the most basic human requirements (Sulukan et al. 2020). Energy consumption has increased in proportion to people's demands as the population has grown and technology has advanced from the past to the present. As energy demand soared, so expanded the diversity of energy sources (Qureshy and Dincer 2020). After the industrial revolution, as a result of energy policies based on fossil-fuel technology, not only political and military difficulties, but also economic, ecological, and health concerns began to emerge (Moser 2010).

Figure 1 illustrates a decrease in energy consumption at specific eras owing to economic, political, military, or health-related issues throughout the world. It is

E. Sulukan (✉) · D. Özkan
Mechanical Engineering Department, National Defence University, Turkish Naval Academy, 34942 Istanbul, Turkey
e-mail: esulukan@dho.edu.tr

A. Sari
Mechanical Engineering Department, Marmara University, 34722 Istanbul, Turkey

M. C. Özekinci
National Defence University, Barbaros Naval Sciences and Engineering Institute, 34942 Istanbul, Turkey

T. S. Uyar
Department of Mechanical Engineering, Faculty of Engineering and Architecture, Beykent University, Ayazaga, Haşim Koruyolu Cd. No:19, 34398 Sariyer, Istanbul, Turkey

Energy Systems Engineering Department, Faculty of Engineering, Cyprus International University, Via Mersin 10, Nicosia, Northern Cyprus, Turkey

T. S. Uyar and N. Javani (eds.), *Renewable Energy Based Solutions*,
Lecture Notes in Energy 87, https://doi.org/10.1007/978-3-031-05125-8_30

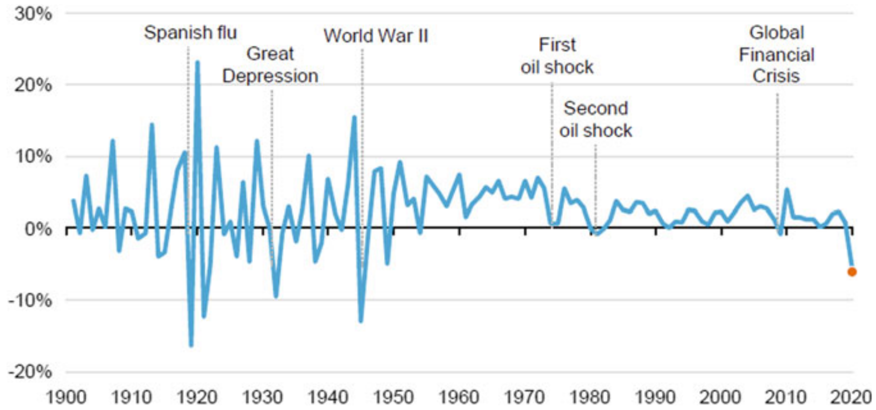

Fig. 1 Rate of change of global primary energy demand, 1900–2020 (IEA, Rate 2021)

expected that there will be an energy scarcity soon, particularly because the production pace of energy resources cannot keep up with the speed of recent technological advances. In this context, it is estimated that various actions should be implemented throughout the world, and the problem may have economic, ecological, health, political, and military implications (Sevim 2011). One of the most noticeable, and arguably the most significant, of these issues is the environmental devastation produced by fossil fuels, as well as the resulting global warming and climate change (Uyar et al. 2019).

1.1 Global Warming and Climate Change Problem

The climate has changed from time to time within the scope of the natural process since the creation of the earth. However, the recent fast increases and reductions in global temperature readings are an indication of the challenge of rapid climate change. To prevent severe effects on human health and environmental events, the CO_2 ratio in the atmosphere should be in the range of 180–350 ppm (Jones 2017). However, according to researches, this level is currently at 410 ppm and is increasing by roughly 3 ppm each year (We and Just 2017). If we do not take action to curb CO_2 emissions, we will suffer severe natural events such as abrupt temperature fluctuations, drought, and flooding (Değişikliği and ve Politikaları Uygulama ve Araştırma Merkezi 2021). The fast climate change problem has evolved into an ecological issue impacting the entire world. When the main source of this problem is investigated, greenhouse gas emissions (GHG) are found to be caused by energy production (Sevim 2011). The majority of the world's energy demands are met by fossil fuels (Sulukan et al. 2021). GHG emitted into the environment as a result of the combustion of fossil fuels damages the ecosystem and ecological equilibrium. When the world's sectors with the greatest GHG emissions are investigated, power generation, industrial, transportation, and residential sectors rise to the top. Many nations, institutions, organizations, and industries throughout the world are taking various actions to prevent global warming and climate change. However, efforts are being made, and advances in high-energy-demanding industries such as marine and aviation remain restricted.

1.2 The Environmental Impact of Maritime Trade and Regulations

Globalization of commerce would not have been feasible without the shipping sector, which has historically been the most useful form of transportation (Sulukan et al. 2018). The price of shipping services has dropped throughout time as a result of the use of larger ships and the growth of the network between the customer, retailer, distributor, carrier, warehouse, supplier, and manufacturer. As a consequence, demand for transportation has risen substantially since the end of the twentieth century. However, the increased shipping supply has a negative impact on the environment. Although environmental impacts are being assessed for all modes of transportation, it is difficult to reach an agreement on international maritime transport regulations (Cullinane and Bergqvist 2014), because a majority of the environmental impacts of maritime transport occur at sea and thus have less perceptible effects on the population.

Almost all emissions from the marine sector are caused by fuel usage. Diesel and fuel oil are used as fuel by nearly all of the world's marine fleet. However, the gasoline used in ships, commonly known as bunker fuel, is of far lesser quality than that used in other modes of transportation (Corbett and Koehler 2003). Because of the poor quality of the fuel used, even the most contemporary ships emit more pollutants per power output and harm the environment than diesel engines used in other sectors. Several strategies to minimize carbon footprint and environmental consequences are still being debated and developed across the world (Sari et al. 2021). The International Maritime Organization is engaged in a global battle to reduce the environmental impacts of the maritime industry (IMO). The IMO serves as a consultancy unit within the United Nations that also deals with administrative and legal issues to encourage and facilitate the overall adoption of the highest standards applicable to marine safety, navigational effectiveness, and the prevention and control of marine pollution from ships.

The IMO has a long history of controlling ship pollution through the International Convention on the Prevention of Pollution from Ships (known as the MARPOL Convention), which is the most important measure that has been enacted to date. MARPOL covers not just intended and unintended oil pollution, but also chemicals, packaged goods, wastewater, garbage, and air pollution. It was ratified in 1973, and the 1978 Protocol came into effect.

Evidence that carbon dioxide (CO_2) concentrations in the atmosphere were increasing was first brought to the agenda by climate experts in the 1960s, and its effects on global warming began to be expressed in the second half of the twentieth century when environmental measures were brought to the agenda. The Kyoto Protocol, which was adopted in Kyoto, Japan in 1997 (Oberthür 2003), is one of these. This protocol is an international agreement associated with the UNFCCC, the most important element of which is the establishment of enforceable objectives for greenhouse gas (GHG) emissions reductions for 37 industrialized nations and the European Union. Greenhouse gases are specified in this protocol as carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydro fluoride carbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6). CO_2 is the heaviest of these gases in terms of mass (Protocol 1997).

Figure 2 shows that CO_2 emissions from the marine sector account for about 3.3% of worldwide energy-related CO_2 emissions and that this rate is growing year after year due to increased demand for maritime transportation.

