ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΩΣ

UNIVERSITY OF PIRAEUS

HYDROGEN AS A MARINE FUEL

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MASTER'S THESIS

MSc: Sustainability and Quality in Marine Industry

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January 2022, Piraeus

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ACKNOWLEDGEMENTS

Firstly, I would like to express special thanks to my supervisor, Professor Ernestos Tzannatos, for his trust in assigning me one very interesting subject of study, as well as for his support, guidance, and overall insights in this field which have made this an inspiring experience for me. I would also like to thank Professor Fani Sakellariadou and Professor Anastasios Tselepides for taking the time to read my work. I would also like to thank my professors, who were always willing to listen and assist me during my Master's program. Lastly, I am grateful to my family, friends and especially Tassos for their steadfast support and patience over this academic year that assisted me in completing my dissertation.

To you (12/02/2021)..

ABSTRACT

Climate change is one of the most significant problems confronting our world, caused mostly by GHG emissions that trap heat in the earth's atmosphere, resulting in global warming. Shipping has a huge impact on global environmental pollution, notably air pollution. Countries are now pursuing aggressive GHG emission reduction measures as a result of the 2015 Paris Agreement. Furthermore, the IMO adopted an initial strategy in 2018 to reduce GHG emissions from international shipping by at least 50% from 2008 levels by 2050, with the objective of completely eliminating them. As a result, shipping's CO_2 emissions must be lowered in the next decades. One of the countermeasures for CO_2 emissions from ships is the use of hydrogen as an eco-friendly fuel.

The current study was focused on the development of a portfolio of hydrogen use as a marine fuel. It was found from 2000 until today 84 hydrogen-powered vessels projects. The Netherlands, Norway, and Germany appear to have the most hydrogen-powered boats with 19%, 18%, and 14%, respectively. FCs are the preferred hydrogen propulsion method with the most important being the PEMFC. Hydrogen is stored either as compressed gas at 350 bar, or in liquid form using a liquefied cryogenic hydrogen storage system, or in solid form with metal hydrides. With a few exceptions, the ships are small in size and have a passenger capacity of roughly 6-300 people. There are various types of hydrogen-powered vessels, the majority of which are ferries. As long as the hydrogen is produced from renewable sources, the use of hydrogen as a marine fuel can offer a viable approach of reducing GHG emissions in a sustainable way.

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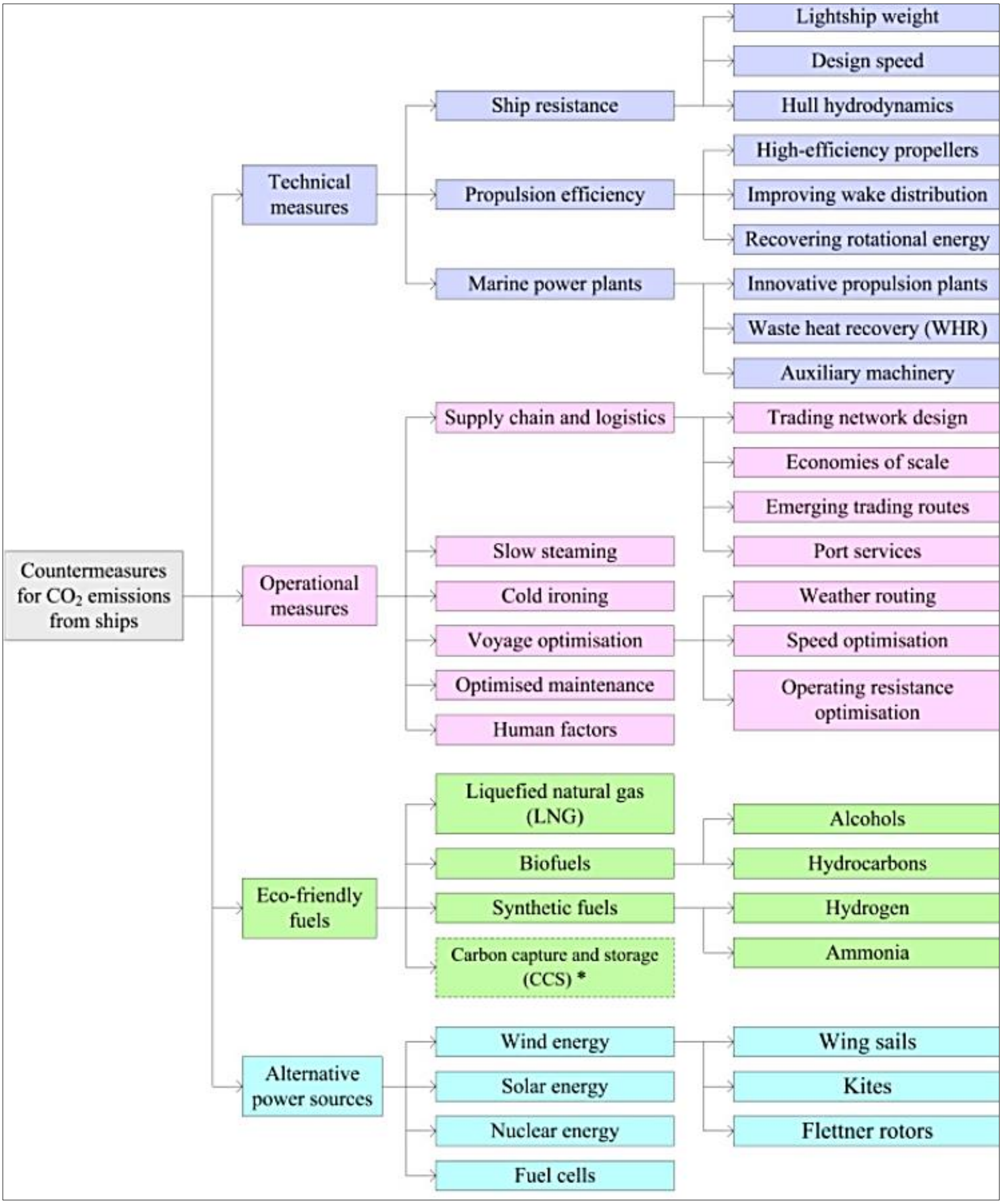
1. Introduction

1.1. Motivation and background

One of the major problems on our planet is climate change. A general definition of climate change could be the alteration in climate patterns mainly caused by greenhouse gas (GHG) emissions (Fawzy et al., 2020). GHG emissions cause heat that is trapped by the earth's atmosphere, and this has, as a result, global warming (Fawzy et al., 2020). These emissions originate mainly from natural systems (e.g. forest fires, oceans, wetlands, volcanoes, etc.) and human activities (Fawzy et al., 2020; YUE and GAO, 2018). Shipping is an important source of global environmental pollution and especially of the air (Ni et al., 2020).

Nowadays, due to the 2015 Paris Agreement, (the first binding agreement for all nations of which the goal is to limit global warming to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels to combat climate change), ambitious actions on GHG emissions mitigation carry out by countries (UNFCCC, n.d.). Furthermore, in 2018, the International Maritime Organization (IMO) adopted an initial strategy to reduce GHG emissions from international shipping by at least 50% from 2008 levels by 2050 while it is trying to eliminate them (Selin et al., 2021; IMO, 2018). Hence, in the coming decades, a reduction of carbon dioxide (CO_2) emissions is required for shipping (Xing et al., 2020). Some countermeasures for CO_2 emissions from ships appeared in Fig. 1.1 below, one of which is hydrogen as an eco-friendly fuel.



*Alternative solution to conventional marine fuels.

Figure 1.1 Countermeasures for shipping CO_2 emissions (Xing et al., 2020).

2. Literature review

2.1. Climate change

The *climate system* covers the atmosphere, the ocean, the land, the cryosphere (ice and snow), and the biosphere (Fig. 2.1) and it is described by such characteristics as temperature, the amount of precipitation, air humidity and soil, the state of the snow and ice cover, and many others (Mikhaylov et al., 2020). Climate is most obviously characterized by the atmospheric component of the climate system and it is often defined as “average weather” (Somerville et al., 2007).

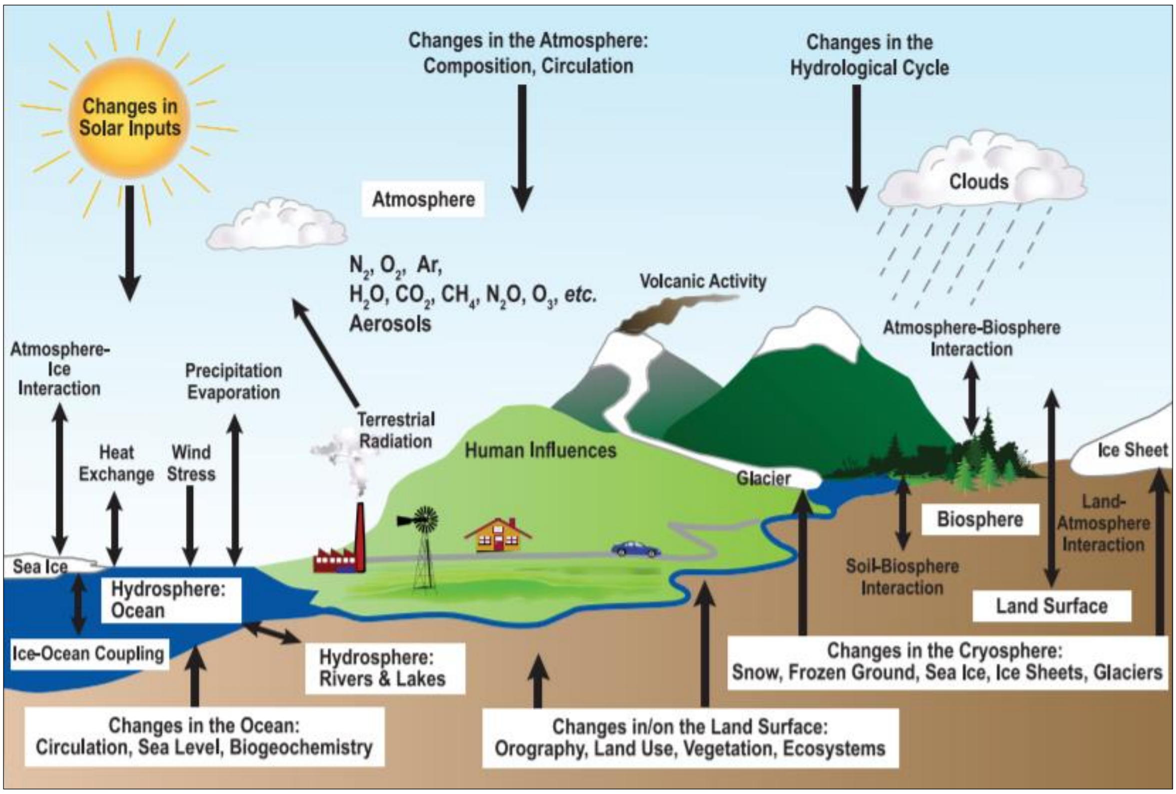


Figure 2.1 Climate system (Somerville et al., 2007).

The problem of climate change began with the industrial revolution at the beginning of the 20^{th} century with a gradual increase in the average annual temperature of the planet (Mikhaylov et al., 2020). It is worth mentioning that the temperature of the Earth grew 0.5-1 °C in the last 100 years and the problem of climate change caused mainly by anthropological activities has become the most serious amongst environmental issues (Mikhaylov et al., 2020).

Climate risks mainly include floods, drought, extreme weather, and landslides, but there are also some slow-onset impacts, such as those in Table 2.1 (UNFCCC, 2019). Another issue due to climate impacts in combination with socio-economic or geographical conditions is vulnerability and it is often described in terms of the sectors most threatened by climate impacts, as shown in Table 2.2 (UNFCCC, 2019).

SLOW-ONSET CLIMATE IMPACTS
HIGHER TEMPERATURES
SEA LEVEL RISE
RAINFALL VARIABILITY
REDUCED RIVER FLOWS
CHANGING SEASONAL PATTERNS
CHANGES IN SPECIES DISTRIBUTION
INVASIVE SPECIES
CHANGES IN DISEASE DISTRIBUTION
SOIL AND COASTAL DEGRADATION, EROSION
DESERTIFICATION
OCEAN ACIDIFICATION, CORAL BLEACHING, SALT WATER INTRUSION, CHANGES IN OCEAN CIRCULATION PATTERNS, AND GLACIER OR PERMAFROST MELTING

Table 2.1 Slow onset climate impacts.

Sector	Observed and projected impacts
Agriculture	› Increased frequency and severity of crop disease › Increased soil erosion › Losses in agricultural production and crop yield due to extreme weather
Water	› Changes in water distribution › Reduced water availability and quality
Health	› Hunger and malnutrition due to increased food insecurity › Increase in water-borne diseases such as diarrhea due to water scarcity › Increase in vector-borne diseases such as malaria due to higher temperatures › Mortality and morbidity due to extreme events
Forestry	› Increase or projected increase in forest fires › Changes in the distribution of forest species
Biodiversity	› Changes in the timing and duration of growing seasons › Changes in the distribution of species › Species endangerment and extinction
Coastal zones	› Increased risk of flooding and inundation due to extreme weather › Increased coastal erosion › Changes to coastal ecosystems › Alterations in sediment deposition patterns
Fisheries	› Changing population numbers and distribution because of ocean acidification and ocean circulation patterns › Habitat loss and degradation for marine animals
Tourism	› Reduced winter tourist traffic due to reduced snow cover › Archaeological sites and ancient buildings threatened by extreme weather › Endangered tourist areas due to coastal erosion and sea level rise
Energy	› Challenges for thermal generation › Higher demand for cooling › Economic losses due to interruptions caused by extreme weather

Table 2.2 Impacts in vulnerable sectors (UNFCCC, 2019).

2.2. Greenhouse effect

The greenhouse effect is known as the warming of the Earth's troposphere, however, the concepts of "greenhouse effect" and "global warming" are not equal, but are interrelated, as the first is the cause of the second (Mikhaylov et al., 2020; Benson, 2008). The greenhouse effect is a natural phenomenon and the "natural" greenhouse heating turns the Earth from an enemy planet to life with a global mean temperature of -18°C into a habitable state with a global average temperature of +15°C (Jones and Henderson-Sellers, 1990).

One of the consequences of the greenhouse effect is its influence on the Earth's climate and especially on global warming (Mikhaylov et al., 2020). In general, global warming is a term that refers to the increase in Earth's average surface temperature due to the release of GHGs into the atmosphere (Benson, 2008). These GHGs are coming mostly from many human activities such as increased fossil fuel consumption, the increasing use of automobiles, the use of nitrogen-based fertilizers, and the rearing and breeding of large methane-belching cattle (Benson, 2008).

The basic greenhouse theory is that whilst gases in the Earth's atmosphere are transparent to incoming solar radiation, some of them absorb outgoing thermal (heat) radiation emitted from the Earth's surface (Jones and Henderson-Sellers, 1990). That causes those gases to warm, and consequently, they reradiate heat in all directions one of which is back down through the atmosphere to the surface (Jones and Henderson-Sellers, 1990) (Fig. 2.2). Mankind's activities are adding increasingly large amounts of these radiatively active gases to the atmosphere, therefore, this planet seems to be committed to global-scale warming and many associated climatic shifts (Jones and Henderson-Sellers, 1990).

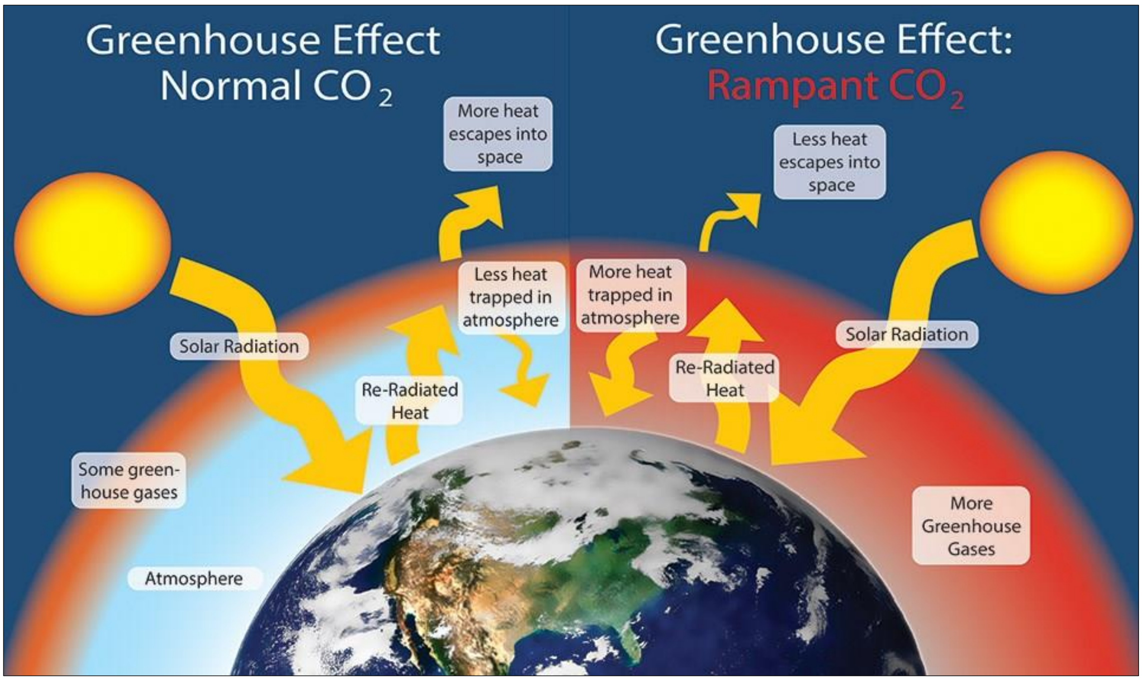


Figure 2.2 Greenhouse effect (Elder, NPS, 2020).

More specifically, GHGs such as CO_2, nitrous oxide (N_2O), water vapor, halocarbons {chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs)}, methane (CH_4), and ozone (O_3) absorb infrared radiation from the Earth's surface, then the stratosphere becomes warm and then re-emits infrared radiation back to the Earth's surface, altering the heat balance of the Earth (Benson, 2008). The basic GHGs that enter the atmosphere are the CO_2, CH_4, N_2O, and fluorinated gases and their emissions in 2019 in the United States were about 80% of CO_2, 10% of CH_4, 7% of N_2O, and 3% of fluorinated gases (USEPA, 2021). The effect on climate change of each gas depends mainly on the answer to the three following questions (USEPA, 2021):

1. ***How much*** *is in the atmosphere?*
2. ***How long*** *do they stay in the atmosphere?*
3. ***How strongly*** *do they impact the atmosphere?*

The main sources of the basic GHGs emissions are described below:

Fluorinated gases (F-gases)

Emitted from:

industrial processes (USEPA, 2021).

CO_2

Emitted from:

burning fossil fuels (coal, natural gas, and oil), solid waste, trees and other biological materials & from chemical reactions (e.g., manufacture of cement) (USEPA, 2021).

N_2O

Emitted from:

agricultural, land use, industrial activities, combustion of fossil fuels and solid waste & from the treatment of wastewater (USEPA, 2021).

CH_4

Emitted from:

the production and transport of coal, natural gas, and oil, from livestock and other agricultural practices, land use and by the decay of organic waste in municipal solid waste landfills (USEPA, 2021).

It is worth noting that shipping is a major source of CO_2 and other GHGs and if global shipping was a country, it would be in the sixth row of the ranking of the largest producer of GHG emissions (Harrould-Kolieb, 2008). On 15 July 2011, IMO adopted, via the International Convention for the Prevention of Pollution from Ships (MARPOL), the first set of international **mandatory** measures to improve ships' energy efficiency {Energy Efficiency Design Index (EEDI) for new ships, Ship Energy Efficiency Management Plan (SEEMP) for all ships} (IMO, 2021). Since then, IMO is making a decade of action on cutting GHG emissions from shipping with a package of mandatory measures combined with implementation support (projects) (IMO, 2021).

2.3. Ship pollution and marine fuels

Ships have various impacts on the environment, the main of them shown in Fig. 2.3 (Andersson et al., 2016). The two major categories include discharges into the sea and air pollution. Marine fuels contribute to both main categories of the impacts on the environment from the vessels. This marine fuels pollution is caused by oil spills and emissions to the air from ships {e.g. CO_2, carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (HCs), sulfur dioxide (SO_2), and particulate matter (PM)} (Andersson et al., 2016).

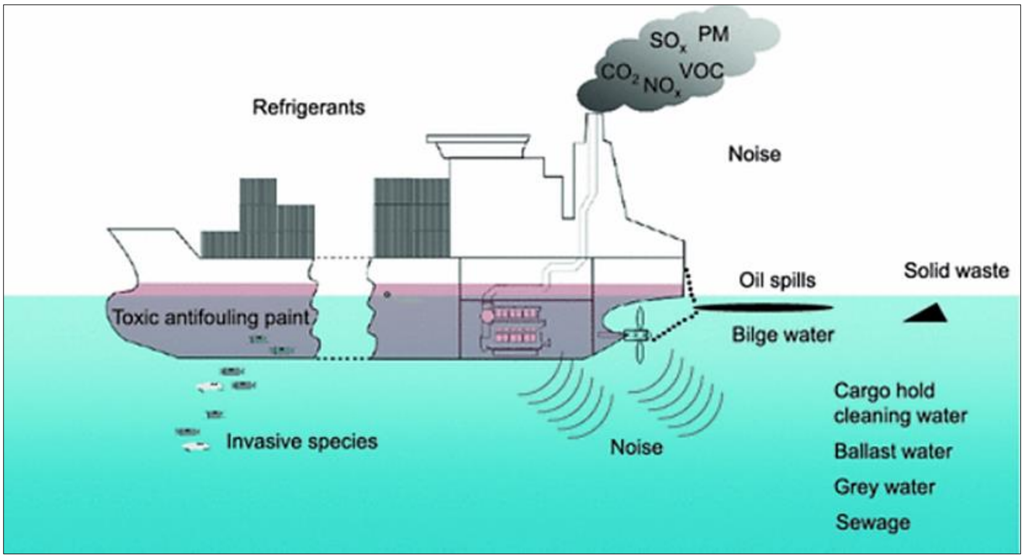


Figure 2.3 Pollution from Ships (Andersson et al., 2016).

More specifically, ship movement through water requires thrust, which is generated in several methods (Andersson et al., 2016). Most of the commercial fleet is converting the chemical energy contained in fuel into ship thrust (Andersson et al., 2016). More specifically, the process involves the conversion of the chemical energy of the fuel to thermal energy through the combustion of the fuel-air mixture and in turn, the conversion of the thermal to mechanical energy based on a thermodynamic cycle that ultimately manifests itself as ship thrust (Andersson et al., 2016).

The technologies that are used as prime movers for ships to produce mechanical power are mostly diesel engines, gas turbines, and steam turbines (Andersson et al., 2016). Prime mover generates mechanical power, then mechanical power is transferred to the propeller by the propeller shaft and the thrust bearing and then the thrust shaft transmits the thrust generated by the propeller to the hull (Andersson et al., 2016).

Marine propulsion engines cause environmental impacts with particular reference to the atmospheric environment. Namely, most exhaust emissions from ships are produced by the combustion process and are dependent on the combustion process, the fuel used, and the engine (Andersson et al., 2016). On the other hand, operational oil pollution originates from various sources, such as bilge water, propeller shaft bearings, and accidental oil spills from the transportation of fuels in tanker vessels and from fuel used for propulsion (Andersson et al., 2016).

Marine propulsion has changed throughout the years (Fig. 2.4) (Andersson et al., 2016). The first fuels at the beginning of the nineteenth century were made from coal and were used for steam engines and steam turbines (Andersson et al., 2016). Before that, shipping was powered by wind and manpower (Fridell, 2019). Over the years, most steam engines were replaced with marine engines fuelled by diesel and residual oil or heavy fuel oil (HFO) (Andersson et al., 2016).

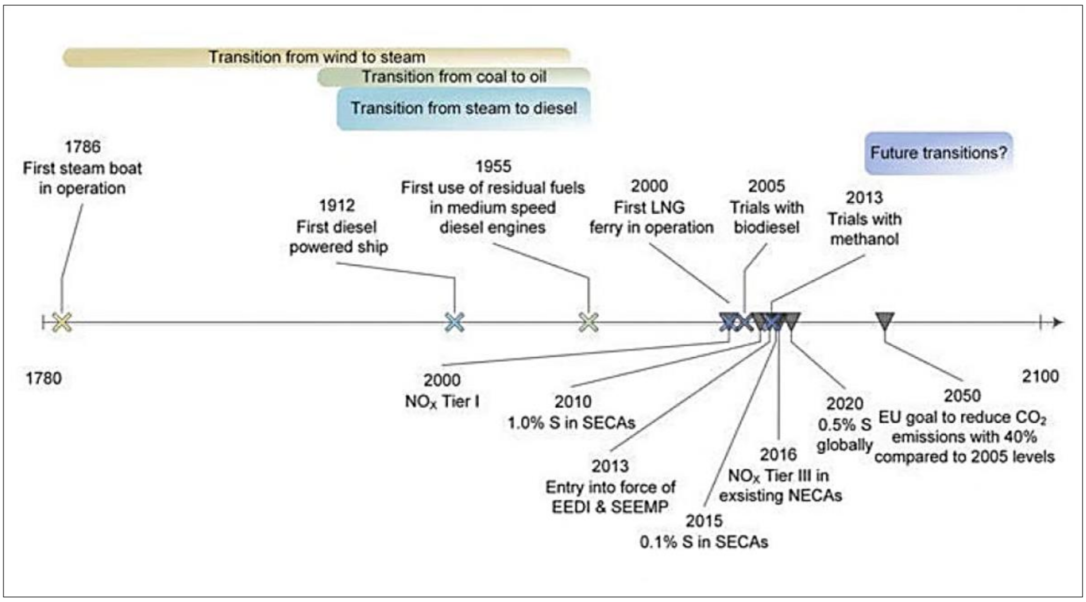


Figure 2.4 Transition of marine fuels from 1780 to 2100 (Andersson et al., 2016).

The main fuels in the shipping industry are the residual type of fuels {marine fuel oil (MFO), or HFO} (Tijdgat, 2020). The residual fuels also include low sulfur heavy fuels oil (LSHFO), and ultra-low sulfur fuel oil (ULSFO), while there are also distillate fuels which include marine gas oil (MGO) and marine diesel oil (MDO) (Tijdgat, 2020). HFO is the dominant shipping fuel, however, several alternative fuels have come to the fore, including liquefied natural gas (LNG), biodiesel, methanol and glycerol, hydrogen, ammonia, biofuel, and electricity (Andersson et al., 2016; Kim et al., 2020). However, electricity is not a fuel, but it is defined as a fuel because battery-electric propulsion is an important technology that has already been applied to vessels to mitigate GHG emissions (Kim et al., 2020). The advantages and disadvantages of five selected alternative marine fuels (LNG, hydrogen, ammonia, biofuel, and electricity produced by battery) will be presented below in Table 2.3 (Kim et al., 2020).

Alternative fuel	Advantages	Disadvantages
LNG	• Competitive fuel price • Available infrastructure and technologies	• Must be stored at insulated tanks • Cannot comply with 50% CO2 reduction
Hydrogen	• Enable zero-emission (with fuel-cell) • Can be produced from electrolysis near ports	• High fuel price • No available piston engine and infrastructure • Must be stored at extremely low tem-perature (liquefied hydrogen)
Ammonia	• Can be used in various combustion engines as well as fuel cells • Can be stored relatively low pressure and high temperature (liquefied ammonia)	• Toxicity and environ-mental impact when leaked • Need to add hydro-gen when used for internal combustion engines
Biofuel	• Can be carbon neutral • Compatible with existing infrastructure and engine systems	• High fuel price • Limited production volume
Electricity produced by Battery	• Enable zero-emission • High efficiency	• Low energy density of mass and volumetric density • High CapEx

Table 2.3 Advantages and disadvantages of five (5) alternative marine fuels (Kim et al., 2020).

2.4. The choice of future marine fuels

Choosing the future marine fuels depends on various aspects such as efficiency, safety, costs, and environmental aspects (BRYNOLF, 2014). The criteria for selecting future marine fuels are divided into four groups i.e. technical, economic, environmental, and other criteria and some of them involve minimum levels that must be satisfied (see Fig. 2.5) (BRYNOLF, 2014).

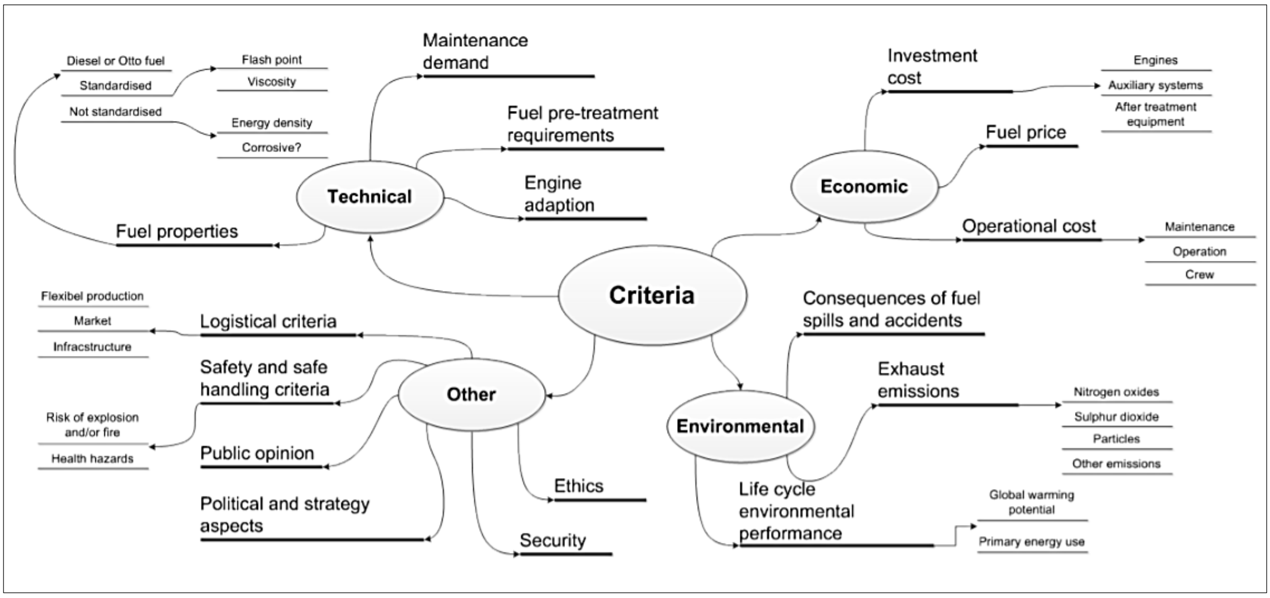


Figure 2.5 Criteria for future marine fuels (BRYNOLF, 2014).

The **technical criteria** concern the technical system associated with the fuel, which includes *engines*, *storage tanks*, *pumps*, *pipes*, and *exhaust funnel*, the *bunkering ships*, and the *fuel storage terminal* (BRYNOLF, 2014). Aspects that could consider are the fuel properties (e.g. indication of the ignition quality, the tendency of the fuel to detonate during combustion, energy density, boiling point, etc.), the propulsion systems, and the fuel pre-treatment requirements (BRYNOLF, 2014).

Regarding the **environmental criteria**, the fuel needs to fulfill the environmental regulations regarding the air emissions and its environmental life cycle performance to be acceptable (BRYNOLF, 2014). Aspects that could consider can be the total extracted energy, the global warming potential (GWP), and the consequences of fuel leaks (BRYNOLF, 2014).

Economic criteria are the investment costs (e.g. engines), the operational costs (e.g. maintenance, crew), and the price of fuel (BRYNOLF, 2014). **Other criteria** include logistics (e.g. requirements concerning the market, flexibility of production), safety (e.g. risk of explosion, fire, health hazards), security, public opinion (like the demand for sustainable transportation), ethics, and political and strategic aspects (like new jobs by producing a fuel locally) (BRYNOLF, 2014).

2.5. Legal framework

Sustainable development was first officially defined by the United Nations (UN) Brundtland Commission report "Our Common Future" in 1987 with the definition that "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland Commission, 1987; Manner, 2021). Regarding the shipping sector, achieving sustainable development objectives requires innovative solutions to tackle emission reduction targets (Manner, 2021).

The regulatory framework for climate change focuses on the UN Framework Convention on Climate Change (UNFCCC), which was adopted in Rio de Janeiro in 1992 and entered into force in 1994, and is the core on which subsequent agreements and tools for combating climate change have been developed (Carpenter et al., 2021). The UNFCCC's ultimate objective is to stabilize GHG concentrations in the atmosphere "at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC 1992, Art. 2). However, UNFCCC commitments include controlling, reducing, or preventing GHGs emissions from human activities not controlled by the Montreal Protocol in all relevant sectors, including transport (UNFCCC 1992, Art. 4.1(c)).

GHG emissions from the shipping sector were handled through the Kyoto Protocol (Andersson et al., 2016). The Kyoto Protocol pursues limitation or reduction of GHGs emissions not controlled by the Montreal Protocol from marine bunker fuels through the IMO (Kyoto Protocol 1997, Art. 2.2). IMO, so far, is completing ten years of action from the first set of international mandatory measures on cutting GHG emissions from shipping, however, IMO was discussing air pollution issues from ships since the 1970s (Table 2.4) (IMO, 2021). Furthermore, the Paris Agreement was adopted in 2015 to enhance the implementation of the UNFCCC regarding the global response to climate change maintaining the global average temperature rise to well below 2°C, ideally at 1.5°C, above pre-industrial levels (Manner, 2021; Paris Agreement 2015, Art. 2(1); Paris Agreement 2015, Art. 2(1)(a)).

YEAR	REGULATIONS
1970s	Discussion for controlling air pollution from ships at IMO.
1988	Inclusion of air pollution issue in Marine Environment Protection Committee (MEPC) work programme.
1991	Adoption of Assembly Resolution A.719(17) by IMO on Prevention of Air Pollution from Ships & appeal of the Resolution to the MEPC to prepare a new draft Annex to MARPOL to prevent air pollution.
1997	Kyoto Protocol operationalized the UNFCCC by committing industrialized countries and economies in transition to reduce GHGs emissions.
1997	IMO adopted MARPOL Annex VI on regulations for the prevention of air pollution from ships.
1997	Consideration of MEPC on CO_2 reduction strategies.
1997	IMO and UNFCCC undertook a study of CO_2 emissions from ships as part of the global inventory of CO_2 emissions.
2011	MARPOL Annex VI Parties adopted **mandatory** energy efficiency regulations for ships (EEDI for new ships and SEEMP for all ships).
2016	IMO's adoption of the **mandatory** IMO Data Collection System (DCS) for ships to collect and report fuel oil consumption data from ships over 5,000 gross tonnage (gt).
2018	IMO's adoption of the Initial Strategy on the reduction of GHG emissions (annual emissions) from international shipping by at least 50% by 2050, compared with their level in 2008 and reducing the carbon intensity of international shipping by at least 40% by 2030, and 70% by 2050, compared to 2008.
2021	IMO's adoption of the a)Energy Efficiency Existing Ship Index (EEXI) for all ships, b) the annual operational carbon intensity indicator (CII) for ships over 5,000 gt and c) CII rating, to cut the carbon intensity of all ships by at least 40% by 2030, in line with the IMO Initial Strategy.

Table 2.4 Regulations to reduce ship's emissions (IMO, 2021).

IMO is also connected with the 2030 Agenda for Sustainable Development, as eight of the Agenda's Sustainable Development Goals (SDGs) (4, 5, 6, 7, 9, 13, 14, and 17) (Fig. 2.6) are relevant to IMO's technical assistance work (TC.1/Circ.69, 2017). For example, IMO's Technical Assistance develops training programs on GHG emissions and SDG number 13 relates to action to combat climate change (TC.1/Circ.69, 2017).

Figure 2.6 Sustainable Development Goals (UN SDGs, 2019).

Environmental law is also very important regarding sustainable development and tackling climate change (Manner, 2021). The principles of **environmental law** are directly in the context of addressing the roles and responsibilities associated with reducing GHG emissions in shipping (Manner, 2021). European Union (EU) policy on the environment is based on the *precautionary principle* and the principles that *preventive* action should be taken, that environmental damage should first be *rectified at the source,* and that *the polluter should pay* (EU, 2016). In order to transform the EU into a capable society to tackle climate and environmental-related challenges, the European Green Deal (Fig. 2.7) comes to the fore by the European Commission (EC) (EC, 2019). According to the Green Deal, a 90% reduction in transport emissions is needed by 2050 and EC adopted a Sustainable and Smart Mobility Strategy in 2020 to tackle all emission sources (EC, 2019). In order to be in legislation the goal of climate neutrality by 2050 set out in the European Green Deal, the EC proposed the European Climate Law so it is irreversible (EC, 2019). Some of the mechanisms that are deployed to implement the GHG reductions objectives from ships are shown in Table 2.5 below.

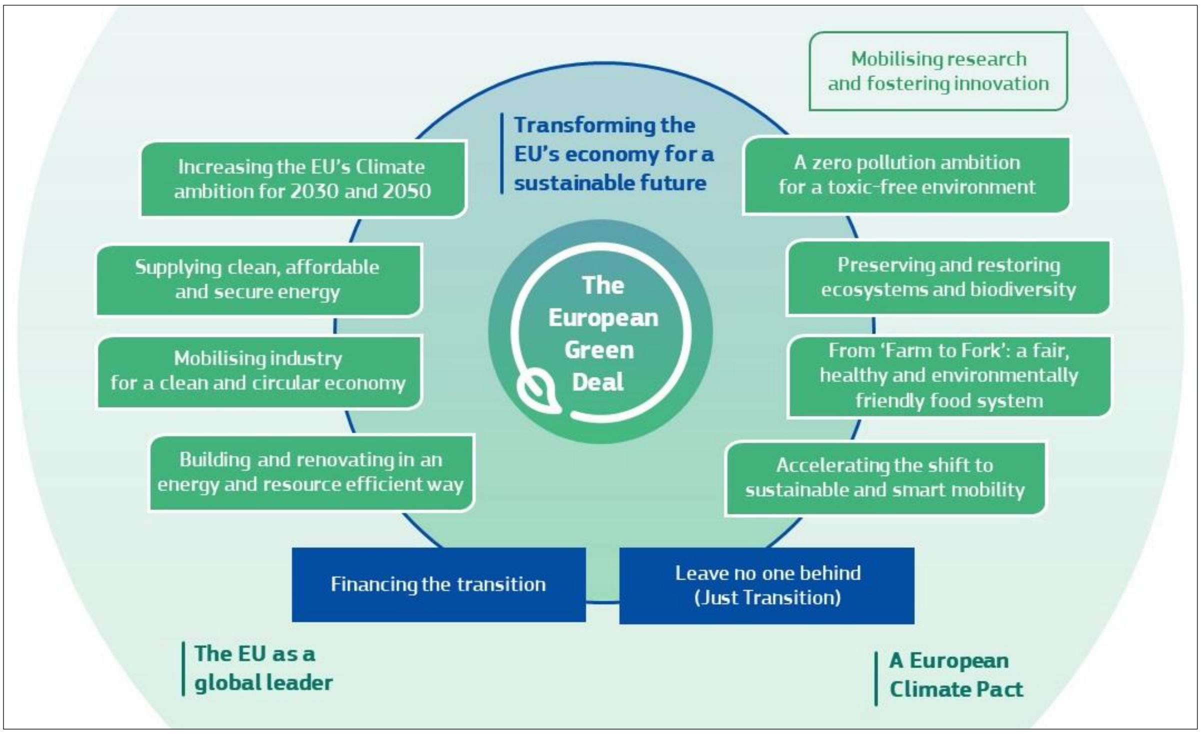


Figure 2.7 Elements of European Green Deal (EC, 2019).

MECHANISMS OF GHG EMISSIONS MITIGATION FROM SHIPS
The Fourth IMO GHG Study 2020
IMO Market-Based Measures (MBMs)
EU MRV Regulation (2015/757) for the monitoring, reporting, and verification of (CO_2) emissions
IMO Data Collection System (DCS) for fuel oil consumption of ships
EEDI (mandatory technical standards for new ships)
SEEMP (mandatory for all ships)
Energy Efficiency Operational Indicator (EEOI) (voluntary monitoring tool)
EEXI (similar requirements as EEDI to all existing ships)
EU Emission Trading System (ETS)
International Maritime Research and Development Board (IMRB) **(**aims at accelerating low-carbon and zero-carbon technologies and fuels)

Table 2.5 Mechanisms of GHG emissions mitigation from ships (Manner, 2021).

Should also be noted that all transport modes, including maritime transport, which has a critical role in the European economy, will have to contribute to the reduction efforts (EC, 2021b). In addition, both increased energy efficiency (less energy) and renewable and low-carbon fuels (cleaner types of energy) are required to be achieved a significant reduction in CO_2 emissions of international maritime transport (EC, 2021b). Hydrogen can be used as a fuel, does not emit CO_2 and almost no air pollution when used, and enjoys rapidly growing attention in Europe and around the world (EC, 2020). Furthermore, there is the European Clean Hydrogen Alliance that has a crucial role in implementing a hydrogen strategy for a climate-neutral Europe and will help to escalate investments in production and demand for renewable sources and low carbon hydrogen (EC, 2020).

Today, there are no regulatory requirements available for hydrogen as a marine fuel (IMO-Norway GreenVoyage2050 Project et al., 2021). In general, regulations, standards and guidance regarding hydrogen are shown in Table 2.6 below (IMO-Norway GreenVoyage2050 Project et al., 2021).

Regulations, standards and guidance		
Body/ Organisation	**Documentation**	**Status/Comment**
IMO	The International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code)	The current edition does not include hydrogen storage or hydrogen as fuel. So, the *alternative design approach* in accordance with *International Convention for the Safety of Life at Sea (SOLAS) Regulation II-1/55* must be followed for hydrogen storage and use. *The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) and IGF Code* cover the storage of liquefied gas on board ships, and the C-tank rules in principle cover liquid hydrogen (LH_2).
International Organization for Standardization (ISO)	ISO/TR 15916:2015 (Technical Report)	Guidelines for the use and storage of gaseous hydrogen (GH_2)/LH_2. Identifies basic safety concerns, hazards and risks, describes properties of hydrogen relevant to safety.
ISO	ISO 20519 - "Ships and marine technology - Specification for bunkering of gas fueled ships"	Under preparation for its final publication. There are presently no bunkering and port regulations in place for bunkering hydrogen fuel. Bunkering of hydrogen-powered ships is subject to national regulations and must thus be assessed on a case-by-case basis.
ISO	ISO 14687	Hydrogen purity regulation.
DNVGL Rules for Classification	Ships–Part 6 Chapter 2 Section 3–Fuel Cell Installations	Although there is no binding international regulatory framework for maritime fuel cell (FC) applications, this can be used to categorize ships equipped with FCs as FC(Power) or FC(Safety).

Table 2.6 Hydrogen regulations, standards and guidance (IMO-Norway GreenVoyage2050 Project et al., 2021).

Regulations, codes, and directives are legally binding requirements (mandatory) imposed by legislative bodies (DNV, 2021). Directives are implemented at EU level and are not utilized as a tool by the IMO (DNV, 2021). Standards, guidelines, and codes of practice, on the other hand, are optional documents (voluntary) unless required by the regulations (DNV, 2021). Maritime regulations and rules are divided into International regulations developed by IMO, National regulations, and Class rules (DNV, 2021).

More specifically, the United Nations agency called IMO is the global authority for setting standards for the safety, security, and environmental performance of international shipping (DNV, 2021). The whole shipping industry follows the regulatory framework that is created by the IMO which covers all aspects of international shipping (ship design, construction, equipment, manning, operation and disposal) (DNV, 2021).

SOLAS sets internationally adopted minimum requirements for the construction, equipment, and operation of ships and Flag States must ensure that these minimum requirements are met. (DNV, 2021). Several Codes become mandatory under SOLAS and usually include detailed technical requirements for specific vessel types (DNV, 2021).

Regarding hydrogen as a marine fuel, there are no specific prescriptive rules and regulations yet, but through SOLAS II-I opens the path for a structured design process (the “Alternative Design” approach) based on risk assessments {like Hazard Identification study (HAZID), Technology Qualification (TQ), Quantitative Risk Analysis (QRA), Explosion Risk Analysis (ERA)} in cases where a ship deviates from the prescribed rules (DNV, 2021).