The Kyoto Protocol also contains rules for reducing greenhouse gas emissions from international aviation and marine transport. Although this protocol compels governments to collaborate with the IMO to reduce greenhouse gas emissions from ships, the IMO published a new protocol in 1997 to address ship air pollution concerns. This protocol was added to MARPOL as Annex VI, and the MARPOL was updated as a result. Since the Kyoto Protocol's validity term will expire in 2020, it has been agreed to sign the Climate Change Agreement (Paris Agreement), which includes the UNFCCC and the Kyoto Protocol, after the 21st Conference of the Parties (COP21) in Paris. The Paris Agreement aims to strengthen the worldwide socioeconomic situation in the context of mitigating climate change in the period

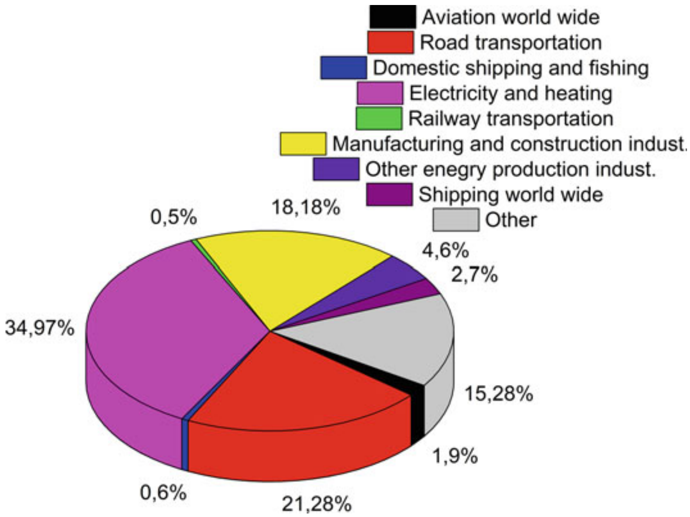

Fig. 2 CO_2 emissions from shipping compared with global total emissions (Dowell and Shah 2012)

after 2020 (Paris agreement. 2015). The Paris Agreement's long-term aim is to limit global temperature rise below 2°C as close to zero as achievable before the industrial revolution, and even less than 1.5 °C (Tschakert 2015). As a result, to reduce and reverse the trend of rising CO_2 emissions, we must cease producing greenhouse gases into the atmosphere.

In this context, the IMO's Marine Environment Protection Committee (MEPC) has placed a strong emphasis on decreasing greenhouse gas emissions from ships, and MEPC.304 (72) on IMO's initial plan for lowering greenhouse gas emissions from ships was approved at MEPC 72 on April 13, 2018 (IMO 2018).

The "Vision" presented in this key "First Strategy" document underlines IMO's commitment to decrease greenhouse gas emissions from international commerce and eliminate them as soon as possible this century. Furthermore, CO_2 emissions from international marine trade are expected to be decreased by 40% by 2030 and 70% by 2050 when compared to 2008 levels for each mode of transport (Chen et al. 2019).

The European Union, on the other hand, plans to lower GHG emissions by 55% by 2030 compared to 1990 and to attain zero GHG emissions by 2050 by updating the Green Deal it established to become the first continent to achieve zero pollution (European Commission et al. 2021).

To achieve these objectives, new energy-efficient ship designs, new machinery, and, most importantly, alternative fuels are necessary, in addition to economic advances. Even though numerous studies have been conducted in this regard all over the world and in Europe, the use of clean fuel appears to be the most pressing issue that must be addressed to realize the zero-emission objective. In the EU's research on alternative fuels, biofuels, methanol, LNG, LPG, and hydrogen came to the fore. However, to meet the 2050 Green Deal objectives, hydrogen stands out as the most suitable of these fuels.

In this context, this chapter aims to offer an overview of the use of hydrogen energy and fuel cells in the marine sector to reach the required environmental conditions soon within the framework of the laws proposed by the European Union under the Green Deal. Therefore, it consists of five sections. The first section contains general information on energy and sustainable energy, global warming and climate change, the influence of marine transport on environmental pollution, and laws in this sector. The second section discusses the European Union's Green Deal and the marine sector's objectives. The following section discusses hydrogen energy, hydrogen fuel cells, utilizing hydrogen energy as a marine fuel, and decreasing emissions from the maritime industry. The fourth section discusses initiatives and applications related to the development of fuel cells and their usage in the marine industry, while the last section provides a conclusion.

2 EU Green Deal and Maritime Transport

Throughout history, maritime transportation has been a resource for economic growth and wealth, as well as for commerce and communication with all European countries.

Sea trade accounts for over 90% of EU imports and exports (Commission et al. 2021). The quality of life on Europe's islands and surrounding maritime regions is directly associated with the availability of maritime transportation services. Overall, the marine sectors contribute significantly to the European economy in terms of jobs and revenue.

The marine industry is not subject to restrictions under climate change agreements, notably the 2015 Paris agreement. The first major move in this direction was taken by IMO in 2018, with the adoption of the first Greenhouse Gas Strategy for International Shipping. Annual total greenhouse gas emissions will be halved by 2050 compared to 2008, and emissions will be eliminated in the longer term.

The European Union has proposed a new roadmap for future carbon-free planning in all sectors. The European Union Green Deal (European Commission et al. 2020), which was designed to reorganize the European Union's (EU) past commitments in a broader and more effective approach in combating climate and environmental issues, is a roadmap set with the goal of making Europe the first carbon-free continent.

Transport accounts for one-quarter of EU greenhouse gas emissions, which are expanding. Figure 3 (Bodewig 2021) shows that maritime transport contributes to 13.4% of CO2 emissions produced by transportation. The EU Green Deal aims to reduce these emissions by 90% by 2050. As a milestone for the marine sector, zero-emission ships will be available for construction in 2030. The EU aims to protect Europe by enforcing highly rigorous safety laws that reduce the environmental effect of maritime trade, as well as by maintaining high shipping standards and a low risk of marine accidents.

Within the framework of the European Green Deal, the EU is focusing on the development and deployment of sustainable alternative transport fuels for all forms

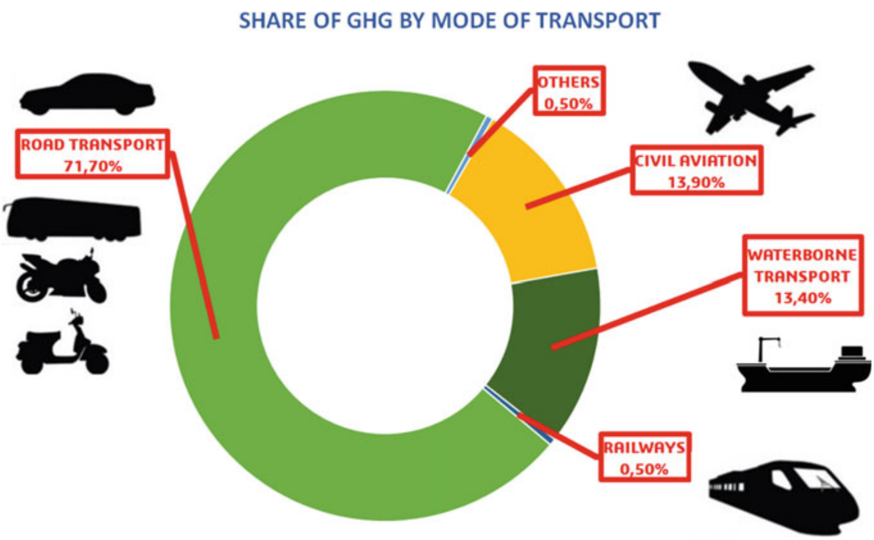

Fig. 3 Share of GHG by mode of transport (Bodewig 2021)

of transportation. It aims to explore the alternative fuels infrastructure directive and the energy taxation directive in this respect, as well as to include the marine sector in the scope of the European emission trade. As the use of alternative fuels in marine transport has some drawbacks within the range of present technology, it can only be used in a limited capacity. Larger fuel tanks are required for clean energy sources to operate aboard ships. Many alternative fuels have a low flash point (below 60 °C), which makes storage and usage hazardous (Dnv 2018).

3 Reducing Emission by Using Hydrogen in the Maritime Sector

The EU Green Deal envisions a carbon-free future for the EU. To achieve this, carbon-free fuels should be favored over the carbon-containing fossil fuels now in use. Figure 4 (Dincer and Rosen 2011) shows the major fuels utilized in the past as well as the C/H ratio. When cutting-edge research and developments on a wide range of alternative fuels are reviewed, hydrogen, ammonia, and methanol stand out as strong possibilities among the fuels now being tested aboard ships.