The main idea behind this is that the chosen solution is providing an equivalent safety level to the one required in SOLAS (DNV, 2021).

The Marine Safety Committee (MSC), which is a sub-committee of the IMO, has a Sub-Committee on Carriage of Cargo and Containers (CCC) that is responsible for work on the IGF Code (DNV, 2021). The IGF Code provides the regulatory framework for adapting low-flashpoint marine fuels like hydrogen and the basis for accepting that an Alternative Design approach is used to verify compliance for ships using gas fuels other than LNG such as hydrogen (DNV, 2021). FCs are expected to be included in the IGF Code in the future in Chapter E as an Amendment of this code (around 2028) (DNV, 2021). In the meantime, FCs will be covered through interim guidelines because of that more experience with FCs is needed before regulations will be included in a revision of the IGF Code (DNV, 2021). Regarding the storage of hydrogen as fuel has not initiated in IMO (DNV, 2021).

The IGF Code is the main international code applicable to hydrogen fueled SOLAS vessels and is considered a mandatory regulation for all cargo ships with and over 500 of gt (DNV, 2021). It is also applicable on passenger vessels using low-flashpoint fuels (flashpoint below 60°C) (DNV, 2021). These ships must have international safety certificates (DNV, 2021). While the IGF Code does contain requirements for LNG as a fuel, all other fuels have to stick by the IGF's "Alternative Design" approach (DNV, 2021). At this point should be clarified that for gas carriers, the IGC Code Chapter 16 applies, not the IGF Code (DNV, 2021).

The "Alternative Design" approach means that although the IGF Code does not contain specific requirements for fuels other than LNG, the other fuels can indeed be used if proven that the safety levels of the ship using the other fuels are equal to a ship using conventional fuel (DNV, 2021). For this exact reason, the approval process has a high degree of variance (DNV, 2021).

Different Classification Societies have designed their own rules regarding FC installations, which do not cover the storage and distribution of low-flashpoint fuels but specify requirements for FC power installation (DNV, 2021). In order to ease the process of "Alternative Design," the Flag Administrations can choose to accept the Class rules if they are deemed that they cover all the safety aspects (DNV, 2021).

The IGF Code Part A states that a low-flashpoint fuel (like hydrogen) can be used as long as the systems that are specifically designed for the low-flashpoint fuel are in accordance with the Alternative Design approach, meaning that both the reliability and the safety levels for those systems are deemed safe compared with the systems used in conventional ships (DNV, 2021). The way that this risk equivalence shall be demonstrated, is specified by the SOLAS regulation II-1/55 and this needs to be approved by the Administration (DNV, 2021). SOLAS regulation II-1/55 refers to the process specified in MSC.1/Circ 1455 (MSC.1/Circ 1455, 2013; DNV, 2021). The IGF Code Part A contains in Paragraph 3.2 functional requirements for the use of low-flashpoint fuels (MSC 95/22/Add.1, 2015; DNV, 2021). It also contains in Paragraph 4.2 requirements about the risk assessments and in Paragraph 4.3 the explosion consequences to ensure that risks are eliminated/mitigated wherever possible (MSC 95/22/Add.1, 2015; DNV, 2021).

The approval process, as stated beforehand, is based mainly on risk and safety (DNV, 2021). Since new technologies are being used there are no set regulations in place (DNV, 2021). As such the design for a hydrogen fuelled ship for example, needs to be highly comprehensive and more often than not quite costly (DNV, 2021). Although the "Alternative Design" has been used in the past and is not specific for low-flashpoint fuels like hydrogen, it does offer solutions that are not covered by rules as it was developed for new technologies and as such offers more leeway (DNV, 2021). The approval process (Alternative Design approval process) is split into two phases, phase 1 (Fig. 2.8) being the preliminary design (Development of a preliminary design and Approval of preliminary design) while phase 2 (Fig. 2.9) is the development of the final design (Development of final design, Final design testing and analyses and Approval (DNV, 2021).

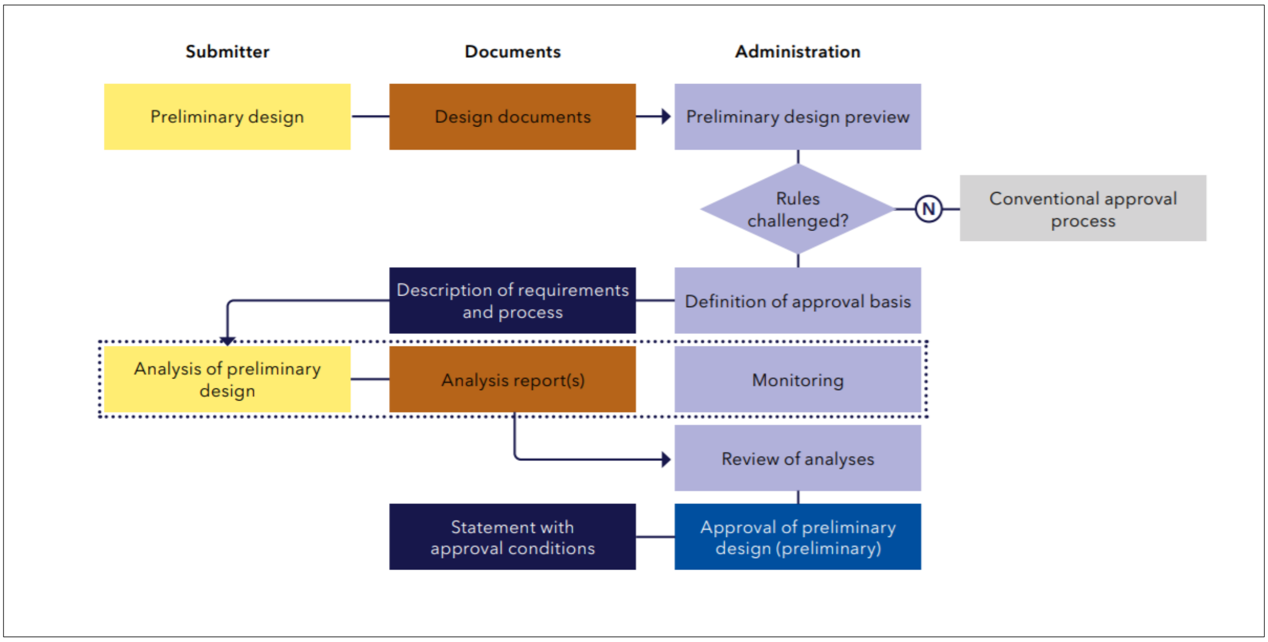


Figure 2.8 Approval process for the preliminary design according to the Alternative Design approach in MSC.1/Circ 1455, 2013 (DNV, 2021).

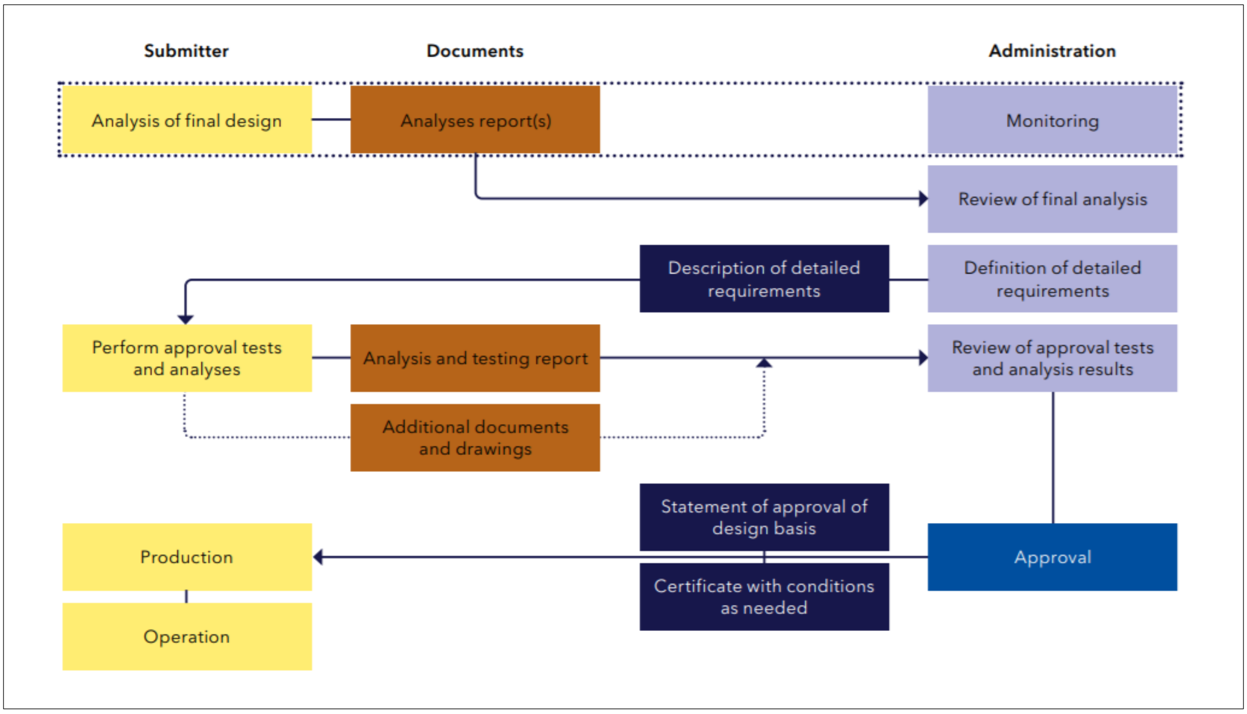


Figure 2.9 Approval process for the final design according to the Alternative Design approach in MSC.1/Circ 1455, 2013 (DNV, 2021).

The general purpose of the IGF Code Part A and the Alternative Design approach is for hydrogen systems to have the same level of safety, reliability, and dependability as new and comparable conventional oil-fueled main and auxiliary machinery (DNV, 2021). The equivalency of the Alternative Design must be shown as stipulated in SOLAS regulation II-1/55, and the process is defined in Circ.1455 (MSC.1/Circ 1455, 2013; DNV, 2021). Neither of these documents specifies which approach or what level of detail should be utilized in showing safety equivalency (DNV, 2021).

The equivalent solutions depend on existing arrangements that are fully covered by regulations and could be placed on board under consideration in accordance with the applicable regulations (DNV, 2021). These could be sometimes the redesign of preventive and mitigating measures based on a selected “worst case” that may not be risk-based (DNV, 2021). Regarding hydrogen, a small hydrogen leak can result in unacceptable scenarios and a worst-case leak size can result in a “showstopper” event for the hydrogen-fuelled ship. Therefore, through a risk-based approach could assess all possible leak sizes up to full-bore rupture of the hydrogen piping and equipment (DNV, 2021). The current hydrogen fuel systems are “new” and “unproven” for maritime applications and there is no adequate regulatory framework, so a Quantitative Risk Analysis (QRA) is needed (DNV, 2021).

For use in the IMO rule-making process, the IMO provides the Guidelines for Formal Safety Assessment (FSA) (MSC98/23/Add.2, 2018), a tool that frames the use of risk analysis and cost-benefit assessment techniques (DNV, 2021). MSC-MEPC.2/Circ.12/Rev.2 (MSC98/23/Add.2, 2018) is the most recent revision of the FSA guidelines. The FSA guidelines offer risk-evaluation criteria based on an individual risk and Societal Risk/FN Diagram, which is the standard foundation for the application of such criteria in the maritime industry (DNV, 2021).

The individual risk depends upon whether the risk is taken involuntarily or voluntarily, and whether or not the individual has control over the risk (DNV, 2021). An example could be that passengers are involuntarily exposed to risks while crew members can be aware and may have control over the same risks (DNV, 2021). Regarding the societal risk, the perception is that a single accident that kills 1000 people is worse than 1000 accidents that kill a single person (MSC98/23/Add.2, 2018) and it is expressed by an FN diagram that shows the relationship between the frequency of an accident and the number of fatalities (DNV, 2021). A QRA is required to determine the ship's societal risk (FN curve) (DNV, 2021).

An explosion risk analysis (ERA) is used to give input to the QRA to calculate the total risk/FN curve (DNV, 2021). This combined QRA and ERA approach (NORSOK QRA and ERA approach) has become standard for the North Sea oil and gas processing platforms and many regions around the world (internationally) use it as well (DNV, 2021). The ERA is a probabilistic approach for explosions because they can have unacceptable outcomes (DNV, 2021). It is used to order these occurrences by frequency and demonstrate that these unacceptable events will not occur with a frequency higher than the acceptance frequency (DNV, 2021). The results from the method set the Design Accidental Load (DAL) (DNV, 2021). Despite the fact that calculating a societal risk curve for the entire ship is a lengthy process, it is possible to run sensitivities and test different mitigating measures without having to calculate the FN curve each time, which is consistent with the Cost-Benefit principles outlined in the FSA approach (DNV, 2021).

Classification Societies' rules are often more thorough and explicit in order to represent the level of safety required by international regulations such as the SOLAS Convention (DNV, 2021). Existing class rules can therefore facilitate the Alternative Design process, provided the rules are recognized by the appropriate Administration (DNV, 2021). Some of the international hydrogen standards that are relevant for introducing hydrogen as ship fuel are shown in Table 2.7 below.

INTERNATIONAL HYDROGEN STANDARDS		
ORGANISATION	DOCUMENTATION	COMMENT
ISO		
	ISO/TC 197-Hydrogen technologies (Technical Committee)	Standardization of systems and devices for hydrogen generation, storage, transportation, measurement, and usage. These standards are not commonly utilized in the maritime industry.
	ISO 19885 series	Recently planned and launched project of a three-standards package under this series for GH_2 fuelling protocols for hydrogen-fuelled vehicles. The basic principles can be applied to the bunkering of maritime vessels, though a separate standard should be developed within this series specifically for maritime applications.
	ISO 19886	LH_2 fuelling protocols. This is a placeholder for future new work item proposals for LH_2 bunkering operations.
	ISO/TR 15916	Safety-relevant properties and related considerations for hydrogen.
	ISO/TC 220	A standard for cryogenic land-based insulated storage vessels (vacuum or non-vacuum) for storage and transport of refrigerated liquefied gases. It also addresses vessel design and safety, gas/material compatibility, insulation performance, and equipment operational requirements.
	ISO 19880-3:2018	GH_2 – Fuelling stations.
	ISO 26142:2010	Hydrogen detection apparatus – Stationary applications.
	ISO 15649:2001	Hydrogen piping network.
	ISO 19882:2018	GH_2 -Pressure-relief devices.

International Electrotechnical Commission (IEC)		
	IEC/TC 105 Fuel Cells	Hydrogen energy and FC technologies.
	IEC 60079-10-1:2015	It covers the classification of areas where flammable gas concentrations may cause an ignition hazard.
American Society of Mechanical Engineers (ASME)		
	ASME B31.12	Hydrogen piping, material compatibility
Compressed Gas Association (CGA)		
	CGA G-5-2017 Hydrogen	Information on the physical and chemical properties of hydrogen, and its proper handling and use.
	CGA G-5.4-2019 Standard for Hydrogen Piping Systems at User Locations	Principles recommended for compressed GH_2 and LH_2 piping systems.
	CGA G-5.5-2014 Hydrogen Vent Systems	It provides design guidelines for hydrogen vent systems for compressed GH_2 and LH_2 systems, and provides recommendations for safe operation of such vents.

Table 2.7 International hydrogen standards (DNV, 2021).

2.6. Hydrogen as a marine fuel

In order to examine hydrogen as a marine fuel, it is necessary to take into account a holistic approach, which includes all activities required to produce this specific fuel and how to use it (Fig. 2.10), the development stages of the particular technology (Fig. 2.11) and the fuel's lifecycle regarding the GHG emissions (Fig. 2.12).

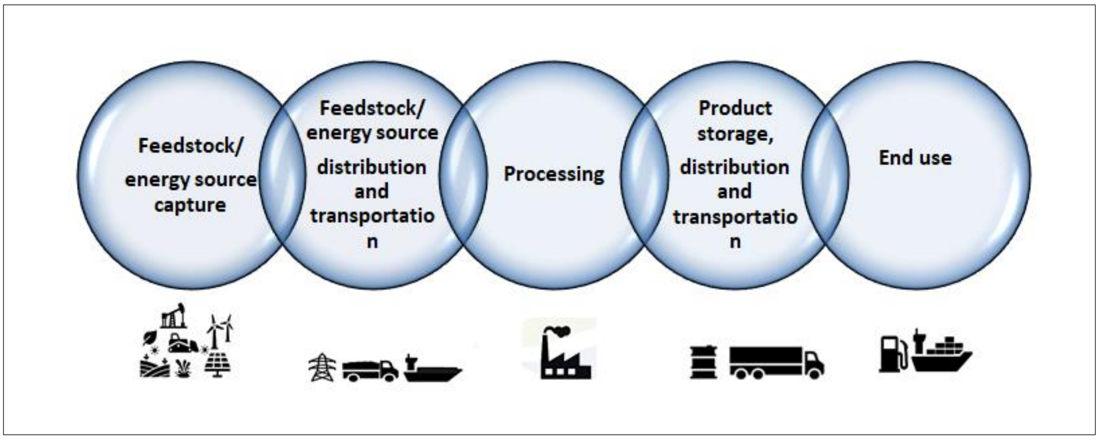


Figure 2.10 Fuel value chain (IMO-Norway GreenVoyage2050 Project et al., 2021).

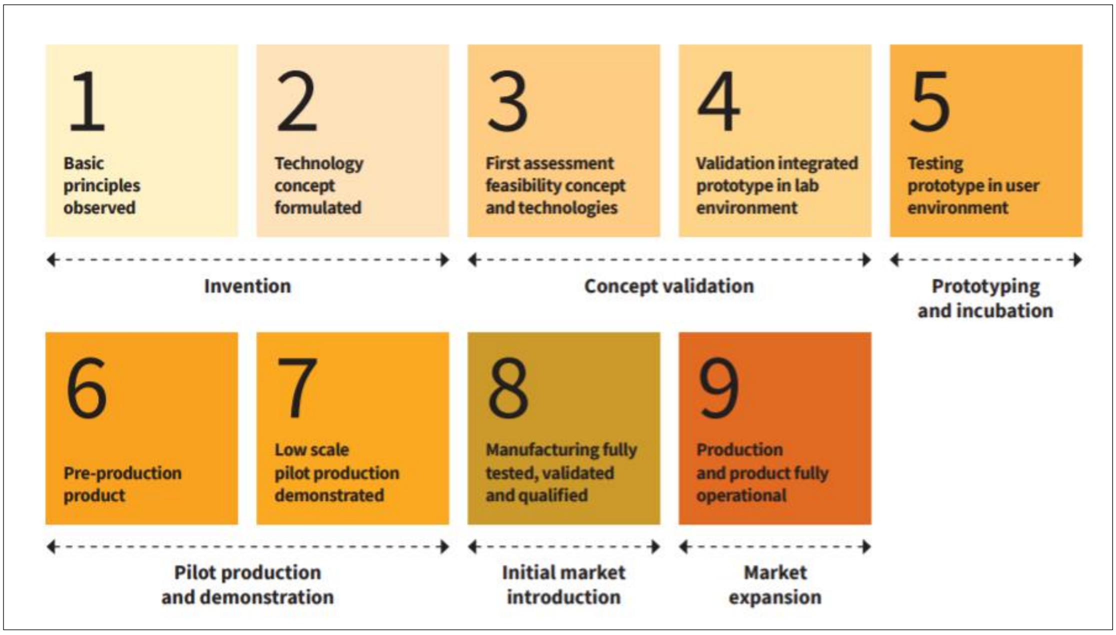


Figure 2.11 Technology readiness level (TRL) by EARTO (LR and UMAS, 2020).

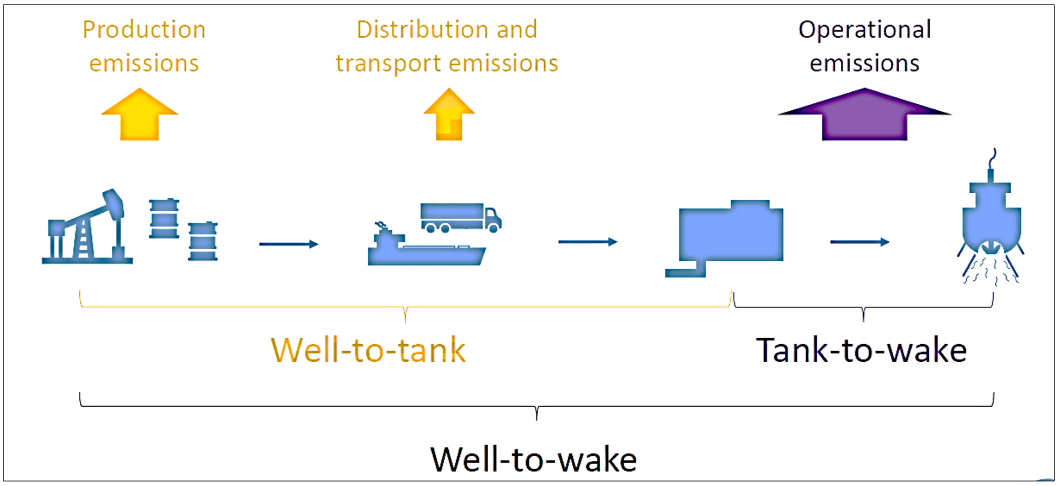


Figure 2.12 Fuel's lifecycle-GHG emissions (IMO-Norway GreenVoyage2050 Project et al., 2021).

In the universe, the most abundant chemical element is hydrogen (Sartbaeva et al., 2008). Nevertheless on Earth, hydrogen is produced from other hydrogen-containing sources using energy, as it is invariably bound up in chemical compounds with other elements (Edwards et al., 2007; Sartbaeva et al., 2008). Hydrogen can be produced from nuclear sources, carbon sources such as natural gas and coal, or renewable sources such as water, biomass, solar, and wind and it covers a whole economy (Fig. 2.13) (Qyyum et al., 2021).