Fossil fuels, which fulfill the majority of the world's energy demands, are progressively depleting, resulting in severe environmental and air pollution. As an energy carrier, hydrogen can solve these issues (Bicer and Dincer 2018). As a result, substantial research and development on hydrogen energy have been conducted in recent

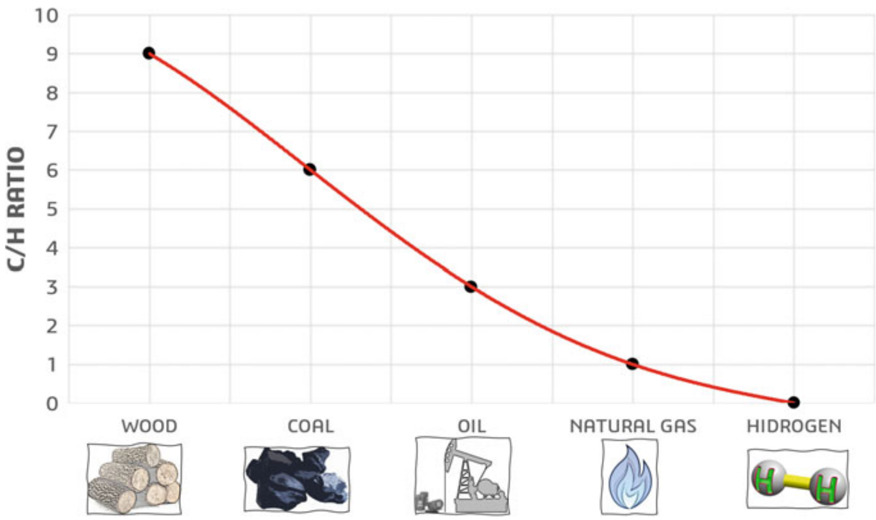

Fig. 4 C/H ratio of energy resources over centuries (Dincer and Rosen 2011)

years. Developed countries are conducting large-scale technical research and development projects in preparation for a future in which clean and renewable hydrogen energy will fulfill the world's rising energy demands (Dinçer 2008).

The transportation industry is the most major user of hydrogen fuel (cars, buses, planes, trains, and other vehicles). In space shuttles and rockets, hydrogen is still utilized as a fuel. Mobile apps (phones, computers, etc.) and built-in applications are also evaluated (backup power units, power requirement in remote locations, etc.).

3.1 Hydrogen Energy System

Recent developments in hydrogen energy point to a future in which hydrogen will replace conventional fuels, particularly in the transportation sector, a trend that has accelerated since 2010. This concept also includes the distribution infrastructure and hydrogen stations needed to transport the hydrogen from diverse production locations to points of usage.

Hydrogen can be generated using several methods and energy sources, and color code nomenclature is often used in this context. Depending on the source of production, hydrogen has color codes of green, blue, and gray. This color-code nomenclature is demonstrated in Fig. 5.

The hydrogen produced from fossil fuels is referred to as "gray hydrogen." Hydrogen can be produced from fossil fuels in two ways: steam methane reformation (SMR) or autothermal reformation (ATR) (Dinçer 2008). Hydrogen derived from fossil fuels contains a significant degree of impurities and must be purified before

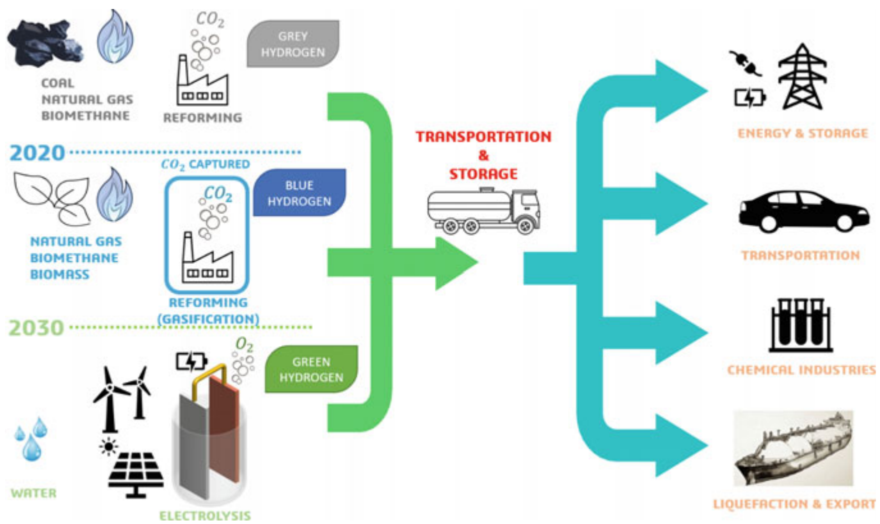

Fig. 5 Hydrogen colors (Gorny 2020)

use. Gray hydrogen releases CO_2, making such hydrogen technologies inappropriate for a path to net-zero emissions.

Blue hydrogen is generated in the same way as gray hydrogen is. However, the goal here is to use Carbon Capture and Storage (CCS) technology to capture and store emissions. However, this technique only allows for the collection of low-level pollutants. In the long run, it does not appear practical to decarbonize the industrial sector with SMR without CCS (Renssen 2020). Natural gas accounts for around 80% of hydrogen production (Salkuyeh et al. 2017). However, the distribution of blue hydrogen has drawbacks such as restricted resource usage, susceptibility to fluctuating fossil fuel prices, and failure to fulfill energy security requirements. Furthermore, blue hydrogen confronts societal acceptability challenges since it incurs additional expenses for CO_2 delivery and storage and necessitates monitoring of stored CO2. Moreover, CCS capture efficiency is estimated to be 85–95% at most, implying that 5–15% of CO2 is still released (Antonini et al. 2020). To summarize, CCS can reduce, but not eliminate, carbon emissions from hydrogen generation. Additionally, these activities require methane, which is a considerably stronger greenhouse gas (GHG) per molecule than CO2. This suggests that while blue hydrogen can reduce CO2 emissions, it does not fulfill the net-zero future criteria. For these reasons, blue hydrogen can only be viewed as a short-term transition to let green hydrogen flourish on the path to net-zero emissions. This, however, makes the procedure extremely complex and costly. SMR with CCS is currently not an industry practice, according to many experts, and does not contribute to commercial growth.

Water electrolysis can also be used to generate hydrogen. If the electric current is generated by a renewable source (such as a solar panel or a wind turbine), the clean hydrogen produced is considered green. During the generation of hydrogen using renewable energy, no hazardous gases are discharged into the atmosphere (Dinçer 2012).

Green hydrogen currently has a few disadvantages that must be overcome. The cost is the most crucial of these. Renewable energy, which is essential for producing green hydrogen via electrolysis, is more expensive to generate, making it more expensive to get (Dincer and Acar 2015). However, the manufacturing of hydrogen in general, and green hydrogen in particular, takes more energy than the production of other fuels. Finally, one of its primary drawbacks is that hydrogen is very volatile and flammable (Hord 1978), requiring extensive safety precautions to prevent leaks and explosions.

Green hydrogen offers advantages as well as drawbacks. Green hydrogen is completely sustainable since it releases no pollutants during combustion or manufacturing. Therefore, hydrogen is simple to store and this enables it to be utilized for various purposes after manufacturing. Compressed hydrogen tanks can store energy for an extended period. It is also more convenient to use than lithium-ion batteries because it is lighter. It is flexible since it can be turned into power or synthetic gas and utilized for household, commercial, industrial, or transportation applications (Midilli et al. 2005). It can be transported at a rate of up to 20% of that of natural gas and can use existing natural gas infrastructure. Increasing this percentage will need the modification of many aspects in current gas infrastructures to make them suitable.

3.2 Hydrogen as a Marine Fuel

Applications that combine renewable energy and hydrogen are considered essential for the marine industry to accomplish the objectives under the EU Green Deal. Although batteries powered by electrical energy can be utilized for short-distance cruises, hydrogen is required for long-distance cruises (McKinlay et al. 2020). Because battery and battery system development is insufficient to fulfill the system's demands. However, in today's technical environment, it is not possible to acquire all of the power a ship will require for long-distance cruises with hydrogen. Thus, battery and battery system development is insufficient to fulfill the system's demands. In this context, it is intended for ships all over the world to employ combustion engines that run on hydrogen and have batteries consisting of hydrogen cells (Dnv 2018).