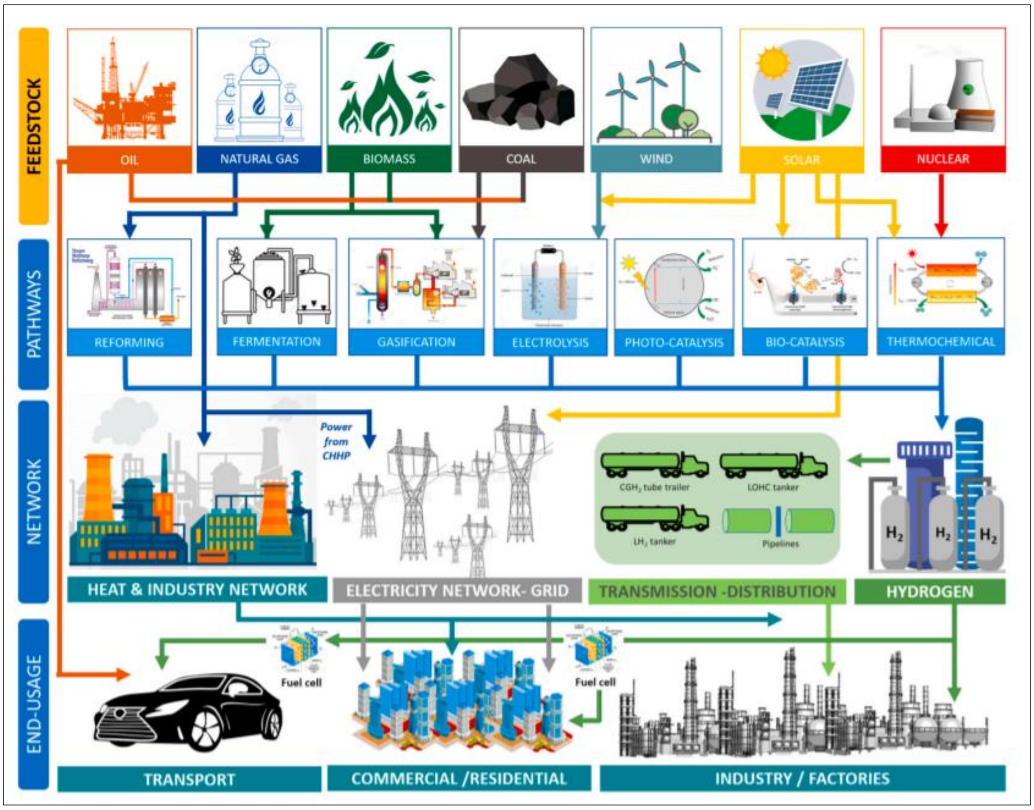


Figure 2.13 Hydrogen economy (Qyyum et al., 2021).

Some of the chemical, physical and thermal properties of hydrogen are provided in Table 2.8 below. In addition, the latest TRLs of hydrogen technology regarding the hydrogen-powered vessels are provided in figure 2.14 below.

Property and unit	Value
Molecular weight (kg/kmol) (H_2)	2.016
Specific volume (m^3/kg)	12.1
Density (kg/m^3)	0.0824
Viscosity (kg/ms)	$9 \cdot 10^{-6}$
Sound velocity in gas (m/s)	1315
Specific heat c_p (J/kgK)	14310
Specific heat ratio	1.405
Gas constant (J/kgK)	4126
Thermal conductivity (W/mK)	0182
Boiling point-saturation pressure 760 mm Hg (K, °C)	20.4, −252.6
Latent heat of evaporation at boiling point (J/kg)	447000
Freezing or melting point at 760 mm Hg	−259.1
Latent heat of fusion (J/kg)	58000
Critical temperature	−240.0
Critical pressure (MPa)	1.30
Heat of combustion (kJ/kg)	144000

Table 2.8 Hydrogen chemical, physical and thermal properties at 25°C (298 K) & atmospheric pressure (Sundén, 2019).

TRL	Bunkering			Storage onboard					Processing and conversion			Propulsion			
	Equipment	Procedures	Fuel quality standards	Structural tank	Membrane containment system	IMO type A tank	IMO type B tank	IMO type C tank	Venting system	Fuel supply system	Reformer	2-Stroke ICE	4-Stroke ICE	FC	Boiler
LSHFO ICE reference ship	9	9	9	9					9	9		9	9		9
Bio-diesel ICE	9	9	9	9					9	9		9	9		9
E-diesel ICE	9	9	9	9					9	9		9	9		9
Bio-methanol ICE	7	6	3	7					7	7		7	6		2
E-methanol ICE	7	6	3	7					7	7		7	6		2
Bio-methanol FC	7	6	3	7					7	7	3		6	7	2
E-methanol FC	7	6	3	7					7	7	3		6	7	2
Bio-LNG ICE	9	9	9		8		9	9	9	9		9	9		9
E-LNG ICE	9	9	9		8		9	9	9	9		9	9		9
Bio-LNG FC	9	9	9		8		9	9	9	9	4			7	
E-LNG FC	9	9	9		8		9	9	9	9	4			7	
E-ammonia ICE	7	2	2			7	7	7	3	7		3	2		2
NG-ammonia ICE	7	2	2			7	7	7	3	7		3	2		2
E-ammonia FC	7	2	2			7	7	7	3	7	2		2	7	2
NG-ammonia FC	7	2	2			7	7	7	3	7	2		2	7	2
E-hydrogen ICE	4	2	3				3	6	2	2		2	5		2
NG-hydrogen ICE	4	2	3				3	6	2	2		2	5		2
E-hydrogen FC	4	2	3				3	6	2	2			5	7	2
NG-hydrogen FC	4	2	3				3	6	2	2			5	7	2
Batteries	4	2	3				3	6	2	2			5	7	

** E-fuel (electro fuels) - Fuels produced from renewable electricity & NG - Natural gas.*

Figure 2.14 TRL ranking for Zero Emission Vessel technologies (LR and UMAS, 2020).

2.6.1. Hydrogen production methods

There are many methods for producing hydrogen, but not all of them are considered green (Van Hoecke et al., 2021). Some selected categories (color codes) according to the methods used to produce hydrogen are the following (Fig. 2.15):

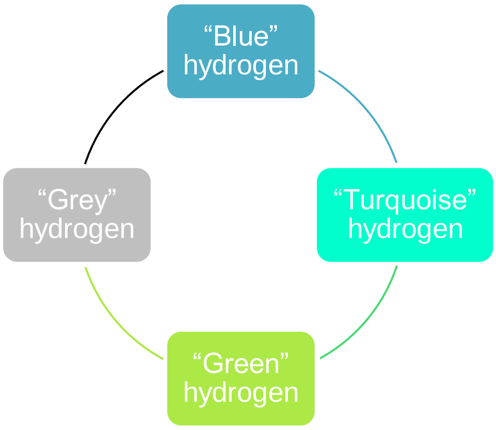


Figure 2.15 Hydrogen production methods color codes.

“**Green**” hydrogen is produced by electrolyzing water with electricity from non-carbon-emitting sources (e.g. wind or solar) (Goncalves et al., 2021). “**Blue**” hydrogen is produced from hydrocarbons, usually by steam reformation and any carbon from the process is possibly captured with the Carbon Capture and Storage (CCS) process (Goncalves et al., 2021). “**Grey**” hydrogen is produced as blue hydrogen without CCS, or green hydrogen with electricity from CO_2 emitting power stations without reducing GHG emissions (Goncalves et al., 2021). “**Turquoise**” hydrogen is a variant of blue hydrogen, but the hydrocarbon is separated into hydrogen gas and carbon black (solid carbon that can be used as a raw material) by pyrolysis without CO_2 that needs to be dealt with (Goncalves et al., 2021). The major hydrogen production methods are shown below.

✓ *Reforming*

Hydrogen (H_2) production arises from **Steam-Methane Reforming (SMR)**, in which the methane from a methane source such as natural gas reacts with steam with a catalyst to produce mostly hydrogen and CO (NCE MCT, 2019; Platzer and Sarigul-Klijn, 2021). Then in the "water-gas shift reaction" (WGSR): $CO + H_2O \rightarrow CO_2 + H_2$ (1), the CO and steam are reacted using a catalyst to produce CO_2 and more hydrogen (Fig. 2.16) (Nikolaidis and Poullikkas, 2017; NCE MCT, 2019; Platzer and Sarigul-Klijn, 2021). CO_2 is separated by "pressure-swing adsorption" (PSA) to produce pure hydrogen (Platzer and Sarigul-Klijn, 2021). The same outcome results using oxygen instead of steam, as an oxidant (**partial oxidation**), or using a combination of steam and oxygen {**autothermal reforming (ATR)**} (NCE MCT, 2019). On the other hand, one technology that can be used for carbon capture is absorption with solvents, like amine technology or the cold capture system Cryocap (NCE MCT, 2019).

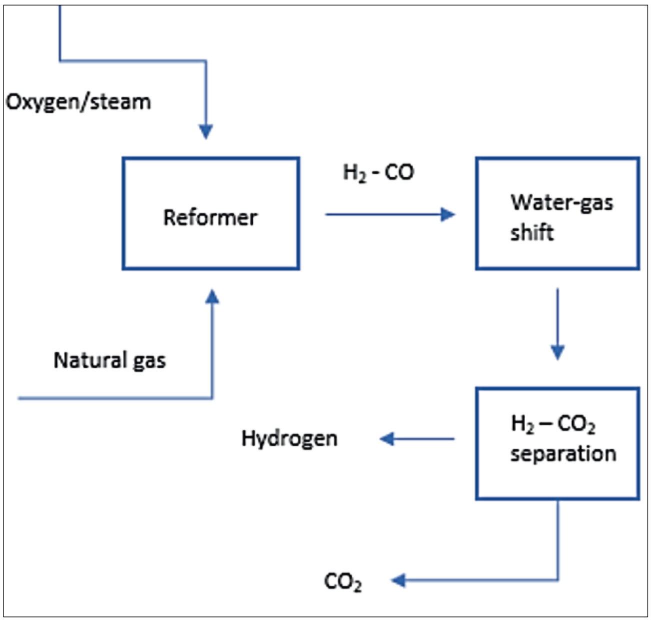


Figure 2.16 Reforming (NCE MCT, 2019).

- ✓ Pyrolysis

Pyrolysis is the process in which biomass or any carbonaceous feedstock is converted into gas, liquid, and solid fuels or chemical feedstock and it takes place in absence of oxygen (Parthasarathy and Narayanan, 2014). During hydrocarbon pyrolysis, hydrocarbon undergoes thermal decomposition through the general reaction: $C_nH_m \rightarrow nC + {}^1/_2\, mH_2$ (2), while the thermal decomposition from biomass pyrolysis, can be given by the following equation: biomass pyrolysis $\rightarrow H_2 + CO + CO_2 +$ HCgases + Tar + Char (3) (Parthasarathy and Narayanan, 2014; Nikolaidis and Poullikkas, 2017). Methane and other hydrocarbon gases produced by biomass pyrolysis can be steam reformed (Nikolaidis and Poullikkas, 2017). Moreover, regarding the carbon produced by hydrocarbon pyrolysis, there is carbon management, which could be used in metallurgy, in chemical industries, can be stored underwater or on land for future uses (Nikolaidis and Poullikkas, 2017).

- ✓ *Gasification*

In the gasification process, fuels (e.g. oil, coal, or biomass) are dried and heated in a gasification medium such as air, oxygen, and/or steam, and syngas is created (NCE MCT, 2019; Nikolaidis and Poullikkas, 2017).

- ✓ Biological processes

There are two basic biological processes for hydrogen production, which are the following:

- Bio-photolysis: is the process by which water molecules dissociate into hydrogen ion and oxygen with light energy by green algae (direct bio-photolysis) or blue-green algae namely cyanobacteria (indirect bio-photolysis) (Nikolaidis and Poullikkas, 2017).

- Fermentations: are processes by which microbial transformations of organic feed materials are carried out, producing alcohols, acetone, hydrogen, CO_2 by anaerobic bacteria under anoxic, dark conditions (dark fermentation) or using light energy and organic acids in deficient nitrogen conditions (photo-fermentation) (Nikolaidis and Poullikkas, 2017). Dark and photo-fermentation can also be used sequentially (Nikolaidis and Poullikkas, 2017).

- ✓ *Electrolysis*

Regarding electrolysis, water splitting is carried out by electricity to produce hydrogen and oxygen (O_2) (Fig. 2.17), and in the case that the source of electricity is renewable there are no CO_2 emissions (NCE MCT, 2019). The commonly used electrolysis technologies are alkaline, proton exchange membrane (PEM), and solid oxide electrolysis cells (SOEC) (Nikolaidis and Poullikkas, 2017). There is also, *photo-electrolysis*, which is a similar process of water splitting with electrolysis but it is using sunlight (Nikolaidis and Poullikkas, 2017).

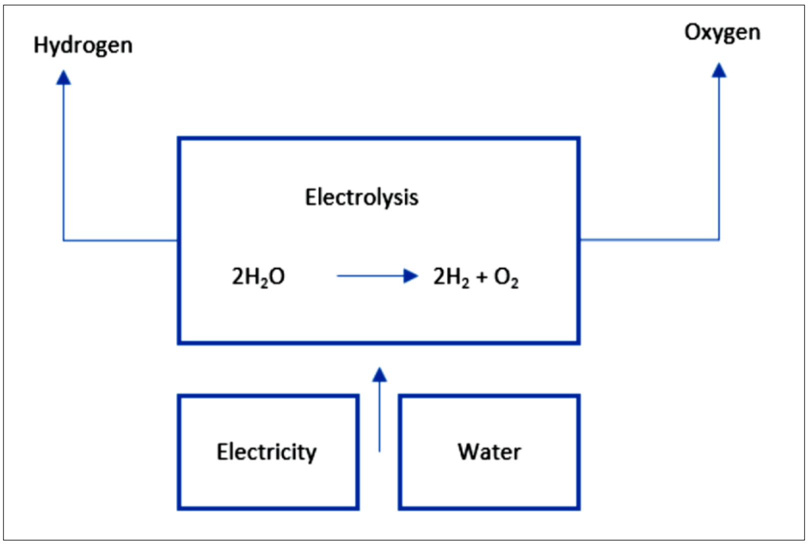


Figure 2.17 Electrolysis (NCE MCT, 2019).

- ✓ *Thermolysis*

Regarding thermolysis, water is heated to a high temperature until decomposed to hydrogen and oxygen (Nikolaidis and Poullikkas, 2017).

2.6.2. Hydrogen storage, transportation, utilization, and bunkering

- **Storage**

Hydrogen can be stored as a gas or liquid and on the surfaces by adsorption or within the solids by absorption (Nikolaidis and Poullikkas, 2017). Hydrogen can be **solid** at *−262°C* with a density of $70.6\ kg \cdot m^{-3}$, **gas** at ambient temperature (298.15 K) or at *0°C* and a pressure of *1 bar* with a density of $0.089886\ kg \cdot m^{-3}$, and **liquid** at *−253°C* with a density of $70.8\ kg \cdot m^{-3}$ (Züttel, 2004). However, it is worth noting that 1 kg of hydrogen gas occupies a volume of 11 m^3 at ambient temperature (298.15 K) and atmospheric pressure (Nikolaidis and Poullikkas, 2017). Due to the enormous hydrogen gas volume, a storage system aims to reduce the volume of the hydrogen gas and consequently increase the hydrogen density (Züttel, 2004). In order to be achieved the above, pressure should be increased (compressed hydrogen) or the temperature should be decreased below the critical temperature (see Chart 2.1), or the repulsion interaction between hydrogen molecules should be reduced by the interaction of hydrogen with another material (Züttel, 2004). Furthermore, the reversibility of the hydrogen uptake and release should be considered (Züttel, 2004). The liquid storage methods have the ability to store the most hydrogen (El-Gohary, 2013). The main hydrogen storage methods are shown below and their basic characteristics are listed in Table 2.9.

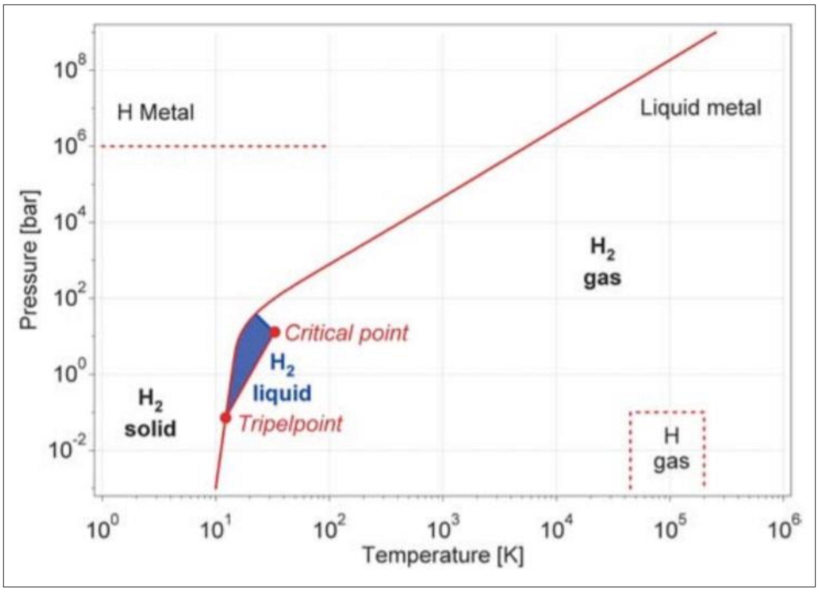


Chart 2.1 Phase diagram for hydrogen - Critical point at 33 K (Züttel, 2004).

Storage method	ρ_m (wt%)	ρ_v (kg/m^3)	T (°C)	P (MPa)
High pressure gaseous H_2	13	40	ambient	77
Cryogenic liquid	–	70.8	−252.87	atmospheric
Adsorbed on carbon nanotubes	10.8	41	−196.15	6
Absorbed to form hydrides	3	150	ambient	atmospheric
Absorbed to form complex hydrides	18	150	> 100	atmospheric

Table 2.9 The basic characteristics of hydrogen storage methods (Nikolaidis and Poullikkas, 2017).

➢ High-pressure gas cylinders

Hydrogen using standard piston-type mechanical compressors can be compressed and stored in cylinders with pressure up to 80 MPa, volumetric density of 36 kg/m^3 and low gravimetric density because it decreases with the high pressure due to the increasing thickness of the walls of the pressure cylinder (Züttel, 2004). The work consumption for compression is much higher than 2.21 kWh/kg because, in a real process, the compression is not isothermal (Züttel, 2004).

- Cryogenic liquid

LH_2 can be stored at 21.2 K and at ambient pressure in cryogenic tanks via a double-step procedure of compression and cooling in a heat exchanger (Nikolaidis and Poullikkas, 2017; Züttel, 2004). More specifically, the gas is compressed, and then cooled in a heat exchanger, subsequently, it passes through a throttle valve where it undergoes an isenthalpic Joule–Thomson expansion, and produces liquid (Linde cycle) (Züttel, 2004). The work consumption is 15.2 kWh/kg due to its low boiling point of -252.87 °C, the volumetric density at atmospheric pressure is 70.8 kg/m^3 and the gravimetric density depends on the tank size (Nikolaidis and Poullikkas, 2017).

- Solid-state storage with adsorption

The adsorption of a gas on a surface occurs due to the field force of the solid surface (adsorbent) that attracts the molecules of the gas or vapour (adsorbate) (Züttel, 2004). In this process, hydrogen (gas molecule) interacts with several atoms at carbon nanotubes (solid surface) where it is bonded and reversibly released when needed (Nikolaidis and Poullikkas, 2017). Generally, solid-state storage of hydrogen is more effective at moderate temperature and pressure (Nikolaidis and Poullikkas, 2017). Also, zeolite is another solid surface that enables the adsorption of gases and can be used for hydrogen storage (Nazir et al., 2020).

- Solid-state storage with absorption to form hydrides

Hydrides can be formed when hydrogen reacts with transitions metals and their alloys, as some metals and alloys absorb hydrogen and form hydrides (Nikolaidis and Poullikkas, 2017; Zhou, 2005). There are the metallic hydrides and the complex hydrides of which the complex hydrides are formed by the transition of metals to ionic or covalent compounds upon hydrogen absorption (Zhou, 2005).

- Chemical carriers

Chemical storage is using substances such as hydrogen carriers, such as ammonia (NH_3), hydrides, liquid organic hydrogen carriers (LOHC), carbohydrates, synthetic hydrocarbons (Sundén, 2019).

Transportation

Hydrogen transportation can be carried in gas, liquid, or metal hydrides form via road transport (using trucks hauling tube-trailers, tanker trucks, container trucks, railcar containers), pipelines for transporting and distributing GH_2, or ocean transport (using LH_2 tanker vessel or intercontinental transport of LH_2 can be performed using ships similar to the ones used for natural gas) (Nazir et al., 2020).

o **Utilization**

Hydrogen can be used in internal combustion engines (ICEs), FCs, turbines, cookers and gas boilers (Momirlan and Veziroglu, 2005). In the marine field, *hydrogen fuel is used in ICEs*, *gas turbines*, and *FCs* (Ammar and Alshammari, 2018). More specifically, hydrogen can be used as a marine fuel in **ICEs** in order to be used the existing diesel engines without manufacturing new systems but with only the appropriate modifications (Ammar and Alshammari, 2018).

Hydrogen gas can be used in the **turbine** and the design is based on the ordinary gas turbines that are designed based on the Brayton cycle (Ammar and Alshammari, 2018; El-Gohary, 2013). It is a good alternative for ordinary marine power plants as no special technologies are needed and it has good performance (El-Gohary, 2013). Finally, in general, the **FC** converts the chemical energy in the fuel (the basic fuel for FCs is hydrogen gas but it can be also compounds including hydrogen like hydrocarbons or alcohols) to electric energy reacting with the atmospheric oxygen, producing electricity, water and heat (El-Gohary, 2013).

In general, when hydrogen is burned in a combustion chamber with air, the result is water vapor and traces of nitric oxides, as nitrogen is contented in the air, but when the hydrogen consumed by either combustion or a FC has as a product only water (El Gohary and Seddiek, 2013).

One of the main problems of hydrogen in ICEs, like with natural gas, is the engine knocking, which is caused mainly due to the air fuel ratio and the intake temperature (Ammar and Alshammari, 2018). Hydrogen is also one of the most flammable and explosive fuels (Das, 2016). Hydrogen produces fewer emissions almost in all engine operating conditions, however, due to the higher combustion temperature in hydrogen engines, NO_x rates have been found high in some cases and many solutions have been produced, like exhaust gas recirculation and catalytic reduction filters (Ammar and Alshammari, 2018).

Regarding the hydrogen gas turbine, it has to be taken into account the adoption of the new type of fuel for waterborne vehicles and the difference between the properties of hydrogen and those of other types of fuels like the combustion characteristics (Ammar and Alshammari, 2018; El-Gohary, 2013). One solution could be the mixture of hydrogen with other types of fuels like natural gas (El-Gohary, 2013).

The advantage of FCs is their modularity and that they reduce CO_2 emission for a given power output and the transmission losses, resulting in higher efficiency (Ammar and Alshammari, 2018). FCs have high initial costs, however, costs are expected to decline as manufacturing capacity and capability increase and designs and integration improve (Ammar and Alshammari, 2018). FCs in the marine field provide the power for propulsion in small units or auxiliary power for large units, however, are not new to the marine sector as they are used for submarines for years (El-Gohary, 2013). There are five dominant types of FCs, which are: Proton Exchange Membrane Fuel Cell (PEMFC), Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC) (Table 2.10) (El-Gohary, 2013).

Fuel cell type	Electrolyte	Temperature range /°C	Output /kW	Efficiency /%	Applications
PEMFC	Solid organic polymer	50-100	<1-250	25-58	Backup power Small distributed generation Transportation
AFC	Aqueous solution of potassium hydroxide	90-100	10-100	60	Military Space
PAFC	Liquid phosphoric acid	150-200	50-1000	>40	Distributed generation
MCFC	Liquid solution of lithium, sodium and/or potassium carbonates	600-700	<1-1000	45-47	Large distributed generation
SOFC	Yttria stabilized zirconia	600-1000	<1-3000	35-43	Auxiliary power Large distributed generation

Table 2.10 The main characteristics of the different types of FCs (El-Gohary, 2013).

- Bunkering

In general, the bunkering method will be dependent on the method of fuel storage (GH_2 or LH_2) (IMO-Norway GreenVoyage2050 Project et al., 2021). More specifically, GH_2 will be transferred to ship by direct compression or via a pressure differential, LH_2 using cryogenic pumps drawing analogies with LNG or in general bunkering could also occur via the direct exchange of container racks (IMO-Norway GreenVoyage2050 Project et al., 2021).

2.6.3. Hydrogen safety

Hydrogen is no more or less dangerous than other flammable fuels such as gasoline and natural gas (El Gohary and Seddiek, 2013). An explosion cannot occur in a tank or any contained location with only hydrogen and an oxidizer, such as oxygen must be in a concentration of at least 10% pure oxygen or 41% air (El Gohary and Seddiek, 2013). Hydrogen can be explosive at concentrations of 18.3-59%, while gasoline can be explosive at concentrations of 13.3% (much lower) (El Gohary and Seddiek, 2013).

It is important the crew of a hydrogen fuelled ship to be trained on how to maintain a hydrogen system on board a ship and how to handle fire safety (IMO-Norway GreenVoyage2050 Project et al., 2021). It should also be considered the safety around the storage of a high-pressure flammable gas on vessels, as high-pressure tanks carry the risk of explosion (IMO-Norway GreenVoyage2050 Project et al., 2021).

Hydrogen has some safety-related properties such as its low density, low ignition energy, wide flammability range, and potential explosiveness (DNV, 2021). Hydrogen is highly buoyant and can be an advantage or a challenge (DNV, 2021). Due to its low density, outdoor hydrogen gas disperses rapidly (DNV, 2021). Buoyancy has a positive effect on lifting gas in the passive zone of hydrogen gas clouds (DNV, 2021). However, for high momentum jets with a release rate above a certain size, the gas is driven by its momentum rather than buoyancy as long as the gas velocity in the plume exceeds the ambient air velocity (DNV, 2021). At this stage, a large gas cloud can be created, similar to a natural gas leak (DNV, 2021).

A stoichiometric mixture is where there is exactly the amount of fuel to fully use up all the oxygen without leaving excess fuel, so that the maximum combustion energy can be released (DNV, 2021). A stoichiometric mixture of hydrogen in the air contains 29.5 volume percent (vol%) hydrogen, whereas natural gas has around 10 vol%, so, it is necessary to have a larger leak rate to get this richer hydrogen concentration, but for hydrogen, it comes naturally as an equal hole size gives about three times the volumetric flow of natural gas (DNV, 2021). Furthermore, due to the wide flammability range of hydrogen, it can create a much larger flammable cloud with less gas compared to methane (DNV, 2021). It is very important when selecting materials that will be in contact with hydrogen, to be compatible with it, so that the probability of ignition is lessened as well as the leaks and embrittlement of hydrogen (DNV, 2021).

2.6.4. Hydrogen fuel cost

Costs of the use of alternative fuel systems on board include Capital expenditures (CapEx) and operational expenditures (OpEx) (Deniz and Zincir, 2016). CapEx refers to the investment expenses of the alternative fuel systems, which include system components, engine retrofits, and engine room changes (Deniz and Zincir, 2016). The cost of engine conversion is determined by the type and dimensions of the ship (Deniz and Zincir, 2016). The operational costs include maintenance costs, consumable costs and fuel price (Deniz and Zincir, 2016).

The major cost of converting a vessel to a hydrogen-powered vessel is storage and availability (ABS, 2021). The cost and availability of hydrogen is now greater than those of natural gas, making it less appealing to the maritime sector (ABS, 2021). Vessels can use grey or brown hydrogen while it is available and then switch to blue or green hydrogen when those production paths become more ubiquitous and cost-effective (ABS, 2021). A reduction in production costs and an increase in availability of hydrogen has the potential to make hydrogen the preferred fuel alternative for maritime vessels (ABS, 2021). As more countries produce hydrogen from renewable sources, the cost of marine hydrogen will fall (ABS, 2021). Currently, hydrogen fuel is predicted to cost four to eight times the price of very low-sulfur fuel oil (VLSFO) (ABS, 2021). Because green hydrogen is reliant on the renewable energy business, as renewable energy gets more affordable, the green hydrogen industry is expected to follow suit (ABS, 2021).

Green or blue hydrogen has the ability to completely decarbonize shipping and meet the IMO's decarbonization targets by 2050 (ABS, 2021). However, electrolysis generating based on a growing renewable electrical grid is predicted to lower the prices of such carbon-free production methods (ABS, 2021). While the cost of fuel is projected to be roughly half of the total transition cost, the cost of storage and new fuel consumers should be considered when transitioning to hydrogen fuel (ABS, 2021). The owner may also need to consider the needed range of the fuel and related volume, which may affect the amount of cargo space offered in the vessel design for fuel storage (ABS, 2021).

An overview of hydrogen fuel cost is shown in Table 2.11 below.

Production route	Grey/Blue H_2	Green H_2	Bio H_2	
Key drivers (Expected trend: positive/negative/either)	• Natural gas price • CCS Capex and OPEX • Cost of carbon	• Green power cost • Electrolyser Capex, utilisation, efficiency	• Biomass feedstock cost and supply • Gasifier capex	
Current cost (per GJ fuel)	11 – 26 USD (unabated) 13 – 27 USD (+ CCS*)	16 – 33 USD	20 – 54 USD	2020 hydrogen market price vs HFO market price
Current cost vs. HFO market price (per GJ fuel)[1]	Additional 5 – 14 USD[1]	Additional 10 – 21 USD[1]	Additional 14 – 42 USD[1]	+5 to +42 USD
Potential for cost reduction vs current cost	High for CCS	High	High for gasification	

*high cost uncertainty associated with CCS technology

Source: E4tech analysis
[1]: Based on HFO market price of 250 – 500 USD/tonne.

Table 2.11 Hydrogen fuel cost overview (IMO-Norway GreenVoyage2050 Project et al., 2021)

3. Portfolio of hydrogen use as a marine fuel

Class U212A & U214 submarines

Figure 3.1 Class 212A submarine (Thyssenkrupp, n.d.).

Figure 3.2 Class 214 submarine (Thyssenkrupp, n.d.).

German types U212A (Fig. 3.1) and U214 (Fig. 3.2) submarines have a hybrid propulsion system with a hydrogen FC and a diesel engine (deliveries from 2003 onwards) (Tronstad et al., 2017; Weaver and Barrett, 2003). They have Air Independent Propulsion (AIP) with 9x 34 kW PEMFC (for the U212A submarine) and 2x 120 kW PEMFC (for the U214 submarine), metal hydride hydrogen storage and liquid oxygen storage (Jong and Corrignan, 2009). The type of these projects is commercial (Vogler and Sattler, 2016). The U212A submarine can accommodate a crew of 27 (McConnell, 2010).

Hydra

Figure 3.3 Hydra water taxi (Sturm, 2016).

Around 2000 appeared in Germany the world's first civilian, electric hydrogen FC boat called Hydra (Fig. 3.3), which is a water taxi for 22 passengers and certified by Germanischer Lloyd (Sturm, 2016; Korkmaz and Cerit, 2016). Hydra's propulsion system is powered by an electric motor, which gets electricity from a 5 kW AFC system (Korkmaz and Cerit, 2016; Vogler and Sattler, 2016). Hydrogen was generated via cleaving water by electricity (Power to Gas technology) and stored on board in a metal hydride energy storage device (Sturm, 2016). This project is a prototype project (Vogler and Sattler, 2016).

Hydrogenesis

Figure 3.4 Hydrogenesis ferry (Bristol Hydrogen Boats, n.d.).

Hydrogenesis (Fig. 3.4) is a prototype project (in 2012) and the UK's first hydrogen-powered ferry with two permanent magnet DC motors powered by a 12 kW PEMFC system (Korkmaz and Cerit, 2016; Vogler and Sattler, 2016; Fuel Cells Bulletin, 2013). This ferry is for 12 passengers and 2 crews (Korkmaz and Cerit, 2016). Hydrogenesis belongs to the Green Capital project that was initiated in 2010 by Bristol City Council, which provided initial funding of US$ 343000 as part of its Bristol Green Capital initiatives (Fuel Cells Bulletin, 2013; Korkmaz and Cerit, 2016). Hydrogen on board is stored in a tank at up to 350 bar (Fuel Cells Bulletin, 2013).

Ross Barlow

Figure 3.5 Ross Barlow canal boat (Book, 2013).

Ross Barlow (Fig. 3.5) is a hydrogen-powered canal boat with $TiMn_2$-based metal hydride store (solid-state hydrogen store), 1 kW PEMFC, lead-acid battery pack and high efficiency, permanent magnet (NdFeB) electric motor (Korkmaz and Cerit, 2016; Bevan et al., 2011). This canal boat is a prototype project, belongs to the Protium project and was converted from British Waterways maintenance craft and used on the UK canal network (Korkmaz and Cerit, 2016; Vogler and Sattler, 2016). High power demand is provided by batteries (Korkmaz and Cerit, 2016). Ross Barlow canal boat launched in 2007 and 2010 embarked on a journey across England from Birmingham to Chester (University of Birmingham, 2007; Bevan et al., 2011).

FCS Alsterwasser

Figure 3.6 FCS Alsterwasser inland passenger vessel (Dirk, 2013).

FCS Alsterwasser (Fig. 3.6) was created via the Zemships project and it is the world's first inland passenger vessel (for 100 passengers) with a hydrogen FC (2x 48 kW PEMFC) propulsion system on board in line operation and operated by the ATG (Korkmaz and Cerit, 2016; Dirk, 2013; Chakraborty et al., 2013). It is worth mentioning that the FCS Alsterwasser vessel had a fire accident in 2010 (Korkmaz and Cerit, 2016). Through the Zemships project, the necessary hydrogen infrastructure was also developed (Korkmaz and Cerit, 2016). The storage of hydrogen on board is gaseous (GH_2) at 350 bar/15°C, and buffer battery is also included in the propulsion system, which consists of a propulsion motor of 100 kW and a bow thruster of 20 kW (Dirk, 2013; Chakraborty et al., 2013). This vessel is a commercial project from Germany (Vogler and Sattler, 2016). The Zemships project started in 2006 and the construction phase of the ship took place in 2008, and the same year, the first commercially used FC passenger ship was put into service (Dirk, 2013; EC-LIFE, 2021). The total budget of the project was 5,158,348 € with an EU contribution of 2,384,424 € (EC-LIFE, 2021).

Duffy-Herreshoff DH30

Figure 3.7 Duffy-Herreshoff DH30 water taxi (Hydrogen House Project, n.d.).

This water taxi (Fig. 3.7) is a prototype project (in 2003) and powered by FC (4x 1.5 kW PEMFC) /battery electric hybrid engine and it is the world's first FC powered public water taxi with hydrogen fuel and zero emissions on the San Francisco Bay (Korkmaz and Cerit, 2016; Vogler and Sattler, 2016; Millennium Cell, 2003). The boat is funded by California's Center for the Commercial Deployment of Transportation Technologies (CCDoTT) (Korkmaz and Cerit, 2016). This water taxi is for 18 passengers and is fitted with the Millennium Cell Hydrogen on Demand™ hydrogen storage, which generates hydrogen from Sodium Borohydride ($NaBH_4$) (Millennium Cell, 2003).

Xperiance NX Hydrogen

Figure 3.8 Xperiance NX Hydrogen leisure boat (Korkmaz and Cerit, 2016).

The Xperiance NX hydrogen (Fig. 3.8) is a hydrogen leisure boat for 12 passengers, power-assisted by an electric motor, which gets its electricity from a 1.2 kW PEMFC and it is a prototype project of 2006 from the Netherlands (Korkmaz and Cerit, 2016; Vogler and Sattler, 2016). Its propulsion system has also a battery and its hydrogen storage system has 4 exchangeable 200 bar tanks (Korkmaz and Cerit, 2016). The Xperiance NX Hydrogen boat participated in the race for solar boats called Frisian Nuon Solar Challenge (Fuel Cells Bulletin, 2006).

Tuckerboot (H_2Yacht)

The Tuckerboot (H_2Yacht) from Germany is an 8-passenger ship power-assisted by an electric motor that gets its electricity from a FC and its design is based on the AMS Tuckerboot 675 (Korkmaz and Cerit, 2016). This sport boat has 2x 1.2 kW PEMFC, battery and the hydrogen is stored on board in metal hydride containers (Nonstop, 2008; Zerta et al., 2019). It is a prototype project of 2005 (Zerta et al., 2019).

Nemo H_2

Figure 3.9 Nemo H_2 canal boat (Tronstad et al., 2017).

The Nemo H_2 canal boat (Fig. 3.9) in the Netherlands (in 2009) is a prototype project which is owned by Boat Company Lovers and it is the first boat powered by FC (2x 30 kW PEMFC) for 86 passengers and 2 crew (Korkmaz and Cerit, 2016; Vogler and Sattler, 2016). It has also 70 kWh battery, electrically powered stern and bow thruster, and hydrogen is stored in 6 cylinders at 350 bar (Korkmaz and Cerit, 2016). The total project cost was 3 million € (approximately 1.8 million € for the boat and 1.2 million € for the station) (Chakraborty et al., 2013).

Gold Green Hygen

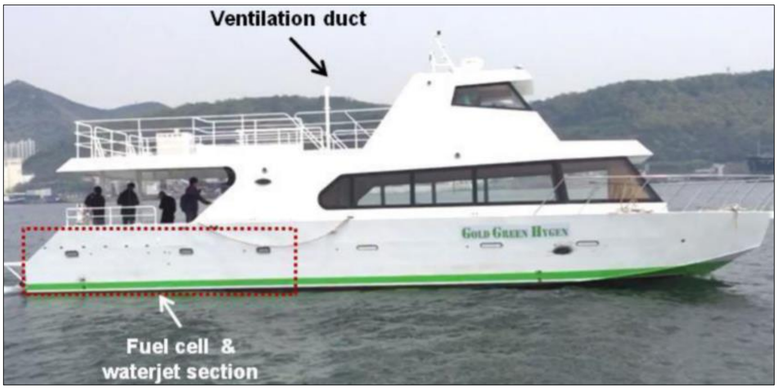


Figure 3.10 Gold Green Hygen tourist boat (Choi et al., 2016).

The Gold Green Hygen is a tourist boat (Fig. 3.10) and the first FC powered boat in Korea which is operated in the coastal waters of Busan and which is powered by a 50 kW PEMFC system (25 kW per module) and 47 kW Li-ion batteries hybrid system (Korkmaz and Cerit, 2016; Choi et al., 2016). The propulsion of the boat is provided by a waterjet and the hydrogen is stored in cylinders at 35 Mpa. (Korkmaz and Cerit, 2016). Its passenger capacity consists of 50 people (Campillo et al., 2019).

HYBRIDship project

Figure 3.11 HYBRIDship project (Fuel Cells Bulletin, 2017).

Fiskerstrand, a Norwegian shipbuilder awarded R&D funding to develop and design a hydrogen FC-powered hybrid ferry, through the PILOT-E scheme (Fuel Cells Bulletin, 2017). This project, as one of the PILOT-E projects, is sharing US$ 8.3 million in funding support (Fuel Cells Bulletin, 2017). The project is called the HYBRIDship project (Fig. 3.11) and it was started in 2016 by Fiskerstrand Holding AS aiming to convert an existing diesel-powered ferry to hydrogen with FCs and batteries (Ventura et al., 2020). It is a pilot project and was scheduled to enter service by 2020 (Fuel Cells Bulletin, 2017; Zerta et al., 2019). The first phase of the HYBRIDship project started in January 2017, identifying the technical and regulatory requirements, testing the FCs under maritime conditions, the operation with hydrogen, and finding a suitable vessel for the pilot project and the second phase focused on rebuilding the chosen ferry, then testing, piloting and operating it (Fuel Cells Bulletin, 2017). The most acceptable methods to produce hydrogen for this project are water electrolysis or using membrane technology to extract hydrogen from syngas (Fuel Cells Bulletin, 2017).

FreeCO2ast project

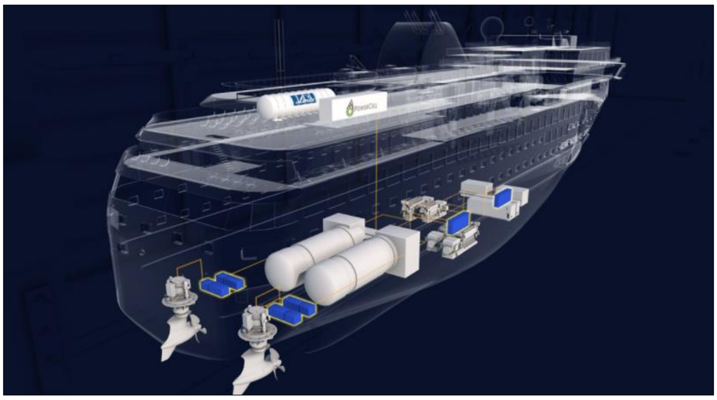


Figure 3.12 FreeCO2ast project (Havyard, 2019).

The FreeCO2ast project (Fig. 3.12) by Havyard Group that has awarded funding under the PILOT-E scheme (US$ 12.3 million) concerns the development of a zero-emissions ROPAX (roll-on/roll-off freight and passenger) vessel (Fuel Cells Bulletin, 2019b). The vessel will be powered by a combination of batteries and hydrogen FCs with liquefied cryogenic hydrogen storage method and 3200 kW FC power (Baumann et al., 2021; Fuel Cells Bulletin, 2019b). The storage location will be on weather deck (Baumann et al., 2021). It will be in operation by the end of 2022 in Norway (Fuel Cells Bulletin, 2019b). According to Kristian Steinsvik (R&D Manager at Havyard Group), the project will develop a hydrogen energy system using it onboard to one of Havila Kystruten's coastal route vessels (for retrofitting) (Fuel Cells Bulletin, 2019b; Havyard, 2019). It is a demonstration in normal operations type of project with large ship size (Fahnestock and Bingham, 2021).

FLAGSHIPS project

Figure 3.13 Inland cargo vessel (Zulu) in France (FLAGSHIPS, 2021).

Figure 3.14 Passenger and car ferry (Hidle) in Norway (Enova, 2021).

Figure 3.15 FPS Waal container transport vessel (FLAGSHIPS, n.d.b).

The FLAGSHIPS project concerns the construction of two commercially operated zero-emission (a total of 1 MW) hydrogen FC vessels in France (push-boat) and Norway (passenger and car ferry) (FLAGSHIPS, 2020). Hydrogen will be produced from renewable energy on-site with electrolyzers and GH_2 will be stored on board (FLAGSHIPS, 2020). Regarding the project's initial plan of a push-boat in Lyon (in France), it changed to an inland cargo vessel (Zulu) (Fig. 3.13) along the River Seine due to the potential for hydrogen in cargo transport (FLAGSHIPS, 2021; Baumann et al., 2021). Both vessels were planned to run on hydrogen during 2021 and it is expected to be maintained in normal commercial operation after the 18-month demonstration period (FLAGSHIPS, 2020). The funding in 2018 from the EU's Research and Innovation programme Horizon 2020, under the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), for the FLAGSHIPS project was 5 million € (FLAGSHIPS, 2021). The total budget of the FLAGSHIPS project is 7 million € (FLAGSHIPS, n.d.a).

The passenger and car ferry (Hidle) (Fig. 3.14) in Norway (retrofitted vessel) will be operated by Norled and it will have 3x 200 kW PEMFC, battery capacity of 0-500 kWh (need for batteries is under consideration), biodiesel generator back-up power, 199 passengers with the crew, 60 cars or 6 trucks (FLAGSHIPS, 2019; Baumann et al., 2021). Hidle ferry will use compressed GH_2 storage at 250 bar and the bunkering will take place every night from shore to ship (daily operation of 19 hours) (Baumann et al., 2021). Zulu vessel will use GH_2 storage at 300 bar, FC power of 400 kW and the bunkering will take place once a week (daily operation of 8-10 hours) (Baumann et al., 2021).

It was announced through the Norled AS official LinkedIn page that the passenger and car ferry Hidle welcomed its first passengers on board at Finnøysambandet in December 2021. In addition, in December 2021 the FLAGSHIPS H2020 Project announced through its official LinkedIn page that the hydrogen cargo vessel Zulu began sea trials on the Danube River and is expected to be traversing the River Seine in Paris with a complete hydrogen system installed by the summer of 2022.

Recently was also scheduled via the FLAGSHIPS project to be retrofitted and in operation, by summer 2023 the FPS Waal container cargo vessel (Fig.