3.3 The Base of Hydrogen Technologies: Fuel Cells

Fuel cells are electrochemical devices that transform the chemical energy in fuels into electrical energy. Fuel cells are made up of an electrolyte with ionic conductivity, as well as an anode and cathode where various reactions occur (O'hayre et al. 2016). Fuel cells, like batteries, are electrochemical cells; however, there are notable distinctions. The most distinguishing characteristic between fuel cells and batteries is that fuel must be supplied continually from outside. While traditional batteries serve as "energy storage devices," fuel cells (batteries) serve as energy generation/conversion systems (Winter and Broad 2004). Fuel cells have a high potential for energy generation since they generate electricity from hydrogen (Ehteshami and Chan 2014). As far as power generation capacity is considered, fuel cells can be manufactured in a variety of sizes. Because of their extensive usage and application possibilities, from automobiles to home and industrial applications, they must be built in a variety of sizes (Edwards et al. 2008). As a result, these systems may be developed with capacities able to produce enough electricity to fulfill the demands of mobile phones or a city.

Fuel cells are a type of energy technology that is clean, sustainable, and efficient. The water electrolysis experiment may simply explain the functioning mechanism of fuel cells. Water is separated into hydrogen and oxygen in the water electrolysis experiment by passing a direct current across it. In fuel cells, the reverse process is carried out (Ogawa et al. 2018). In other words, during water dissolution, electrical current is applied and water separation occurs, while electrical energy is obtained as a result of the interaction of hydrogen and oxygen. As seen in Fig. 6, the fuel cell transforms the energy of the fuel directly into electrical energy via an electrochemical process.

Fuel cells, which are limitless and never need to be recharged, use electrochemistry to transform the energy of the fuel directly into electrical energy. The fuel cells operate as a continuous battery when the anode provides fuelling and cathode oxidation. This

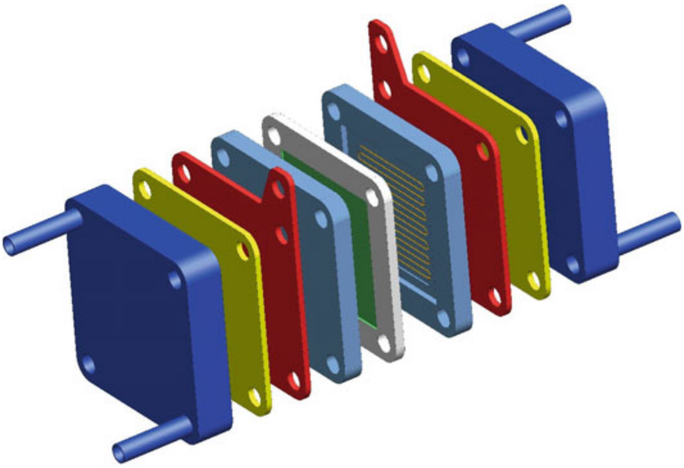

Fig. 6 Fuel cell (Hortal and Miranda 2005)

gains to it, as quiet and unmoving as a battery. It varies from the battery, however, in two respects. It contains no harmful chemicals and can be recycled without polluting the environment. Therefore, it is utilized as a source of energy.

The fuel cell requires hydrogen–oxygen or hydrogen-air to operate (Cook 2002). Temperature, heat, water vapor, and electric current from the flow of electrons from the anode to the cathode are by-products of this electrochemical process due to the great efficiency in fuel usage, as illustrated in Fig. 7 (Abdalla et al. 2018). Fuel cells obtain their energy from actual combustion first. They transform this energy

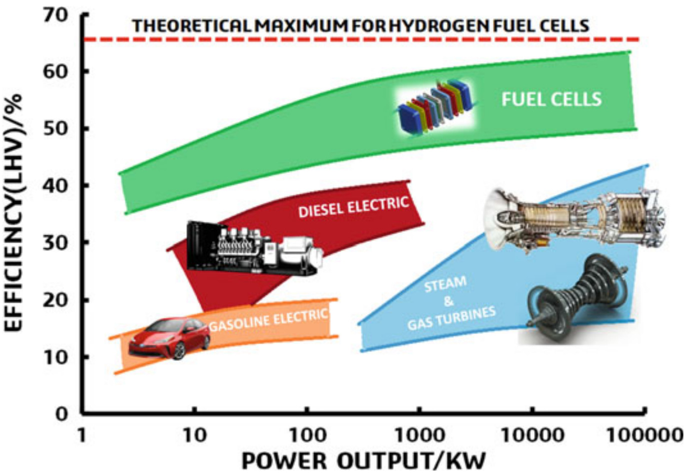

Fig. 7 Comparison of the efficiency achieved with the output power of different fuel sources (Abdalla et al. 2018)

into mechanical (motion) energy using the turbine. Finally, they use a dynamo to transform mechanical energy into electrical energy. Fuel cells; By chemically mixing the fuel and the oxidizing agent without burning, it minimizes energy losses in conventional combustion and does not pollute the environment.

3.4 Hydrogen Fuel Cell Types

Fuel cells, which are still under development, are one of the most investigated energy technologies. Even at this beginning period, a broad range of fuel cell types have been developed. These various fuel cells differ in terms of use, economic value, and market potential. In terms of application and commercial potential, some fuel cells are more beneficial than others. In any case, the fuel cells themselves have a considerable diversity. Polymer electrolyte membrane fuel cells (PEMFC), Direct methanol fuel cells (DMFC), Alkaline fuel cells (AFC), Phosphoric acid fuel cells (PAFC), Molten carbonate fuel cells (MCFC), and Solid oxide fuel cells (SOFC) are the most often investigated fuel cells nowadays (Evrin and Dincer 2019). The method fuel is delivered to the fuel cell and the operating temperature of the fuel cell varies across different types of fuel cells. Figure 8 shows a high-level overview of various types of fuel cell technology.

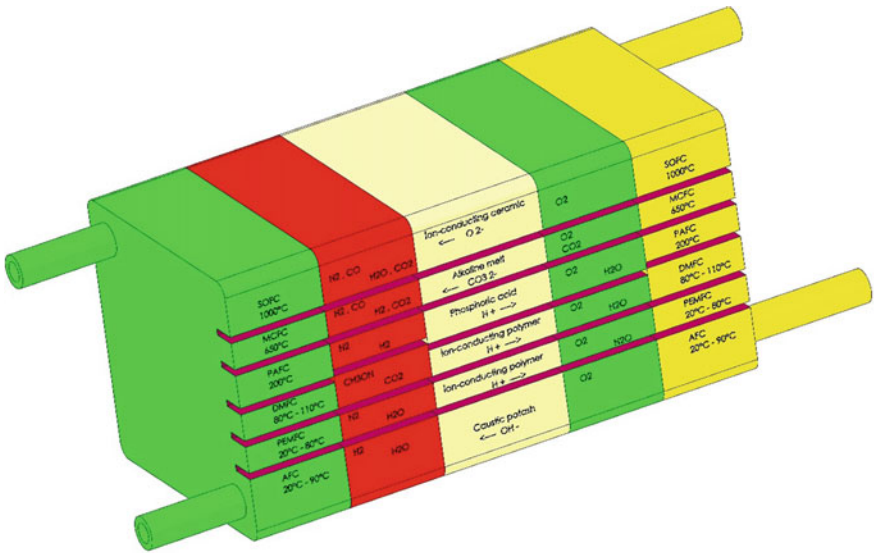

Fig. 8 Overview of the various types of fuel cell technology (Benz et al. 2003)

3.4.1 Alkaline Fuel Cells (AFC)

The research on alkaline fuel cells done by Francis Thomas Bacon is regarded to be the most important study that has brought the fuel cell to its current position. The Pratt and Whitney firm, which recognizes the significance of this innovation, licensed it and allowed it to be utilized in NASA projects. Alkaline fuel cells were one of the earliest fuel cell technologies to be invented, and they were also the first form of fuel cell utilized by NASA in spacecraft (Yılmaz et al. 2017).

The efficiency of a fuel cell can reach up to 70% while operating at temperatures ranging from 20 to 90 °C. Ni catalysts are utilized in the anode of the alkali fuel cell, whereas Ag catalysts are used in the cathode. For this reason, power generation is limited, which is a disadvantage. The oxidizing capabilities of the components in the alkaline fuel cell's body are relatively sensitive to the carbon dioxide in the fuel. Because carbon dioxide mixes with potassium hydroxide in the electrolyte owing to its chemical property, a chemical reaction ensues that consumes the electrolyte and negatively affects the electrodes through which the current flows more than necessary (Andújar and Segura 2009). The usage of pure hydrogen and oxygen is required in this circumstance therefore, it is not often used in the marine industry or on ships.