3.15), owned and operated by Future Proof Shipping in the Netherlands that will sail on the river Rhine between Rotterdam (NL) and Duisburg (DE) (FLAGSHIPS, n.d.b). This vessel with the former name Fenny 1 was built in 1993 and after the retrofitting its propulsion system will include FCs (PEMFC), battery packs, an electric motor and hydrogen storage (FLAGSHIPS, n.d.b).

Aero 42 H_2

Figure 3.16 Aero 42 H_2 fast ferry (Strømgren et al., 2017).

The Brødrene Aa shipyard in Western Norway has developed the Aero 42 H_2 vessel type (Fig. 3.16) which is a battery (672 kWh) and hydrogen FC (2800 kW) powered fast ferry (high-speed craft-HSC) (Torvanger, 2021; (Munkvold, 2020). This vessel is equipped for 277 passengers (Strømgren et al., 2017). Storage tanks are for pressurized hydrogen at 250 bar (Munkvold, 2020). The Aero 42 H_2 has a price of MNOK 169 and will be able to be delivered by 2023 (Strømgren et al., 2017).

ULSTEIN SX190 Zero Emission DP2

Figure 3.17 ULSTEIN SX190 Zero Emission DP2 vessel (ULSTEIN, 2021).

The ULSTEIN SX190 Zero Emission DP2 vessel (from the Netherlands) (Fig. 3.17) is Ulstein's first hydrogen-powered offshore construction vessel with a Nedstack 2 MW FC (PEMFC) power system (ULSTEIN, 2021). The FCs are fuelled by hydrogen that is stored in containerized pressure vessels on deck at 500 bar that can be loaded and unloaded by container handling operations and equipment, eliminating the need for bunkering infrastructure (ULSTEIN, 2021; Baumann et al., 2021). The design of the ship is based on its existing SX190 vessel platform with a total installed power of 7.5 MW, 2x 1280 kW propulsion thrusters and 2x 750 kW tunnel thrusters (Fuel Cells Bulletin, 2019a). For extended missions, the vessel can use its conventional diesel-electric system using low-sulfur marine diesel oil (Fuel Cells Bulletin, 2019a). Sea trials of a new build ship could begin in 2022 (Fuel Cells Bulletin, 2019a). it is a demonstration in normal operations type of project and the ship size is small (Fahnestock and Bingham, 2021).

HySHIP project

Figure 3.18 HySHIP project (Wilhelmsen, 2020a).

The HySHIP project (Fig. 3.18) includes the design and construction of a new liquid green hydrogen (LH_2) powered ro-ro demonstration vessel, and the establishment of a LH_2 supply chain and bunkering platform (Wilhelmsen, 2020a). The vessel will be a “two-in-one” solution namely that it will be carrying both coastwise customer cargo and containerized LH_2 to the bunkering hubs (Wilhelmsen, 2020a). Norwegian maritime industry group Wilhelmsen will operate the ship along the Norwegian coast and it is expected to be operational from 2024 (Wilhelmsen, 2020a). The vessel will be going under the concept name Topeka and it will have a 1 MWh battery capacity and 3 MW hydrogen FC (PEMFC) (Wilhelmsen, 2020a). The project is granted 8 million € in European funding and its total budget is about 10 796 560 € (Wilhelmsen, 2020a; CORDIS | EC, 2020). The type of the project is “demonstration in normal operations” (Fahnestock and Bingham, 2021). Finally, the vessel’s vehicles capacity is 56 semi-trailers or 180 cars and the hydrogen is stored in storage tanks (65-100 m^3) (Baumann et al., 2021). Wilhelmsen’s Topeka hydrogen project focuses on the building of two ro-ro vessels and was awarded NOK 219 million (MUSD 25) by the Norwegian government-owned organization Enova (Wilhelmsen, 2020b).

Hydrogen Hybrid Harbour Tug project (Green Tug)

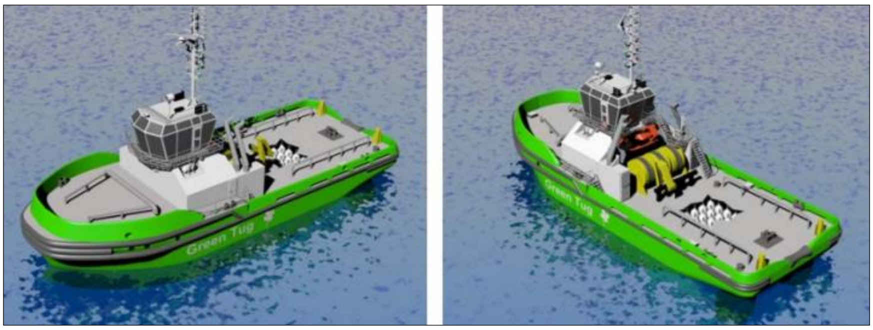


Figure 3.19 Hydrogen Hybrid Harbour Tug project (HHHT) (Green Tug) (Jong and Corrignan, 2009).

The Dutch Green Design project called Hydrogen Hybrid Harbour Tug (HHHT) (Fig. 3.19) applies a hybrid propulsion system involving both diesel generators and hydrogen-fuelled FCs (Jong and Corrignan, 2009). It has 2x 100 kW PEMFC with hydrogen stored at 430 bar (Díaz-de-Baldasano et al., 2014). It will run on FCs for standby and mobilization power levels and diesel engines for the pulling/pushing operations in the Netherlands (El-Gohary, 2013).

H2SHIPS project

Figure 3.20 MS Havenbeheer vessel (Lensing, 2020).

Figure 3.21 The new vessel Neo Orbis (Port of Amsterdam, 2021).

The project H2SHIPS (2019-2022) includes two pilot projects and an action plan (Interreg North-West Europe H2SHIPS, 2021). More specifically, the project includes a new hydrogen-powered port vessel in Amsterdam, a H_2 refueling system suitable for open sea operation in Belgium and an action plan for the implementation of a H2SHIPS pilot on the river Seine in Paris in 2022 (Interreg North-West Europe H2SHIPS, 2021). The new built vessel in Amsterdam will be a slightly enlarged version of the current vessel of the Port of Amsterdam, the MS Havenbeheer (Fig. 3.20) (Lensing, 2020). The new vessel will operate with FC and battery, $NaBH_4$ will be used as a hydrogen carrier for hydrogen storage and its passenger capacity is 25 (Baumann et al., 2021). The type of the project is “demonstration in normal operations” (Fahnestock and Bingham, 2021). The project has a total budget of 6.33 million € (Interreg North-West Europe H2SHIPS, 2021). The new vessel will be called the Neo Orbis (Fig. 3.21) (meaning the New World from the Greek “Neo” and the Latin “Orbis”) (Port of Amsterdam, 2021).

Hydroville project

Figure 3.22 Hydroville catamaran (Saverys, 2020).

Hydroville (Fig. 3.22) is a crewboat catamaran with gas-fuelled engines (hydrogen gas) (De Witte, 2018). Hydroville's propulsion system consists of two dual-fuelled (hydrogen and diesel) ICEs with a total shaft power of 441 kW and service pressure in hydrogen tanks-cylinders is 200 bar (De Witte, 2018). It launched in November 2017 and was the first certified passenger shuttle with hydrogen in diesel engine (Saverys, 2020). Belgium is the route area of the project (Baumann et al., 2021).

Hydrotug

Figure 3.23 Hydrotug (Saverys, 2020).

Hydrotug (Fig. 3.23) is a 65 ton bollard pull-tractor tug with two dual-fuel (hydrogen and diesel) engines (2x V12-2000 kW) (BEHYDRO dual-fuel engine) for the port of Antwerp (Belgium) (BeHydro, n.d.; Saverys, 2020). Hydrotug will be the first tug in the world powered with hydrogen-diesel ICEs (Baumann et al., 2021; Fahnestock and Bingham, 2021). It is a “demonstration in normal operations” type of project and the size of the ship is small (Fahnestock and Bingham, 2021). Finally, the hydrogen storage pressure is at 250 bar (Baumann et al., 2021).

HydroCat

Figure 3.24 HydroCat (Saverys, 2020).

HydroCat (Fig. 3.24) (from Belgium) based on Hydroville technology, is developed in a joint venture with Windcat Workboats and CMB to be operated at an offshore wind park in the North Sea and its design is based on the WindCat MK3.5 (Campe, 2019; Saverys, 2020; Baumann et al., 2021). It has a dual-fuel engine power of 1498 kW (dual fuel hydrogen–diesel ICEs) (Campe, 2019; Fahnestock and Bingham, 2021; Baumann et al., 2021). It is a Crew Transfer Vessel (CTV) with 24 passengers (Saverys, 2020; Baumann et al., 2021). The vessel stores pressurized hydrogen at 350 bar (Fahnestock and Bingham, 2021). It is a “demonstration in normal operations” type of project with £100k support from the Carbon Trust in the framework of the Low Emissions Vessels competition (Fahnestock and Bingham, 2021).

HydroBingo

Figure 3.25 HydroBingo (Saverys, 2020).

HydroBingo (in Japan, in 2021) (Fig. 3.25) is a shuttle for 80 passengers and is powered with 2x 400kW hydrogen-diesel ICEs (Saverys, 2020). The hydrogen is stored inside a mobile trailer (Fahnestock and Bingham, 2021) The type of the project is “demonstration in normal operations” (Fahnestock and Bingham, 2021).

MF Vågen

Figure 3.26 MF Vågen (Svendsen and Opdahl, 2017).

The MF Vågen (Fig. 3.26) is a small passenger ship (commuter ferry) in Norway (in 2010) that has a 12,5 kW HT-PEMFC system (type of PEMFC that can operate at temperatures up to 200°C) and it is a prototype project (Zerta et al., 2019; Tronstad et al., 2017). It uses metal hydride as the source of hydrogen (Tronstad et al., 2017).

Elektra

Figure 3.27 Elektra push boat (E4ships, n.d.).

Elektra (Fig. 3.27) (in Germany) is the world's first zero-emissions push boat and its propulsion power will be powered by 3x 100 kW FC modules (PEMFC) and 2.5 kWh of modular batteries (Fuel Cells Bulletin, 2019c). Hydrogen is stored at 500 bar (compressed gaseous) and compressed hydrogen storage is located on racks on weather deck (Baumann et al., 2021). The type of the project is commercial and it will be completed in 2024 (Zerta et al., 2019; Baumann et al., 2021). Elektra has also photovoltaic modules and total funding of 1.173.348,88 € (E4ships, n.d.; NOW GmbH, n.d.).

Hornblower Hybrid

Figure 3.28 Hornblower Hybrid (Hydrogenics, 2013).

Hornblower Hybrid ferry (Fig. 3.28) in the USA (in 2012) is a prototype project with PEMFC power of 32 kW (Zerta et al., 2019). The 600-passengers NYC hybrid ferry has also, diesel generator, batteries, solar panels and wind turbines (Tronstad et al., 2017; Fuel Cells Bulletin, 2011).

SF-BREEZE

Figure 3.29 SF-BREEZE ferry (Tronstad et al., 2017).

The SF-BREEZE project is a Feasibility Study of a passenger ferry (Fig. 3.29) (high-speed) with LH_2 and a hydrogen refueling station in the San Francisco bay area (started in 2015) (Tronstad et al., 2017). The ferry has a passenger capacity of 150 people and two electro motors (Tronstad et al., 2017). The FCs (41 PEMFC units of 120 kW each) and the fuel storage system are above deck (Tronstad et al., 2017). The SF-BREEZE project led to the **Zero-V Research Vessel** (Klebanoff, 2019). The "Golden Gate Zero Emission Marine" co-founder and CEO/CTO Dr. Joe Pratt led the landmark SF-BREEZE study (GGZEM, n.d.).

SEA CHANGE (ex. WATER-GO-ROUND)

Figure 3.30 SEA CHANGE (Water-Go-Round, n.d.).

Golden Gate Zero Emission Marine Sea Change (Fig. 3.30) in the USA is a hydrogen and battery powered passenger ferry with 3x 120 kW PEMFC power and 100 kWh battery capacity (Zerta et al., 2019; Baumann et al., 2021). The compressed GH_2 is stored at 250 bar (Baumann et al., 2021). It has 84 passenger capacity and electric motor power of 2x 300 kW (Baumann et al., 2021). The project is expected to launch in 2021 (Baumann et al., 2021). It is a demonstration project (Zerta et al., 2019).

Kamine boat

Figure 3.31 Kamine test boat (Toyota Tsusho Corporation, 2018).

Kamine boat is a test boat (Fig. 3.31) under the project, which has been started in 2015, on developing safety guidelines for hydrogen FC-powered boats (below gt of 20 tonnes) in Japan’s coastal waters (Fuel Cells Bulletin, 2018; Toyota Tsusho Corporation, 2018). That boat has 60 kWh lithium-ion battery, 2x 30 kW polymer electrolyte fuel cell (PEFC) (also known as PEMFC) and 50 kW IPM motors x 2 units (Fuel Cells Bulletin, 2018; Toyota Tsusho Corporation, 2018). Yanmar and Toyota Tsusho researched the 60 kW FC system for boats (Toyota Tsusho Corporation, 2018). A demonstration trial was conducted during the last year of the plan (three-year plan) (Toyota Tsusho Corporation, 2018).

Cobalt 233 Zet

Figure 3.32 Cobalt 233 Zet boat (Nonstop, 2008).

Zebotec Cobalt 233 Zet (Fig. 3.32) (in 2007) in Germany (sport boat) is a prototype project with a hybrid propulsion system using batteries for peak power (Zerta et al., 2019; Tronstad et al., 2017). The hybrid propulsion system is composed of electrical engine, batteries and a PEMFC system (Zerta et al., 2019; Nonstop, 2008).

Race for Water

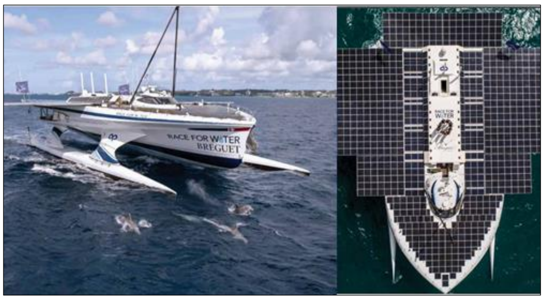


Figure 3.33 Race for Water catamaran (Race for Water Foundation, 2018).

The Race for Water expedition (Swiss project) started in France in 2015 to assess the plastic pollution of the oceans (Race for Water Foundation, 2018). In 2017, the Race for Water expedition started on a new five-year (2017-2021) Odyssey around the world to propose solutions for the preservation of the oceans (Race for Water Foundation, 2018). The vessel (Swiss origin) (Fig. 3.33) that is used for the 5 years Odyssey is an environmentally-friendly vessel and is powered with clean energies (Race for Water Foundation, 2018). It is the first vessel powered by a solar-hydrogen-kite energy mix (Race for Water Foundation, 2018). It has space for 11 passengers, compressed hydrogen is stored at 350 bar, FC power of 2x 30 kW, electric and wind propulsion and a photovoltaic system (Baumann et al., 2021). The first name of this catamaran vessel was “MS Tûranor PlanetSolar” and it was renamed “Race for Water” in 2015 from the name of the Foundation that now operates it (Fondation PlanetSolar, n.d.).

Generally, seawater is pumped, desalinated, stored on board and using the surplus photovoltaic energy is purified, then being electrolyzed at 50 bars hydrogen is produced, which is then dried, compressed at 350 bars, and stored in cylinders (Race for Water Foundation, 2018). The FCs maintain the charge level of the batteries or supply the electric engine (propellers) directly (Race for Water Foundation, 2018). Energy is also stored via solar panels in lithium-ion batteries (Race for Water Foundation, 2018). The project is currently in service (Baumann et al., 2021). The towing kite enables greater range while increasing the boat speed in certain conditions (Race for Water Foundation, 2018).

MF HYDRA (Norled)

Figure 3.34 MF HYDRA ferry (Westcon Yards AS, n.d.).

The MF HYDRA car ferry (Fig. 3.34) (in Norway, 2021 project completion) was delivered in June 2021 by Westcon Yards AS, to ship-owner Norled AS in Stavanger and it is a battery, hydrogen, diesel hybrid plug-in car and passenger ferry (Baumann et al., 2021; Westcon Yards AS, n.d.). It has 1.36 MWh battery, 400 kW FC power, liquefied cryogenic hydrogen storage, 299-passenger capacity and can carry 80 cars/10 trucks (Baumann et al., 2021).

GKP7H2 project

Figure 3.35 GKP7H2 project (Reinertsen New Energy, 2018).

The GKP7H2 (Fig. 3.35) is a project for a hydrogen and FC-driven high-speed passenger ferry (Aarskog et al., 2020). The ship has a capacity of 100 passengers, a hydrogen storage capacity of 450 kg at 250 bar and an installed propulsion power of 1.2 MW (Aarskog et al., 2020). The ship was designed by the Brødrene Aa and belongs in the 24 MEuro MoZEES program (Arena Ocean Hyway Cluster, 2019). The GKP7H2 is part of the DNV GL Green Coastal Shipping Program and was completed from 2016 to 2019 (Arena Ocean Hyway Cluster, 2019). The project GKP7H2 aims to have a high-speed light craft (HSLC) in operation between Florø and Måløy (in Norway) by 2021 (Reinertsen New Energy, 2018).

Zero-V

Figure 3.36 Zero-V vessel (Madsen et al., 2020).

It's a Feasibility Study of the Zero-V which is a coastal research vessel (Fig. 3.36) powered solely by hydrogen FCs in the USA (Madsen et al., 2020). It has 1800 kW PEMFC power supplemented with lithium-ion bridging batteries that provide both propulsion and ship service electrical needs (Madsen et al., 2020). LH_2 (cryogenic liquid) is stored in two LH_2 tanks (Madsen et al., 2020). The Zero-V has berths for 18 scientists and 11 crew (Madsen et al., 2020). The technical team consists of Sandia National Laboratories, Glosten, the Scripps Institution of Oceanography ("Scripps") at UC San Diego and DNV GL and the final project report-out was in 2017 (Madsen et al., 2020). The anticipated capital construction cost is about $79 M (Madsen et al., 2020).

No.1

No.1 is the first yacht with a FC propulsion system certified by safety auditor Germanischer Lloyd (Fuel Cells Bulletin, 2003). The propulsion system comprises 4x 1.2 kWe PEMFC modules with 9 lead-gel batteries (Fuel Cells Bulletin, 2003). It is a sailing yacht (prototype project) in Germany (2002-2004) (Vogler and Sattler, 2016).

Zeff project (Hyon AS)

Figure 3.37 ZEFF (Zero Emission Fast Ferry) (NCE MCT, n.d.).

In the project ZEFF (Zero Emission Fast Ferry) (Fig. 3.37), which is under the Norwegian government's PILOT-E scheme, the propulsion power of the vessel will be produced by FCs fueled by hydrogen (produced from electrolysis and renewable energy), in combination with batteries and the vessel will have passenger capacity around 100 to 300 (Fuel Cells Bulletin, 2019b). It is a concept study project in Norway (2018-2020) (Fahnestock and Bingham, 2021). In 2018, project ZEFF was awarded 10.5 MNOK from the scheme PILOT-E (Fahnestock and Bingham, 2021).

Rødne E-Maran project

Figure 3.38 Rødne E-Maran project (Rødne, 2019).

The Rødne E-Maran project (Fig. 3.38), in Norway, will be completed in 2023 (Baumann et al., 2021). It is a concept about fast boats with a FC power of 500-625 kW, a passenger capacity of 130-195 people and hydrogen storage in tanks (Baumann et al., 2021; Rødne, 2019). Three different vessel sizes were investigated (lengths of 20 m, 24 m, 28 m) (Baumann et al., 2021).

Energy Observer

Figure 3.39 Energy Observer vessel (Energy Observer, 2021a).

The Energy Observer vessel (Fig. 3.39) (in France) was at first a sailing racing catamaran, which was later converted into a research/campaign vessel (Baumann et al., 2021). It has electric and wind propulsion (2 OceanWing soft wingsails) and an onboard electrolyzer, supplied by a photovoltaic system and hydrogeneration under wind power (Baumann et al., 2021). Compressed hydrogen is stored at 350 bar (Baumann et al., 2021). It also features 60 kW PEMFC power and batteries and it is in operation since 2017 (Baumann et al., 2021; Energy Observer, 2021b).

DeepC project

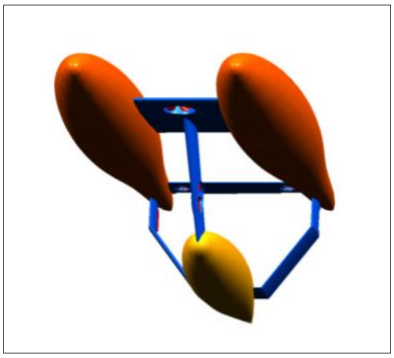


Figure 3.40 DeepC vehicle design (Hornfeld, 2003).

DeepC project (Fig. 3.40) (in Germany, in 2004), is a prototype project about the development of an Autonomous Underwater Vehicle (AUV) for great diving depths (Hornfeld, 2003; Zerta et al., 2019). Electrical energy on board is provided by a H_2/O_2-PEMFC system that is buffered via batteries and the hydrogen and oxygen are stored in pressure gas bottles of 250 bar and 350 bar (Hornfeld, 2003).

HySeas III

Figure 3.41 RoPax ferry (HySeas III, 2021).

HySeas III (in Scotland) is the final stage of a programme on what the team hopes will be, the world's first sea-going vehicle and passenger ferry (RoPax ferry) (Fig. 3.41) with carbon-free hydrogen as energy source (2018-2022) (EC, 2021a; Zerta et al., 2019; CORDIS | EC, 2021a). A part of the project includes the vessel’s hybrid FC power system that is constructing and testing at full scale and in a later stage, the vessel will be built (EC, 2021a). The vessel has PEMFC power of 600 kW, compressed hydrogen stored at 350 bar and a passenger capacity of 120 people with 16 cars/2 trucks (Baumann et al., 2021; Zerta et al., 2019). The total cost of the project is 12,579,610 € and the EU contribution is 9,276,373 € (EC, 2021a). It is a demonstration in normal operations type of project with small ship size (Fahnestock and Bingham, 2021).

Urashima

Figure 3.42 AUV Urashima (Maeda et al., 2004).

The AUV Urashima (in 2003) (Fig. 3.42) is a test vehicle for the development of an AUV (in Japan) (Maeda et al., 2004; Zerta et al., 2019). It is the world's first AUV powered by FCs (prototype project) (Maeda et al., 2004; Zerta et al., 2019). It has 4 kW PEMFC and storage of hydrogen gas is made by metal hydride (Maeda et al., 2004; Zerta et al., 2019). The vehicle is also powered by lithium-ion rechargeable battery for hybrid use as the auxiliary power source (Maeda et al., 2004).

Hydroxy 3000

Figure 3.43 Hydroxy 3000 (Büchi et al., 2004).

The Hydroxy 3000 leisure boat (Fig. 3.43) is a prototype project (in Switzerland, in 2003) and is propelled by two electric motors, powered by 3 kW water-cooled PEMFC and a 9 kWh lead-acid battery electric storage unit (Büchi et al., 2004; Vogler and Sattler, 2016). It is for 6 passengers and the hydrogen is stored at 200 bar (Büchi et al., 2004).

E5 tug

Figure 3.44 E5 tug (Tokyo Kisen Co., Ltd. and e5 Lab Inc, 2019).

E5 tug (Fig. 3.44) is a concept design of an electric tug powered by battery and hydrogen FC with 2x 1500 kW azimuth thruster (Tokyo Kisen Co., Ltd. and e5 Lab Inc, 2019). It is aiming to launch for commercial operations at Yokohama Port and Kawasaki Port in 2022 (in Japan) (Tokyo Kisen Co., Ltd. and e5 Lab Inc, 2019). The battery system is used as the main power source and a hydrogen FC and generator as the auxiliary power source (Tokyo Kisen

Co., Ltd. and e5 Lab Inc, 2019). In the future, in combination with renewable energy, it will be possible to achieve zero emissions on Well-to-Propeller basis (Tokyo Kisen Co., Ltd. and e5 Lab Inc, 2019).

Elding I (SMART H_2 project)

Figure 3.45 Elding I ship (Nonstop, 2008).

The Elding I (in 2008, prototype project) is a whale-watching ship (Fig. 3.45) with a hydrogen auxiliary power unit (APU) (10 kW PEMFC power system operated by compressed hydrogen providing electricity for the ship operation) in addition to the regular diesel engine (Nonstop, 2008; Vogler and Sattler, 2016). The Elding I, originally built in Iceland as a rescue ship, can carry 150 passengers (Nonstop, 2008). It is part of the demonstration SMART-H_2 project, which is testing various types of hydrogen-fuelled equipment for vehicles and vessels, and it started in 2007 and ended in 2010 (Nonstop, 2008).

Aranda (MARANDA project)

Figure 3.46 Research vessel Aranda (MARANDA, n.d.).

In the MARANDA project (2017-2022, in Finland), an emission-free hydrogen-fuelled PEMFC {165 kW (2x 82.5 kW AC)} based hybrid (with a battery) powertrain system is developed for marine applications and validated both in test benches and on board the research vessel Aranda (Fig. 3.46) (CORDIS | EC, 2021b). Hydrogen will be stored in a mobile hydrogen storage container, refillable in any 350 bar hydrogen refuelling station (CORDIS | EC, 2021b). It is a demonstration in normal operations type of project with small ship size (Fahnestock and Bingham, 2021). The overall budget of the MARANDA project is 3 704 757,50 € and the EU contribution is 2 939 457,50 € (CORDIS | EC, 2021b).

Hynovar project

Figure 3.47 The passenger vessel (Vasquez, 2019).

A hydrogen maritime shuttle (Fig. 3.47) was planned to be developed through the Hynovar project (in France, in 2017) (MÉDITERRANÉE DU FUTUR, n.d.). It is a pilot project (Hyseas Energy, n.d.). The vessel has 200 passengers, FC power and compressed hydrogen storage at 350 bar (Baumann et al., 2021).

X/V-1

HaveBlue developed a propulsion and power generation system that produces renewable hydrogen from purified seawater using clean energy power sources such as solar panels, wind generators and regenerative electric drive motors and in cooperation with Catalina Yachts built its first full-scale technology demonstrator, the X/V-1 (Fuel Cells Bulletin, 2004). The vessel is a modified Catalina 42 Mark II yacht that has been fitted with HaveBlue's system to provide all required power and propulsion from renewable hydrogen energy (Fuel Cells Bulletin, 2004). It is a sailing yacht (in the USA, in 2005) with 10 kW PEMFC power (prototype project) (Vogler and Sattler, 2016). The hydrogen is stored with metal hydride technology (Fuel Cells Bulletin, 2004).

VEGA (Pilot Vaporetto)

Figure 3.48 VEGA/Pilot Vaporetto (Hydrogenics, 2013).

It is a prototype project about a boat (Fig. 3.48) (in Italy, 2005-2006) with 12 kW PEMFC power (Vogler and Sattler, 2016).

Solgenia

Figure 3.49 Solgenia research hybrid boat (Leiner, 2014).

Solgenia (in Germany, in 2007) is a research hybrid boat (Fig. 3.49), which is powered by photovoltaic cells and uses FCs as a back-up system (Leiner, 2014; Vogler and Sattler, 2016). The hydrogen is produced by stationary photovoltaic cells (Leiner, 2014). The boat has a battery capacity of 210 Ah, 3x 1.2 kW PEMFC and hydrogen storage tank onboard of up to 350 bar but the hydrogen is stored at 300 bar (Leiner, 2014). It is a prototype project (Vogler and Sattler, 2016).

Frauscher 600 Riviera HP

Figure 3.50 Frauscher 600 Riviera HP (Barche Magazine, 2009).

Frauscher 600 Riviera HP is a leisure boat/sport boat (Fig. 3.50) (in Austria, in 2009) with 4 kW PEMFC power (commercial project) (Vogler and Sattler, 2016; Zerta et al., 2019). The hydrogen is green and it is extracted from water using a photovoltaic system and electrolyzer (Fuel Cells Bulletin, 2009). It is worth mentioning that an economic advantage compared with conventional electric boats is that no time has to be spent charging the batteries, as for conventional electric boats, 6–8 h of charging corresponds to 4–6 h of actual use (Fuel Cells Bulletin, 2009). The boat is the realization of the partners' Future Project Hydrogen (Fuel Cells Bulletin, 2009).

BELBIM

Figure 3.51 BELBIM (Hydrogenics, 2013).

It is a ferry (Fig. 3.51) (in Turkey, in 2009), which has 48 kW PEMFC power (prototype project) (Vogler and Sattler, 2016).

FPS Maas vessel

Figure 3.52 FPS Maas vessel (FPS, n.d.).

FPS Maas is an inland container vessel (Fig.3.52) that will be retrofitted to run 100% on hydrogen in 2022 (in the Netherlands) (FPS, n.d.). Its ICE will be removed and a new system including FCs (825 kW power), a battery pack (battery capacity of 504 kWh for peak-shaving and emergency power), an electric motor and hydrogen storage will be installed on board (Baumann et al., 2021). Compressed hydrogen will be stored at 300 bar (Baumann et al., 2021).

Marti boat

Figure 3.53 Marti boat (Hürriyet Daily News, 2011).

Marti (Fig. 3.53) which means “seagull” is a passenger boat (in Turkey, in 2012) with an 8 kW PEMFC power module (prototype project) (Zerta et al., 2019; Fuel Cells Bulletin, 2012). Hydrogen is stored at 200 bar (Fuel Cells Bulletin, 2012).

Jules Vernes 2 (Navibus)

Figure 3.54 Jules Vernes 2, Navibus (Energy Observer, 2018).

Jules Vernes 2, Navibus (Fig. 3.54) is a passenger ferry (in France, in 2017) with 2x 5 kW PEMFC power (prototype project) (Zerta et al., 2019). The vessel can carry 12 passengers and 6 bicycles (request for exemption for 25 passengers and 1 pilot in progress) (Energy Observer, 2018; Gerard, n.d.). Hydrogen is stored on board in pressure tanks at 350 bar (Gerard, n.d.).

Germanischer Lloyd feeder ship

Figure 3.55 Container feeder ship design (Plump et al., 2013).

It is a study project from Germanischer Lloyd about a zero-emission container feeder vessel (Fig. 3.55) with 5 MW FC systems, 3 MWh battery systems to provide peak power and LH_2 (in Germany, in 2012) (Vogler and Sattler, 2016; Plump et al., 2013). The vessel has multiple type C tanks to store the LH_2 (Plump et al., 2013). The concept design for this ship was developed by Germanischer Lloyd Group's subsidiary FutureShip and was convincing due to the commercial-off-the-shelf technology and the lack of speculation about potentially evolving equipment (Rohde et al., 2013).

Zero Emission ferry (Scandlines)

Figure 3.56 Zero Emission ferry (Scandlines) (Rohde et al., 2013).

FutureShip designed in 2012 the zero-emission ferry (Fig. 3.56) for Scandlines' Vogelfluglinie that would link Puttgarden in Germany to Rødby in Denmark (study project) (Vogler and Sattler, 2016; Goodwin and Storaker, 2015). The vessel is a passenger/car ferry with 8.3 MW high-temperature FCs powered with LH_2 (Vogler and Sattler, 2016; Goodwin and Storaker, 2015). The hydrogen is stored in C-type tanks on deck (Goodwin and Storaker, 2015). A battery system of 2.4 MWh is installed to store excess electricity from the FCs and supply booster power rapidly when needed (Rohde et al., 2013). The hydrogen is produced by excess wind power from wind power plants near the terminals and the ferry has a truck capacity from 30 to 96 and a passenger capacity from 1150 to 1500. (Rohde et al., 2013). The zero-emission ferry could be operational by 2017 (Rohde et al., 2013).

MF Ole Bull (CMR Prototech)

Figure 3.57 MF Ole Bull car ferry (Svendsen and Opdahl, 2017).

The MF Ole Bull (Fig. 3.57) concerns a car ferry (in Norway, in 2016) with 200 kW PEMFC power (Zerta et al., 2019). The MF Ole Bull ferry belongs to the Osterøy ferry company, which has agreed to participate in a demonstration project, with CMR Prototech, aiming to test a hydrogen FC system on a full scale (Goodwin and Storaker, 2015). The ferry has two diesel engines one of which will be replaced by an electric motor powered by hydrogen FCs in combination with 100 kWh batteries (Fuel Cells Bulletin, 2016). CMR Prototech with the experience from the MF Vågen ship provided the foundation for the new project with the MF Ole Bull (Fuel Cells Bulletin, 2016). The cost of transforming MF Ole Bull into a hybrid ferry is 542 000 € financed by Enova but the rebuild is estimated to save around 100 000 € annually (Grannas, 2019).

ZEUS (Fincantieri)

Figure 3.58 ZEUS–Zero Emission Ultimate Ship (FINCANTIERI SI, n.d.).

ZEUS–Zero Emission Ultimate Ship (Fig. 3.58) (in Italy) is an experimental vessel that is to be delivered in 2021 and it is designed and built by Fincantieri (FINCANTIERI, 2020; Baumann et al., 2021). ZEUS will be fitted with 2 diesel generators and 2 electric motors (FINCANTIERI, 2020). It will also be equipped with a 130 kW hydrogen FC system with the hydrogen to be stored in 8 metal hydride cylinders and with a battery system (FINCANTIERI, 2020; Baumann et al., 2021).

Cruise ship (Viking Cruises)

The Norwegian shipping company, Viking Cruises, is working on what could be the world's first cruise ship with zero-emission technology (NCE MCT, 2019). The ship will be fuelled by LH_2 and will have the capacity for more than 900 passengers and a crew of 500 (NCE MCT, 2019). It's a study project and it will be equipped with FCs (in Norway, in 2017) (Zerta et al., 2019).

Hydro Motion Project

Figure 3.59 Hydro Motion boat (TU Delft Solar Boat Team, 2021).

The Hydro Motion Project concerns the refitting of a solar boat to sail on green hydrogen (Fig. 3.59) that was built by the solar boat team of TU Delft in the Netherlands (TU Delft Solar Boat Team, n.d.; TU Delft Solar Boat Team, 2021). It is about the first flying hydrogen-powered boat (hydrofoiling trimaran) (TU Delft Solar Boat Team, n.d.; TU Delft Solar Boat Team, 2021). The boat has 30 kW PEMFC, a battery pack for peak shaving and the hydrogen is stored at 350 bar (TU Delft Solar Boat Team, 2021). The team will continue with the Hydro Motion project and will again design, build, test and race a hydrogen-powered boat in the *Open Sea Class* at the world championships in Monaco (TU Delft Solar Boat Team, n.d.).

Figure 3.60 HYNOVA 40 (ENERGY BOAT CHALLENGE, 2021b).

Other notable participants with hydrogen boats in the competition in Monaco include for example the Hynova Team from France (ENERGY BOAT CHALLENGE, 2021a). **HYNOVA 40** (Fig. 3.60) competed in the Open Sea Class of the 8th Monaco Energy Boat Challenge in July 2021 (ENERGY BOAT

CHALLENGE, 2021b). HYNOVA 40 is a recreational boat with a capacity for 12 people and two electric engines powered by a hydrogen-electric hybrid system using green hydrogen (ENERGY BOAT CHALLENGE, 2021b).

WEVA Project

Figure 3.61 Hydrogen electric cargo ship Antonie (De Laat, 2021).

WEVA project is about building hydrogen electric cargo ship Antonie (Fig. 3.61) that will run on green hydrogen (2021-2023, in the Netherlands) (De Laat, 2021). The ship will be 135 meters long and will transport salt from the Nouryon factory in Delfzijl to the Botlek in Rotterdam (De Laat, 2021). It has a 4 M Green Deal subsidy (De Laat, 2021). The WEVA project is from the Dutch abbreviation for hydrogen electric cargo ship Antonie (first FC-powered inland waterway vessel) and it is focused on the construction and deployment of the Antonie as a 100% hydrogen vessel for shipping company Lenten Scheepvaart BV (Fuel Cells Bulletin, 2020). Dutch PEMFC manufacturer Nedstack is participating in the WEVA project (Fuel Cells Bulletin, 2020).

Hydrogen-powered rescue boat (MSN)

Figure 3.62 Hydrogen-powered rescue boat (MSN, 2020).

Marine Service Noord (MSN) worked with students from Noorderpoort Energy & Maritime and built their hydrogen-powered rescue boat (Fig. 3.62) (in 2019, in the Netherlands) (MSN, 2020).

Hydrogen-powered high-speed vessel for the Port of Narvik

Figure 3.63 Hydrogen-powered vessel for the Port of Narvik (TECO 2030 ASA, 2021).

The Port of Narvik (in Norway) will build one of the world's first hydrogen-powered high-speed vessels (long-range, high-speed passenger vessel) (Fig. 3.63) (Fuel Cells Bulletin, 2021). The boat will have hydrogen FCs from TECO 2030 and will be built by the shipyard Grovfjord Mekaniske Verksted (Fuel Cells Bulletin, 2021). The project also involves the establishment of a hydrogen filling station aiming to become the world's first hydrogen filling station for ships and road traffic (Fuel Cells Bulletin, 2021). The boat is planned to be completed in 2023 and when completed it will replace one of the port's diesel vessels (Fuel Cells Bulletin, 2021).

ZEPS Patria

Figure 3.64 ZEPS Patria (De Laat, 2021).

The ZEPS (Zero Emission Passenger Ship) is a pilot project (2020-2022, in the Netherlands), which converts an existing passenger ship (MPS Patria) into a hypermodern, hydrogen-powered ship (ZEPS Patria) (Fig. 3.64) (De Laat, 2021). The existing diesel engines will be replaced, a combination of a PEMFC and a Li-battery pack form will be the basis of the energy supply and for back-up energy, solar and wind energy will be used (De Laat, 2021).

Ecolution

Figure 3.65 Ecolution (De Laat, 2021).

Ecolution sailing yacht of Wubbo Ockels (Fig. 3.65) has been retrofitted into hydrogen vessel by the coalition WadDuurzaam in 2021 (De Laat, 2021; WadDuurzaam, n.d.). This ship belongs to hydrogen ships of Lauwersoog in Netherlands (De Laat, 2021).

Hydrogen Watertaxi

Figure 3.66 Hydrogen Watertaxi (De Laat, 2021).

This project (2020-2023, in the Netherlands) is developed within the zero-emission shipping program THRUST as it is called and all hydrogen-related components are to be developed by zepp.solutions (De Laat, 2021). The hydrogen Watertaxi (Fig. 3.66) is part of the Speckless Water-based Inland Mobility (SWIM) consortium (Enviu, Zepp Solutions, Flying Fish and Watertaxi Rotterdam) and it is running entirely on hydrogen (De Laat, 2021). The first passengers aimed to be able to board in 2021 (De Laat, 2021).

H_2 harbour tug (OSD-IMT)

Figure 3.67 H_2 harbour tug (OSD-IMT, 2019).

OSD-IMT, a ship design and maritime consultancy business, and PEMFC Market Leader Nedstack have collaborated to create a concept design for a completely electric-powered 65-tonne bollard pull harbour tug (Fahnestock and Bingham, 2021). The propulsion motors' electric power is generated onboard by hydrogen FCs, resulting in a zero-emission tug (Fahnestock and Bingham, 2021). The tug (Fig. 3.67) has a FC power of 2000 kW and the hydrogen storage location is containerized on deck (Baumann et al., 2021). The project takes place in the Netherlands (Baumann et al., 2021).

Noe (Barillec Marine)

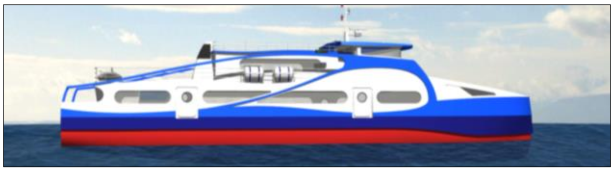


Figure 3.68 Noe ferry (Coprexma, n.d.).

This project is about a ferry (Fig. 3.68) (in France, in 2020) with 2x 1000 kW PEMFC power (pilot project) (Zerta et al., 2019). The ferry has a capacity of 200 passengers (Coprexma, n.d.).

Cheetah Marine hydrogen catamaran

Figure 3.69 Cheetah Marine hydrogen catamaran (Cheetah Marine, 2016a).

Cheetah Marine has been developing and testing a hydrogen-powered catamaran in collaboration with ITM Power, a specialist in hydrogen energy systems (Cheetah Marine, 2016a). The 9.95m Cheetah uses a hydrogen ICE that produces only water and no CO_2 (Cheetah Marine, 2016a). The catamaran

(Fig. 3.69) designed and built at Cheetah's workshops on the Isle of Wight (Island in England) and has hydrogen stored in twin tanks at 350 bar (Cheetah Marine, 2016b).

HyDIME (Hydrogen Diesel Injection in a Marine Environment) project

Figure 3.70 Shapinsay ferry (HyDIME, n.d.).

HyDIME (Hydrogen Diesel Injection in a Marine Environment) is a 12-month UK project that will use green hydrogen produced by wind and tidal power as a fuel for an existing commercial passenger and vehicle ferry (Fig. 3.70) operating between Shapinsay and Kirkwall in Orkney (HyDIME, n.d.). The ferry will have a hydrogen injection system, which is a hydrogen dual fuel system that uses compressed hydrogen gas to displace diesel in ICEs (HyDIME, n.d.). The project is funded by Innovate UK with £430,000 (HyDIME, n.d.). Hydrogen tanks will be located below decks so will have very little effect on the capacity of the vessel (HyDIME, n.d.).

CTV H_2 PIRIOU

Figure 3.71 CTV H_2 PIRIOU (PIRIOU, 2020).

PIRIOU (in France) aims to create a CTV (Fig. 3.71) with hydrogen hybrid propulsion (PIRIOU, 2020). The CTV has 2x 1000 kW main engines power, 2x 140 kW FCs power, a crew of 3, personnel of 24 people and the hydrogen is stored in 20’ container (PIRIOU, 2020).

Green Pearl River project

Through the project of Green Pearl River, designed and developed the hydrogen FC demonstration ship by China State Shipbuilding Corporation (Fahnestock and Bingham, 2021). The ship is an inland river self-unloading ship with 4x 125kW hydrogen PEMFC as the main power source and a 4x 250kWh lithium battery pack for peak shaving compensation (Fahnestock and Bingham, 2021). Hydrogen is stored in a 35 MPa high-pressure hydrogen cylinder group. It is a demonstration in normal operations project (in China, 2020-2021) (Fahnestock and Bingham, 2021).

Coastal Liberty (ACTA MARINE)

Figure 3.72 Coastal Liberty ship (ACTA MARINE, n.d.).

On October 20, 2020, was confirmed the feasibility for upgrading the supply vessels for the Mittelplate drilling and production island in the German North Sea with a hydrogen hybrid propulsion system (Wintershall Dea, 2020). The first supply ship that would be refitted with the hybrid propulsion system is the Coastal Liberty (Fig. 3.72) (Wintershall Dea, 2020). The present diesel-mechanical propulsion system will be upgraded to a hydrogen-hybrid propulsion system with electric engines that are powered by hydrogen FCs with the generated electricity from the FCs to be stored in batteries (Wintershall Dea, 2020; Baumann et al., 2021). The vessel has liquefied cryogenic hydrogen storage system located containerized on deck (Baumann et al., 2021). The feasibility study done under EnTec's (EnTec Industrial Services GmbH) leadership serves as the starting point for the planned retrofitting (Wintershall Dea, 2020).

DFDS hydrogen ferry

Figure 3.73 DFDS hydrogen ferry (DFDS, 2020).

This project (in Denmark, project completion in 2027) is about a 100% green hydrogen-powered ferry (Fig. 3.73) for DFDS' Oslo–Frederikshavn–Copenhagen route (DFDS, 2020; Baumann et al., 2021). The ship, with the working name Europa Seaways, will have 23000 kW PEMFC power, 1800 passenger capacity and 2300 lane meters car/truck capacity and compressed GH_2 storage (DFDS, 2020; Baumann et al., 2021). A projected offshore wind energy-powered electrolyser plant in Greater Copenhagen will generate the green hydrogen (DFDS, 2020).

With Orca vessel

Figure 3.74 With Orca vessel (Norwegian Ship Design, 2021).