3.4.2 Polymer Electrolyte Membrane Fuel Cells (PEMFC)

In terms of design and function, the proton exchange membrane fuel cell (PEM) is the most elegant. It was initially developed for spacecraft in the 1960s by PEM General Electric. A solid polymer electrolyte membrane is sandwiched between two platinum-catalyzed porous electrolytes in this case. A fuel cell is another name for a polymer electrolyte membrane (membrane). When compared to other fuel cells, it has a higher power density, a smaller volume, and lighter weight. The electrolyte in the fuel cell is a thin polymer membrane. The proton-permeable membrane has a thickness of microns. Operating temperatures are usually in the 60–80 °C range (Gasteiger and Yan 2004), and are less than 100 °C. The use of noble metals (often platinum) as a catalyst raises the price. The high carbon monoxide sensitivity of platinum catalysts requires the separation of any carbon dioxide contained in the fuel which adds to the processing and cost. To address this issue, several designs employ platinum/ruthenium catalysts with extremely low carbon monoxide sensitivity.

The European Maritime Safety Agency (EMSA) investigated 23 ships utilizing fuel cells in its report on the deployment of fuel cells in ships. It was discovered that 15 of these ships employed PEM fuel cells. PEM fuel cells are favored in the marine industry because of their smaller size, high efficiency, minimal maintenance costs, and extended life (Tronstad et al. 2017).

3.4.3 Direct Methanol Fuel Cells (DMFC)

When hydrogen is used directly in fuel cells, very high efficiencies are attained. However, due to hydrogen's extremely low volumetric energy density, it is difficult to use this gas in tiny electronic devices (Kamarudin et al. 2009). Hydrogen, despite its great energy density, is difficult to store. Due to its high liquid state under air circumstances and high volumetric energy density, methanol has an advantage over hydrogen and expands the application fields of fuel cells (Adamson and Pearson 2000). The Direct Methanol Fed Fuel Cell is a type of proton exchange membrane fuel cell. The most important feature that separates this fuel cell type from others is that it uses liquid methanol as fuel. The following are the benefits of using this fuel: Storage is simple, the cost is low, and the energy density is great. Aside from these benefits, the high cost of key components, such as catalysts, is the most major obstacle to the commercialization of DMFC. Other drawbacks of the methanol transition and the slow rate of methanol oxidation in the anode, in addition to its high cost, include low power density and electrical efficiency (Hamnett 2010). The working temperature of DMFC is between 80 and 110 °C, and it is primarily utilized in electrical equipment. DMFC is not utilized to meet the ship's energy requirements.

3.4.4 Phosphoric Acid Fuel Cells (PAFC)

In a phosphoric acid fuel cell, phosphoric acid is used as an electrolyte and in the early 1990s, these fuel cells were commercially accessible (Lee 2021). These types of fuel cells are more suited for stationary power generation systems in which electrodes, porous carbon electrodes with a platinum catalyst layer are employed. When compared to other types of fuel cells, the efficiency of electricity generation in phosphoric acid fuel cells is lower. At low temperatures, phosphoric acid has a lower conductivity. As a result, these systems should be run at high temperatures. One of the most significant issues reducing efficiency is CO poisoning of the Pt catalyst in the anode. The slow kinetics of the oxygen reduction process have an impact on the performance of these fuel cells. When compared to acid electrolytes, this kinetics is faster in alkaline electrolytes (Sammes et al. 2004). Although PAFC is one of the fuel cells used in ships, its utilization rate is lower than that of other fuel cells due to its disadvantage in terms of a lifetime when compared to other fuel cells.

3.4.5 Molten Carbonate Fuel Cells (MCFC)

This type of fuel cell's electrolyte is made up of a mixture of lithium, sodium, and potassium carbonates. Natural gas whose operating temperature is around 650 °C, is mostly utilized as a fuel and is favored in power plants, industrial applications, and military purposes (Dicks 2004). Because the ionic conductivity of the high-temperature electrolyte is quite high, noble metals are required as catalysts Under normal conditions, their efficiency is approximately 60%, but in the case of cogenerative applications, it can reach up to 80%. The absence of an external fuel processor, which is necessary for conventional fuel cells, is an important feature of the molten carbonate fuel cell. Because of the high operating temperature, fuels can be converted into hydrogen via the cell's internal fuel conversion mechanism. This has a beneficial impact on processes and costs. The combination of carbon monoxide and carbon dioxide in the fuel does not affect the performance of a molten carbonate fuel cell. The most significant drawbacks are their insecurity. Operating at high temperatures reduces fuel cell life due to performance degradation caused by corrosive electrolytes and corrosion formation (Randström et al. 2006). Although the usage of traditional marine fuels makes MCFCs appealing for maritime applications, SOFC and PEMFC are expected to be used for the carbon-free future envisioned by the EU Green Deal.

3.4.6 Solid Oxide Fuel Cells (SOFC)

SOFCs with ceramic electrolytes are a type of fuel cell that can function at extremely high temperatures, such as 1000 °C. Evaporation and electrolyte leakage do not occur since the electrolyte used in the fuel cell with an efficiency of up to 60% is solid. As a result, an issue like the completion of the depleted electrolyte never happens (Brandon et al. 2013). They are utilized in applications that require a huge amount of power, such as continuous power and heat generating. Furthermore, SOFC is used in the transportation industry to produce supplementary power in commercial vehicles, as well as in military projects, night vision equipment, global positioning systems, and target determiners (Singhal 2002).

SOFCs offer greater energy production efficiency, easier industrial application, higher mechanical strength and thermal stability of the ceramic cell employed as a solid electrolyte, more industrial application areas, and so on. Because of their characteristics, SOFCs have a wide range of applications. Nevertheless, when considering industrial applications in other nations, it is clear that the usage of SOFC type cells, rather than all fuel cell cells, is more common, particularly in power production facilities. For all of these reasons, SOFCs are also being used in the marine sector. However, with today's technology, SOFCs are not only made using clean fuels but also use fossil fuels. As a consequence, the EU is no longer well-positioned to achieve the Green Deal's objectives.

4 Fuel Cell Projects in Shipping

Fuel cell technologies were first used in the marine industry in the early 2000s. The first ship built in this area is the small passenger transport boat "Hydra" built-in Germany (Xing et al. 2021). The Hydra ship is especially significant since it is approved by Germanischer Lloyd. The use of fuel cells in the marine industry, which began with Hydra, was expanded for use in short-distance passenger transportation

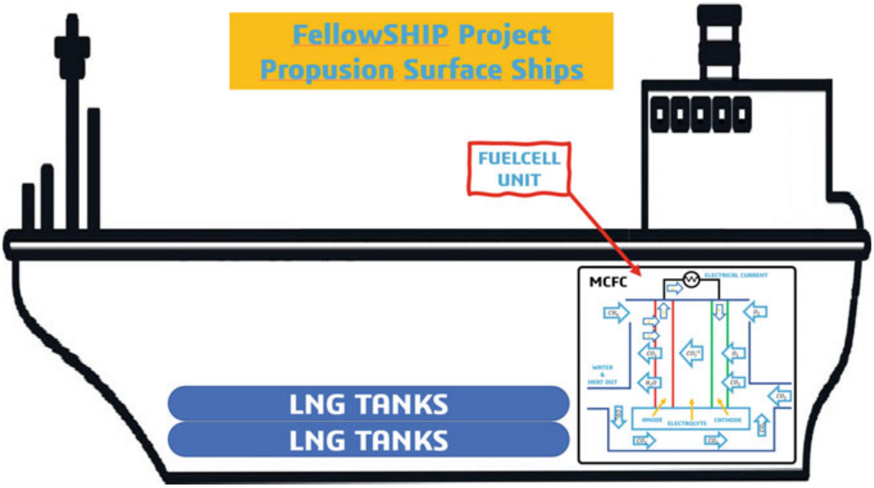

Fig. 9 Viking lady prototype (Winkler 2010)

in other European nations. In 2006, the German military built a hydrogen fuel cell submarine for the first time, elevating the work done in this field to a new level.

Under the leadership of Europe, Norway, and Germany, the FellowSHIP project was launched in 2003 to investigate the application of battery, hybrid, and fuel cell technologies in the marine sector. This project also resulted in the development of classification standards, with DNV establishing the first worldwide classification rule in this sector (Dnv 2018).

The first fuel cell developed as part of the FellowSHIP project was installed aboard the ship Viking Lady, which was built in Turkey's Torlak Shipyard, and the learning phase was carried out by executing the project (de-Troya Jet al. 2016). However, the fact that the Viking Lady's LNG-powered fuel cells represent an important step toward a carbon-free future is inadequate. Figure 9 (Winkler 2010) is a prototype image of the Viking Lady utilizing MCFC and SOFC developed by the German company MTU.

The E4Ships project is another German project involving the use of fuel cells in other ships. The German government is financially supporting this project as part of the hydrogen and fuel cell innovation program. Two separate fuel cells were placed on two different ships as part of the experiment. A 100 kW PEMFC powered by methanol was installed aboard Viking Line's MS Mariella, while a 60 kW diesel fuel SOFC was installed on the MS Forester cargo ship (Dnv 2018).

The FCSHIP project was started by the EU as part of the framework programs (FP 5) for research and technical development (Meek-Hansen 2002). The NEW-H-SHIP project, which was established later, used this project's knowledge to identify technological hurdles (demonstrative barriers) for fuel cell and hydrogen aboard ships. The route to hydrogen propulsion aboard ships will be charted, and recommendations for future research and development will be made by creating a reference list of fuel

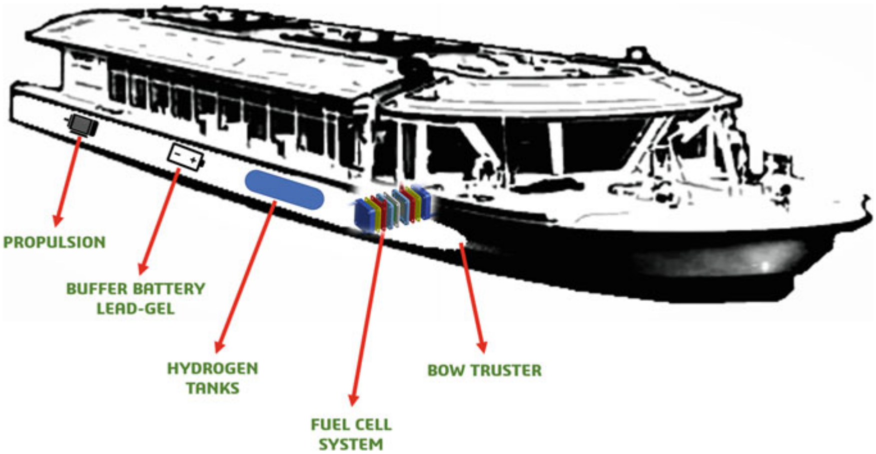

Fig. 10 FCS Alsterwasser (Schneider and Dirk 2010)

cell and hydrogen research and development efforts. The project was launched to find prospective European partners and supporting European initiatives in the field of hydrogen and fuel cells in marine applications (Dall'Armi et al. 2021).

At the end of this project, it was discovered that hydrogen storage is the most difficult problem in ships used for international transportation, although fuel cells can be utilized for short-distance and inland transportation. Another emerging issue is the infrastructure for bunkering. Furthermore, one of the benefits is the requirement for worldwide class regulation.

The zero-emission ship (Zemship) project was established in 2006 to utilize hydrogen energy in a passenger ship for passenger transportation on the Alster river in Hamburg, Germany. 100 kW of PEMFC were developed and used in this project, which was funded by the European Union. This research was carried out on FCS Alsterwasser, as illustrated in Fig. 10 (Schneider and Dirk 2010).

The FELICITAS project was one of several fuel cell research and development projects conducted in Europe between 2005 and 2008 (Dnv 2018). This project was created to conduct research and development on fuel cells that can be utilized not only in maritime transportation but also in road and rail transportation. The project is divided into four parts, with the first focusing on the needs and theoretical research of the application of fuel cells to heavy vehicles. The focus in the second phase was on meeting the demands for Auxiliary Power Unit (APU) with 250 kW SOFC in the marine industry. PEMFC was used in the third stage to evaluate its applicability in all heavy transport industries. The most forward-thinking research at FELICITAS was focused on directly connecting SOFC and PEMFC systems by combining the advantages of SOFC and PEMFC technologies. This technique, which focuses on the fourth phase, can be defined as a particular reform technology for the PEMFC masses. The utilization of not just pure hydrogen but also various hydrocarbon-based fuels in most heavy-duty applications is a precondition for FELICITAS' major research

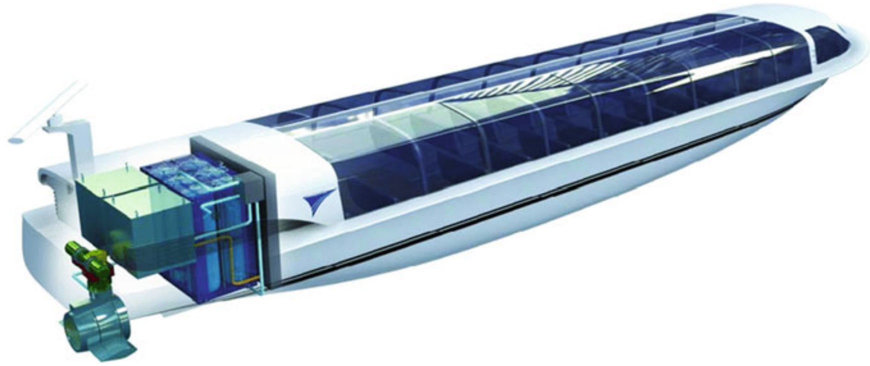

Fig. 11 Fuel cell boat NEMO H2 (Chakraborty et al. 2013)

subject. The primary objective of FELICITAS was to develop fuel cell drive trains for road, rail, and marine applications that can meet the needs of heavy-duty transport.

However, neither the produced SOFC nor the developed PEMFC was sufficient for the main propulsion system of road-rail and marine vehicles in the studies. But, it is understood that the SOFC technology can be modernized and used in the maritime sector (Commission 2017).

Holland participated engaged in hydrogen fuel cell project development in 2009. On cruises utilizing PEMFC with 60 KW electricity, Nemo H2 can travel for roughly 9 h at a speed of 9 knots. With an estimated 125 trips per day on Amsterdam's canals, it was hoped to expand the number of passenger ships by generating a budget for fuel cell research and development in the marine industry by charging 50 euros extra each trip on Nemo H2 cruises (Chakraborty et al. 2013) (Fig. 11).

Hydrogenesis was developed as a proof-of-concept model to demonstrate the availability of hydrogen fuel cell technology. The vessel serves as the foundation for long-term hydrogen fuel cell-powered activities in Bristol's harbor. Hydrogenesis can travel with 12 guests and 2 crew members utilizing 12 kW of PEMFC (Dnv 2018). Today, after the EU Green Deal, a European hydrogen strategy has been developed, and efforts have been made to reduce emissions in the marine industry, particularly in domestic transportation.

5 Result and Conclusions

Almost the majority of the energy used in the marine sector today comes from fossil fuels. The marine sector's energy demand is rapidly growing in direct proportion to population expansion, industrialization, and new demands portfolio. On the other hand, there has been no increase in fossil resources, which are the primary energy source in today's world; in other words, we are approaching a point when supplies are insufficient to satisfy demand. Furthermore, the fossil fuels utilized send hazardous emissions into the environment, contributing to global warming and climate change. The EU Green Deal aims to achieve a zero-emission objective by 2050 in the context of combatting global warming and climate change. All of these factors need the development of new energy sources in Europe's marine sector. It is also critical that these energy sources be innovative, renewable, clean, and long-lasting. In conclusion, hydrogen is extremely appealing among alternative energy sources due to its current global potential, recyclability, reliability, and availability, as well as qualities such as not causing environmental concerns. However, several issues, including production costs, storage issues, and explosion, restrict its application.

Hydrogen fuel cells are regarded as one of the most promising technologies for reducing and eliminating greenhouse gas emissions in the maritime industry. The usage of fuel cells and hydrogen energy in the marine industry following the EU Green Deal goals in the context of mitigating global warming and climate change is investigated in this chapter. To meet the EU Green Deal targets, hydrogen must be utilized directly as fuel or in the primary propulsion system of ships, with hydrogen obtained from renewable sources. Although fuel cells have been developed by consortiums organized in various European nations since the early 2000s, no fuel cell has been produced to fulfill the energy demands of ships involved in long-distance transport. As a consequence, in terms of meeting the 2030 EU Green Deal objectives, hydrogen for fuel cells must be produced from lower-emission fuels, and fuel cell technologies must be developed. After 2030, to meet the EU Green Deal's zero-emission objective in all sectors, hydrogen must be utilized directly or green hydrogen must be used in fuel cells used in the marine sector.

Three fuel cells stand out when the fuel cells used in ships are evaluated. There are three of them: DMFC, SOFC, and PEMFC. Only PEMFC use hydrogen as the primary fuel in their fuel cells. Recent studies in the marine industry show that SOFC and PEMFC fuel cells are preferred due to their high energy output. Although PEMFC stands out due to its ability to use hydrogen as the primary fuel and its capacity to fulfill high energy demands, it is thought that improving it by combining it with the advantages of other fuel cells can help the EU accomplish the Green Deal 2050 objective.

To become the first carbon-free continent under the EU Green Deal, Europe must take a comprehensive strategy that considers the role of the entire marine cluster, including fixtures, ports, and energy suppliers. For hydrogen to be used in the maritime sector and aboard ships, all leading companies, including fuel providers and marine operations, must collaborate. One of the critical shortcomings that must be addressed is the establishment of a fuel standard as a requirement for fuel providers, in addition to the emission limits imposed on the marine sector and ships. Following this, it is important to establish a standardization of hydrogens such as conventional fuels and LNG by overcoming the inadequacies in transportation, storage, bunkering, and security on a global scale. It is also critical to develop and make worldwide accepted class regulations for the use of fuel cells aboard ships.

Disclaimer The authors' views and conclusions are their own and should not be interpreted as representing the official policies or endorsements, expressed or implied, of National Defence University, Turkish Naval Forces, Turkish Armed Forces, Marmara University, Beykent University, or any affiliated organization or government.

References

Abdalla AM, Hossain S, Petra PM, Ghasemi M, Azad AK (2018) Achievements and trends of solid oxide fuel cells in clean energy field: a perspective review. Front Energy 1–24. https://doi.org/10.1007/s11708-018-0546-2

Adamson KA, Pearson P (2000) Hydrogen and methanol: a comparison of safety, economics, efficiencies and emissions. J Power Sources 86(1–2):548–555. https://doi.org/10.1016/S0378-7753(99)00404-8

Andújar JM, Segura F (2009) Fuel cells: history and updating. A walk along two centuries. Renew Sustain Energy Rev 13(9):2309–2322. https://doi.org/10.1016/j.rser.2009.03.015

Antonini C, Treyer K, Streb A, van der Spek M, Bauer C, Mazzotti M (2020) Hydrogen production from natural gas and biomethane with carbon capture and storage—a techno-environmental analysis. Sustain Energy Fuels 4(6):2967–2986. https://doi.org/10.1039/D0SE00222D

Benz J, Ortiz B, Roth W, Sauer DU, Steinhüser A (2003) Fuel cells in photovoltaic hybrid systems for stand-alone power supplies. In: Paper presented at the 2nd European PV-hybrid and mini-grid conference, Kassel (Germany), 25–26 Sept 2003

Bicer Y, Dincer I (2018) Clean fuel options with hydrogen for sea transportation: a life cycle approach. Int J Hydrogen Energy 43(2):1179–1193. https://doi.org/10.1016/j.ijhydene.2017.10.157

Bodewig K European Coordinator of the Motorways of the Sea. https://project-iwts20.eu/wp-content/uploads/2020/10/20201008_Kurt_Bodewig_Green_Deal.pdf. Accessed on 29 Apr 2021

Brandon N, Dincer I, Shao ZP, Xia C, Hill JM et al (2013) Solid oxide fuel cells: from materials to system modeling. Royal Society of Chemistry

Boğaziçi Üniversitesi İklim Değişikliği ve Politikaları Uygulama ve Araştırma Merkezi. Net Sıfır Salım Mı, %100 Yenilenebilir Enerji Mi?. [Çevrimiçi]. http://climatechange.boun.edu.tr/net-sifir-salim-mi-%100-yenilenebilir-enerji-mi/. Accessed on 30 Apr 2021

Chakraborty S, Dzielendziak AS, Koroglu T, Yang K (2013) Evaluation of smart eco-friendly public transport options in coastal cities: towards a green future for the city of Southampton

Chen J, Fei Y, Wan Z (2019) The relationship between the development of global maritime fleets and GHG emission from shipping. J Environ Manage 242:31–39. https://doi.org/10.1016/j.jenvman.2019.03.136

Cook B (2002) Introduction to fuel cells and hydrogen technology. Eng Sci Educ J 11(6):205–216. https://doi.org/10.1049/esej:20020601

Corbett JJ, Koehler HW (2003) Updated emissions from ocean shipping. J Geophys Res Atmos 108(D20). https://doi.org/10.1029/2003JD003751

Cullinane RK, Bergqvist R (2014) Emission control areas and their impact on maritime transport. Transp Res Part D Transp Environ 28:1–5. https://doi.org/10.1016/j.trd.2013.12.004

Dall'Armi C, Micheli D, Taccani R (2021) Comparison of different plant layouts and fuel storage solutions for fuel cells utilization on a small ferry. Int J Hydrogen Energy 46(26):13878–13897. https://doi.org/10.1016/j.ijhydene.2021.02.138

de-Troya JJ, Alvarez C, Fernández-Garrido C, Carral L (2016) Analysing the possibilities of using fuel cells in ships. Int J Hydrogen Energy 41(4):2853–2866. https://doi.org/10.1016/j.ijhydene.2015.11.145

Dicks AL (2004) Molten carbonate fuel cells. Curr Opin Solid State Mater Sci 8(5):379–383. https://doi.org/10.1016/j.cossms.2004.12.005

Dinçer I (2008) Hydrogen and fuel cell technologies for sustainable future. Jordan J Mech Indust Eng 2(1):1–14

Dinçer I (2012) Green methods for hydrogen production. Int J Hydrogen Energy 37(2):1954–1971. https://doi.org/10.1016/j.ijhydene.2011.03.173

Dincer I, Acar C (2015) Review and evaluation of hydrogen production methods for better sustainability. Int J Hydrogen Energy 40(34):11094–11111. https://doi.org/10.1016/j.ijhydene.2014.12.035

Dincer I, Rosen MA (2011) Sustainability aspects of hydrogen and fuel cell systems. Energy Sustain Dev 15(2):137–146. https://doi.org/10.1016/j.esd.2011.03.006

Dnv GL (2018) Assessment of selected alternative fuels and technologies. DNV GL—Maritime

Dowell NM, Shah N (2012) Shipping and CCS: a systems perspective. Sustainable technologies, systems & policies 19; Special issue: Carbon capture and storage workshop, Texas A&M University in Qatar. https://doi.org/10.5339/stsp.2012.ccs.19

Edwards PP, Kuznetsov VL, David WI, Brandon NP (2008) Hydrogen and fuel cells: towards a sustainable energy future. Energy Policy 36(12):4356–4362. https://doi.org/10.1016/j.enpol.2008.09.036

Ehteshami MM, Chan SH (2014) The role of hydrogen and fuel cells to store renewable energy in the future energy network–potentials and challenges. Energy Policy 73:103–109. https://doi.org/10.1016/j.enpol.2014.04.046

European Commission (2017) Final report summary—FELICITAS (Fuel cell power trains and clustering in heavy-duty transports). https://cordis.europa.eu/project/id/516270/reporting. Accessed on 29 Apr 2021

European Commission. Maritime what do we want to achieve? https://ec.europa.eu/transport/modes/maritime_en. Accessed on 29 Apr 2021

European Commission. A European green deal, 11 Dec 2020. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. Accessed on 21 Jan 2021

European Commission. A European green deal: striving to be the first climate-neutral continent. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. Accessed on 29 Apr 2021

Evrin RA, Dincer I (2019) Thermodynamic analysis and assessment of an integrated hydrogen fuel cell system for ships. Int J Hydrogen Energy 44(13):6919–6928. https://doi.org/10.1016/j.ijhydene.2019.01.097

Gasteiger HA, Yan SG (2004) Dependence of PEM fuel cell performance on catalyst loading. J Power Sources 127(1–2):162–171. https://doi.org/10.1016/j.jpowsour.2003.09.013

Gorny T (2020). The colours of hydrogen. Gas Connect Austria. https://www.gasconnect.at/en/news/news-press/news/detail/News/die-farben-des-wasserstoffs. Accessed on 30 Feb 2021

Hamnett A (2010) Direct methanol fuel cells (DMFC). In: Handbook of fuel cells. Wiley

Hord J (1978) Is hydrogen a safe fuel? Int J Hydrogen Energy 3(2):157–176. https://doi.org/10.1016/0360-3199(78)90016-2

Hortal MA, Miranda JL (2005) El hidrógeno: fundamento de un futuro equilibrado una introducción al estudio del hidrógeno como vector energético. Díaz de Santos, Madrid

IEA, Rate of change of global primary energy demand, 1900–2020, IEA, Paris https://www.iea.org/data-and-statistics/charts/rate-of-change-of-global-primary-energy-demand-1900-2020. Accessed on 19 Jan 2021

IMO (2018) Marine Environment Protection Committee (MEPC), 72nd session, 01 Mar 2018

Jones N (2017) How the world passed a carbon threshold and why it matters. Yale Environment 360. https://e360.yale.edu/features/how-the-world-passed-a-carbon-threshold-400ppm-and-why-it-matters. Accessed on 29 Apr 2021

Kahn B (2017) We just breached the 410 PPM threshold for CO_2. https://www.scientificamerican.com/article/we-just-breached-the-410-ppm-threshold-for-co2/. Accessed on 29 Jan 2021

Kamarudin SK, Achmad F, Daud WRW (2009) Overview on the application of direct methanol fuel cell (DMFC) for portable electronic devices. Int J Hydrogen Energy 34(16):6902–6916. https://doi.org/10.1016/j.ijhydene.2009.06.013

Kyoto Protocol (1997) United Nations framework convention on climate change. Kyoto Protocol 19, 8, 11 Dec 1997

Lee D (2021) Functional material developments of fuel cells and the key factors for real commercialization of next-generation energy devices. Sustain Mat Next Gen Energy Dev 85–100. Elsevier. https://doi.org/10.1016/B978-0-12-820628-7.00004-6
McKinlay CJ, Turnock S, Hudson D (2020) A comparison of hydrogen and ammonia for future long distance shipping fuels. In: Paper presented at the LNG/LPG and alternative fuel ships, London, UK, 29–30 Jan 2020
Meek-Hansen B (2002) Fuel cell technology for ferries. In: Paper presented at the IMTA conference, in the prestigious Chateau Laurier, Ottowa, 22–24 Oct 2002
Midilli A, Ay M, Dincer I, Rosen MA (2005) On hydrogen and hydrogen energy strategies: I: current status and needs. Renew Sustain Energy Rev 9(3):255–271. https://doi.org/10.1016/j.rser.2004.05.003
Moser SC (2010) Communicating climate change: history, challenges, process and future directions. Wiley Interdiscipl Rev Climate Change 1(1):31–53. https://doi.org/10.1002/wcc.11
O'hayre R, Cha SW, Colella W, Prinz FB (2016) Fuel cell fundamentals. Wiley
Oberthür S (2003) Institutional interaction to address greenhouse gas emissions from international transport: ICAO, IMO and the Kyoto Protocol. Climate Policy 3(3):191–205. https://doi.org/10.1016/S1469-3062(03)00060-3
Ogawa T, Takeuchi M, Kajikawa Y (2018) Analysis of trends and emerging technologies in water electrolysis research based on a computational method: a comparison with fuel cell research. Sustainability 10(2):478. https://doi.org/10.3390/su10020478
Paris agreement (2017) In: Report of the conference of the parties to the united nations framework convention on climate change (21st Session, 2015: Paris). Retrived December, vol 4
Qureshy AM, Dincer I (2020) A new integrated renewable energy system for clean electricity and hydrogen fuel production. Int J Hydrogen Energy 45(41):20944–20955. https://doi.org/10.1016/j.ijhydene.2020.04.218
Randström S, Lagergren C, Capobianco P (2006) Corrosion of anode current collectors in molten carbonate fuel cells. J Power Sources 160(2):782–788. https://doi.org/10.1016/j.jpowsour.2006.04.069
Renssen SV (2020) The hydrogen solution? Nat Clim Chang 10(9):799–801. https://doi.org/10.1038/s41558-020-0891-0
Salkuyeh YK, Saville BA, MacLean HL (2017) Techno-economic analysis and life cycle assessment of hydrogen production from natural gas using current and emerging technologies. Int J Hydrogen Energy 42(30):18894–18909. https://doi.org/10.1016/j.ijhydene.2017.05.219
Sammes N, Bove R, Stahl K (2004) Phosphoric acid fuel cells: fundamentals and applications. Curr Opin Solid State Mater Sci 8(5):372–378. https://doi.org/10.1016/j.cossms.2005.01.001
Sari A, Sulukan E, Özkan D (2021) Analysis and modeling the energy system of a chemical tanker by LEAP. J Ship Prod Design 37(01):45–53. https://doi.org/10.5957/JSPD.07190034
Schneider J, Dirk S (2010) ZEMShip. In: Paper presented at the 18th world hydrogen energy conference 2010—WHEC 2010, Essen, 16–21 May 2010
Sevim C (2011) Enerji teknolojilerindeki anlayiş model değişimi ve hizli iklim değişikliği. J Yaşar Univ 6 (21):3515–3522. https://doi.org/10.19168/jyu.41266
Singhal SC (2002) Solid oxide fuel cells for stationary, mobile, and military applications. Solid State Ionics 152:405–410. https://doi.org/10.1016/S0167-2738(02)00349-1
Sulukan E, Uyar TS, Beşikci D, Özkan D, Sarı A (2020) Energy system analysis, simulation and modelling practices in Turkey. In: Uyar TS (ed) Accelerating the transition to a 100% renewable energy era. Springer, Cham, pp 485–506
Sulukan E, Özkan D, Sarı A (2018) Reference energy system analysis of a generic ship. J Clean Energy Technol 6(5):371–376. https://doi.org/10.18178/JOCET.2018.6.5.492
Sulukan E, Sarı A, Özkan D, Uyar TS (2021) A decision-making tool based analysis of onboard electricity storage. In 14th international renewable energy storage conference 2020 (IRES 2020), pp 19–25. Atlantis Press
Tronstad T, Åstrand HH, Haugom GP, Langfeldt L (2017) Study on the use of fuel cells in shipping. European Maritime Safety Agency

Tschakert P (2015) 1.5 or 2°C: a conduit's view from the science-policy interface at COP20 in Lima, Peru. Climate Change Responses 2(1):1–11. https://doi.org/10.1186/s40665-015-0010-z

Uyar TS, Beşikci D, Sulukan E (2019) An urban techno-economic hydrogen penetration scenario analysis for Burdur, Turkey. Int J Hydrogen Energy 45(50):26545–26558. https://doi.org/10.1016/j.ijhydene.2019.05.144

Winkler W (2010) Fuel cells in aircraft and maritime application

Winter M, Broad R (2004) What are batteries, fuel cells, and supercapacitors? Chem Rev 104(10):4245–4270. https://doi.org/10.1021/cr020730k

Xing H, Stuart C, Spence S, Chen H (2021) Fuel cell power systems for maritime applications: progress and perspectives. Sustainability 13(3):1213. https://doi.org/10.3390/su13031213

Yılmaz A, Ünvar S, Ekmen M, Aydın S (2017) Yakit pili teknolojisi. Technological. Appl Sci 12(4):185–192