With Orca vessel is a cargo ship (Fig. 3.74) that will be powered by hydrogen-fueled ICE with auxiliary wind propulsion provided by two Flettner rotors (Norwegian Ship Design, 2021; Baumann et al., 2021). The ship is planned to operate off the coast of Norway, transporting aggregates and grains (in Norway, vessel launch is expected in 2024) (Baumann et al., 2021). HeidelbergCement Norway and Felleskjøpet AGRI are the project leaders (Baumann et al., 2021). It will have compressed GH_2 storage (Baumann et al., 2021).

Project SeaShuttle (Hyon AS)

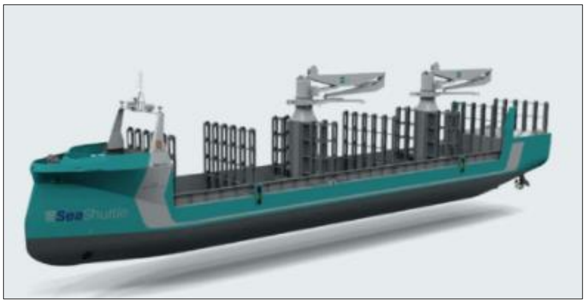


Figure 3.75 Project SeaShuttle container vessel (Hyon, n.d.).

In project SeaShuttle, which is under the Norwegian government's PILOT-E scheme, will be developed and demonstrated a zero-emission coastal freighter with automated cargo handling, for profitable container transport in the short-sea market (Fig. 3.75) (Fuel Cells Bulletin, 2019b). The project has been awarded 6 million € by the Norwegian government (Fahnestock and Bingham, 2021). It is a "demonstration in normal operations" project in Norway (in 2018) (Fahnestock and Bingham, 2021; Baumann et al., 2021). The project includes two all-electric container ships (Hyon, n.d.). The vessels will have hydrogen FCs (2,000 kW FC power) for their propulsion power and diesel-electric and battery operation (Baumann et al., 2021; Hyon, n.d.).

Project AQUA

Figure 3.76 Project AQUA (Lateral Engineering, n.d.).

Lateral Engineering's project AQUA (in the UK) in cooperation with SINOT Yacht Architecture & Design utilizes hydrogen-electric propulsion and energy system architecture to deploy a yacht for transatlantic operation (Fig. 3.76) (Lateral Engineering, n.d.; Baumann et al., 2021). AQUA is fitted with Lateral's TREADWATER propulsion idea that uses a Contra Rotating Propeller (CRP) and two Voith Schneider Propellers (VSP) (Lateral Engineering, n.d.). The yacht has liquefied cryogenic hydrogen storage system located below the deck and PEMFC power of 4 MW (Baumann et al., 2021; Lateral Engineering, n.d.).

NYK Line hydrogen-powered tourist ship

NYK Line develops a 100-passenger tour boat powered by electric batteries and hydrogen FCs (in Japan, completion in 2024) (Fahnestock and Bingham, 2021). A feasibility study will be conducted first, followed by design work on the boat and its hydrogen fuel supply system (Fahnestock and Bingham, 2021). The project will contain the development of new shipboard technology, including the fuel supply system and the creation of an energy management system to combine power from the battery and the FC (Fahnestock and Bingham, 2021). The vessel and the hydrogen supply system are being designed following a feasibility study, with construction slated to begin in 2023 and a pilot demonstration in 2024 (Baumann et al., 2021).

Royal IHC hydrogen dredger

Figure 3.77 Royal IHC hydrogen dredger (Royal IHC, 2021).

Royal IHC got “approval in principle” (AiP) from the classification society Bureau Veritas for the design of a trailing suction hopper dredger (TSHD) powered by hydrogen (Royal IHC, 2021). Royal IHC is investigating a new type of vessel known as the “LEAF” (low energy adaptive fuel) hopper in collaboration with the Dutch Rijkswaterstaat (Royal IHC, 2021). The vessel (Fig. 3.77) can be operational in 2024 and it is intended to be used to maintain the Dutch coastline (Royal IHC, 2021). Only during the vessel's construction and the production of green hydrogen is a little quantity of CO_2, sulfur oxides (SO_x), NO_x, and particulate matter emitted (Royal IHC, 2021). Furthermore, various design elements on the LEAF hopper, such as an electric drive train and energy recovery systems, contribute to low energy consumption (Royal IHC, 2021).

ULSTEIN J102 jack-up WTIV

Figure 3.78 ULSTEIN J102 jack-up WTIV (ULSTEIN, 2020).

ULSTEIN J102 jack-up vessel (in the Netherlands) is a zero-emission wind turbine installation vessel (WTIV) (Fig. 3.78) (Baumann et al., 2021; ULSTEIN, 2020). The vessel has a PEMFC system, battery energy storage system (BESS), and containerized storage of compressed hydrogen (Baumann et al., 2021; ULSTEIN, 2020).

VEZ–Vaporetto a Zero Emissioni

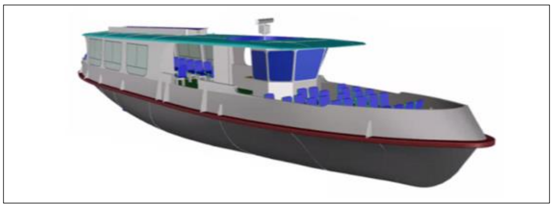


Figure 3.79 VEZ–Vaporetto a Zero Emissioni boat (S.A.T.E., n.d.).

VEZ, Vaporetto a Zero Emissioni (Fig. 3.79) (zero-emission water-bus) is a project funded under Horizon 2020, (in Italy, 2014-2015) regarding a zero-emission Vaporetto type vehicle ideal for public water transport (S.A.T.E., n.d.). Two version studies were conducted one of which includes the boat powered by roof-mounted PV cells, batteries and hydrogen-air FCs (PEMFC) (S.A.T.E., n.d.).

HYDROMER dredger

Figure 3.80 HYDROMER dredger (PIRIOU, 2021).

PIRIOU received an order from the French Occitanie Region on the design and realization of a trailing suction hopper dredger (Fig. 3.80) fitted with a hydrogen FC (PIRIOU, 2021). The usage of a hydrogen FC is predicted to help save up to 20% of the vessel fuel oil consumption (PIRIOU, 2021). The dredger has a 1500 m^3 capacity to transport sediments and is planned to be delivered in Sète-south France- in the 3rd quarter of 2023 (PIRIOU, 2021). The crew capacity includes 14 people (PIRIOU, 2021).

NYK Super Eco Ship 2050

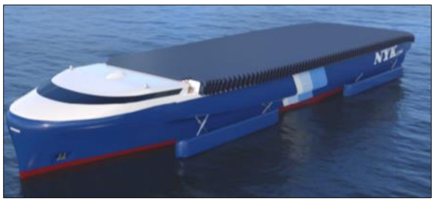


Figure 3.81 NYK Super Eco Ship 2050 (NYK Group, 2016).

The Super Eco Ship 2050 (in Japan) (Fig. 3.81) by NYK is a concept design (concept study) that envisions what a future zero-emissions vessel would resemble (Fahnestock and Bingham, 2021). Along with many other features, the vessel is powered by hydrogen FCs (SOFC) with hydrogen produced by renewable energy sources (NYK Group, 2016). It also has about 9,000 m^2 of solar panels (NYK Group, 2016).

4. Results and discussion

aa	VESSEL or PROJECT	COUNTRY	HYDROGEN PROPULSION	HYDROGEN STORAGE ONBOARD	PASSENGER & VEHICLE CAPACITY	VESSEL TYPE
1	**CLASS U212A & U214**	GERMANY	PEMFC	METAL HYDRIDE	27 CREW (U212A)	SUBMARINES
2	**HYDRA**	GERMANY	AFC	METAL HYDRIDE	22 PASSENGERS	WATER TAXI
3	**HYDROGENESIS**	UK	PEMFC	TANK AT UP TO 350 BAR	12 PASSENGERS & 2 CREWS	FERRY
4	**ROSS BARLOW**	UK	PEMFC	$TiMn_2$-BASED METAL HYDRIDE	-	CANAL BOAT
5	**FCS ALSTERWASSER**	GERMANY	PEMFC	AT 350 BAR/15°C	100 PASSENGERS	INLAND PASSENGER VESSEL
6	**DUFFY-HERRESHOFF DH30**	USA	PEMFC	$NaBH_4$	18 PASSENGERS	WATER TAXI
7	**XPERIANCE NX HYDROGEN**	NETHERLANDS	PEMFC	4 EXCHANGEABLE 200 BAR TANKS	12 PASSENGERS	LEISURE BOAT
8	**TUCKERBOOT (H_2YACHT)**	GERMANY	PEMFC	METAL HYDRIDE CONTAINERS	8 PASSENGERS	SPORT BOAT
9	**NEMO H_2**	NETHERLANDS	PEMFC	6 CYLINDERS AT 350 BAR	86 PASSENGERS AND 2 CREW	CANAL BOAT
10	**GOLD GREEN HYGEN**	KOREA	PEMFC	CYLINDERS AT 35 MPA	50 PASSENGERS	TOURIST BOAT
11	**HYBRIDship PROJECT**	NORWAY	FC	-	-	FERRY
12	**FreeCO2ast PROJECT**	NORWAY	FC	LIQUEFIED CRYOGENIC	-	ROPAX
13	**FLAGSHIPS PROJECT-*ZULU***	FRANCE	FC	AT 300 BAR	-	INLAND CARGO VESSEL
14	**FLAGSHIPS PROJECT-*HIDLE***	NORWAY	PEMFC	AT 250 BAR	199 (PASSENGERS & CREW)	PASSENGER AND CAR FERRY
15	**FLAGSHIPS PROJECT-*FPS WAAL***	NETHERLANDS	PEMFC	-	-	CONTAINER CARGO VESSEL
16	**AERO 42 H_2**	NORWAY	FC	AT 250 BAR	277 PASSENGERS	FAST FERRY (HSC)

17	**ULSTEIN SX190 ZERO EMISSION DP2**	NETHERLANDS	PEMFC	IN CONTAINERIZED PRESSURE VESSELS AT 500 BAR	-	OFFSHORE CONSTRUCTION VESSEL
18	**HySHIP PROJECT-TOPEKA**	NORWAY	PEMFC	STORAGE TANKS (65-100 m^3)	56 SEMI-TRAILERS or 180 CARS	RO-RO DEMONSTRATION VESSEL
19	**HHHT PROJECT (GREEN TUG)**	NETHERLANDS	PEMFC	AT 430 BAR	-	TUG
20	**H2SHIPS PROJECT**	NETHERLANDS	FC	$NaBH_4$	25 PASSENGERS	PORT VESSEL
21	**HYDROVILLE PROJECT**	BELGIUM	HYDROGEN-DIESEL ICE	TANKS-CYLINDERS 200 BAR	-	CREWBOAT CATAMARAN (PASSENGER SHUTTLE)
22	**HYDROTUG**	BELGIUM	HYDROGEN-DIESEL ICE	250 BAR	-	BOLLARD PULL-TRACTOR TUG
23	**HYDROCAT**	BELGIUM	HYDROGEN-DIESEL ICE	350 BAR	24 PASSENGERS	CTV
24	**HYDROBINGO**	JAPAN	HYDROGEN-DIESEL ICE	INSIDE A MOBILE TRAILER	80 PASSENGERS	SHUTTLE
25	**MF VÅGEN**	NORWAY	PEMFC	METAL HYDRIDE	SMALL PASSENGER SHIP	COMMUTER FERRY
26	**ELEKTRA**	GERMANY	PEMFC	500 BAR	-	PUSH BOAT
27	**HORNBLOWER HYBRID**	USA	PEMFC	-	600 PASSENGERS	FERRY
28	**SF-BREEZE**	USA	PEMFC	ABOVE DECK	150 PASSENGERS	HIGH-SPEED PASSENGER FERRY
29	**SEA CHANGE (EX. WATER-GO-ROUND)**	USA	PEMFC	AT 250 BAR	84 PASSENGERS	PASSENGER FERRY
30	**KAMINE BOAT**	JAPAN	PEMFC	-	-	TEST BOAT
31	**COBALT 233 ZET**	GERMANY	PEMFC	-	-	SPORT BOAT
32	**RACE FOR WATER**	SWITZERLAND	FC	AT 350 BAR IN CYLINDERS	11 PASSENGERS	ENVIRONMENTALLY-FRIENDLY VESSEL-CATAMARAN
33	**MF HYDRA (NORLED)**	NORWAY	FC	LIQUEFIED CRYOGENIC	299 PASSENGERS & 80 CARS/10 TRUCKS	FERRY
34	**GKP7H2 PROJECT**	NORWAY	FC	250 BAR	100 PASSENGERS	HIGH SPEED PASSENGER FERRY

35	**ZERO-V**	USA	PEMFC	LH_2 TANKS	18 SCIENTISTS AND 11 CREW	COASTAL RESEARCH VESSEL
36	**No.1**	GERMANY	PEMFC	-	-	SAILING YACHT
37	**ZEFF PROJECT (Hyon AS)**	NORWAY	FC	-	100-300 PASSENGERS	FAST FERRY
38	**RØDNE E-MARAN PROJECT**	NORWAY	FC	TANKS	130-195 PASSENGERS	FAST BOAT
39	**ENERGY OBSERVER**	FRANCE	PEMFC	AT 350 BAR	-	RESEARCH/CAMPAIGN VESSEL (SAILING RACING CATAMARAN ORIGINALLY)
40	**DEEPC PROJECT**	GERMANY	PEMFC	IN PRESSURE GAS BOTTLES	-	AUV
41	**HYSEAS III**	SCOTLAND	PEMFC	AT 350 BAR	120 PEOPLE WITH 16 CARS/2 TRUCKS	ROPAX FERRY
42	**URASHIMA**	JAPAN	PEMFC	METAL HYDRIDE	-	AUV
43	**HYDROXY 3000**	SWITZERLAND	PEMFC	AT 200 BAR	6 PASSENGERS	LEISURE BOAT
44	**E5 TUG**	JAPAN	FC	-	-	TUG
45	**Elding I (SMART H_2 PROJECT)**	ICELAND	PEMFC	-	150 PASSENGERS	WHALE-WATCHING SHIP
46	**ARANDA (MARANDA PROJECT)**	FINLAND	PEMFC	MOBILE HYDROGEN STORAGE CONTAINER	-	RESEARCH VESSEL
47	**HYNOVAR PROJECT**	FRANCE	FC	AT 350 BAR	200 PASSENGERS	PASSENGER VESSEL
48	**X/V-1**	USA	PEMFC	METAL HYDRIDE	-	SAILING YACHT
49	**VEGA (PILOT VAPORETTO)**	ITALY	PEMFC	-	-	BOAT
50	**SOLGENIA**	GERMANY	PEMFC	300 BAR	-	RESEARCH BOAT
51	**FRAUSCHER 600 RIVIERA HP**	AUSTRIA	PEMFC	-	-	LEISURE BOAT/SPORT BOAT
52	**BELBIM**	TURKEY	PEMFC	-	-	FERRY
53	**FPS Maas**	NETHERLANDS	FC	AT 300 BAR	-	INLAND CONTAINER VESSEL

54	**MARTI BOAT**	TURKEY	PEMFC	AT 200 BAR	-	PASSENGER BOAT
55	**JULES VERNES 2 (NAVIBUS)**	FRANCE	PEMFC	350 BAR	12 PASSENGERS AND 6 BICYCLES	PASSENGER FERRY
56	**Germanischer Lloyd FEEDER SHIP**	GERMANY	FC	TYPE C TANKS	-	CONTAINER FEEDER SHIP
57	**ZERO EMISSION FERRY (SCANDLINES)**	GERMANY	FC	TYPE C TANKS	TRUCK CAPACITY: 30-96, AND PASSENGER CAPACITY: 1150-1500	PASSENGER/ CAR FERRY
58	**MF OLE BULL (CMR PROTOTECH)**	NORWAY	PEMFC	-	-	CAR FERRY
59	**ZEUS (FINCANTIERI)**	ITALY	FC	METAL HYDRIDE CYLINDERS	-	EXPERIMENTAL VESSEL
60	**CRUISE SHIP (VIKING CRUISES)**	NORWAY	FC	-	900 PASSENGERS AND A CREW OF 500	CRUISE SHIP
61	**HYDRO MOTION PROJECT**	NETHERLANDS	PEMFC	350 BAR	-	HYDROFOILING TRIMARAN
62	**WEVA PROJECT**	NETHERLANDS	FC	-	-	CARGO SHIP
63	**HYDROGEN POWERED RESCUE BOAT (MSN)**	NETHERLANDS	-	-	-	RESCUE BOAT
64	**HYDROGEN-POWERED HIGH-SPEED VESSEL FOR THE PORT OF NARVIK**	NORWAY	FC	-	-	LONG-RANGE, HIGH-SPEED PASSENGER VESSEL
65	**ZEPS PATRIA**	NETHERLANDS	PEMFC	-	-	PASSENGER SHIP
66	**ECOLUTION**	NETHERLANDS	-	-	-	SAILING YACHT
67	**HYDROGEN WATERTAXI**	NETHERLANDS	-	-	-	WATER TAXI
68	**H_2 HARBOUR TUG (OSD-IMT)**	NETHERLANDS	FC	CONTAINERIZED ON DECK	-	TUG
69	**NOE (BARILLEC MARINE)**	FRANCE	PEMFC	-	200 PASSENGERS	FERRY
70	**CHEETAH MARINE HYDROGEN CATAMARAN**	UK	HYDROGEN ICE	IN TWIN TANKS AT 350 BAR	-	CATAMARAN
71	**HyDIME**	UK	HYDROGEN-DIESEL ICE	TANKS BELOW DECK	-	PASSENGER AND VEHICLE FERRY

72	**CTV H_2 PIRIOU**	FRANCE	FC	IN 20' CONTAINER	CREW OF 3, PERSONNEL OF 24 PEOPLE	CTV
73	**GREEN PEARL RIVER PROJECT**	CHINA	PEMFC	35 MPa	-	INLAND RIVER SELF-UNLOADING SHIP
74	**COASTAL LIBERTY (ACTA MARINE)**	GERMANY	FC	LIQUEFIED CRYOGENIC	-	SUPPLY VESSEL
75	**DFDS HYDROGEN FERRY**	DENMARK	PEMFC	COMPRESSED GH_2 STORAGE	1800 PASSENGER CAPACITY & 2300 LANE METERS CAR/TRUCK CAPACITY	FERRY
76	**WITH ORCA VESSEL**	NORWAY	HYDROGEN ICE	COMPRESSED GH_2 STORAGE	-	CARGO SHIP
77	**PROJECT SEASHUTTLE (HYON AS)**	NORWAY	FC	-	-	CONTAINER SHIP
78	**PROJECT AQUA**	UK	PEMFC	LIQUEFIED CRYOGENIC BELOW DECK	-	YACHT
79	**NYK LINE HYDROGEN-POWERED TOURIST SHIP**	JAPAN	FC	-	100 PASSENGERS	TOUR BOAT
80	**ROYAL IHC HYDROGEN DREDGER**	NETHERLANDS	-	-	-	TRAILING SUCTION HOPPER DREDGER (TSHD)
81	**ULSTEIN J102 jack-up WTIV**	NETHERLANDS	PEMFC	CONTAINERIZED STORAGE OF COMPRESSED HYDROGEN	-	JACK-UP WTIV
82	**VEZ– VAPORETTO A ZERO EMISSIONI**	ITALY	PEMFC	-	-	WATER-BUS
83	**HYDROMER DREDGER**	FRANCE	FC	-	14 CREW PEOPLE	TRAILING SUCTION HOPPER DREDGER
84	**NYK SUPER ECO SHIP 2050**	JAPAN	SOFC	-	-	ECO SHIP

Table 4.1 Hydrogen use as a marine fuel.

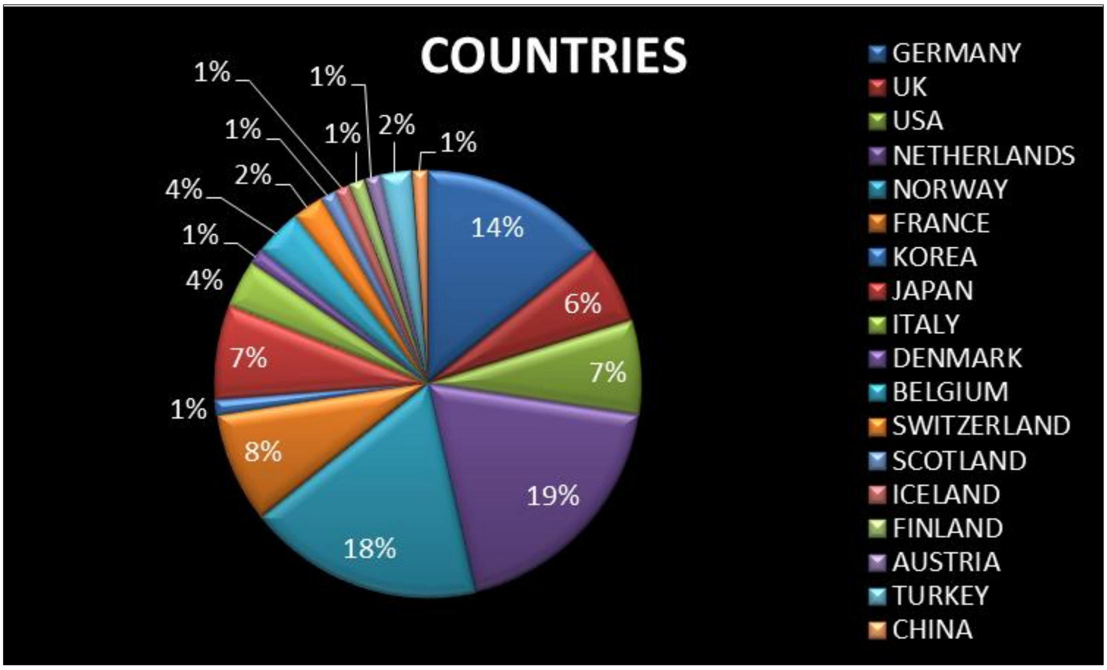


Chart 4.1 Countries with hydrogen as marine fuel projects.

From Pie 4.1 it can be observed that 18 countries have deployed projects with hydrogen as a marine fuel all over the world. Most important is that Netherlands, Norway and Germany have the biggest number of these projects with 19%, 18% and 14% respectively of projects that have been found after the research. Following France (8%), Japan (7%), USA (7%) and UK (6%) etc.

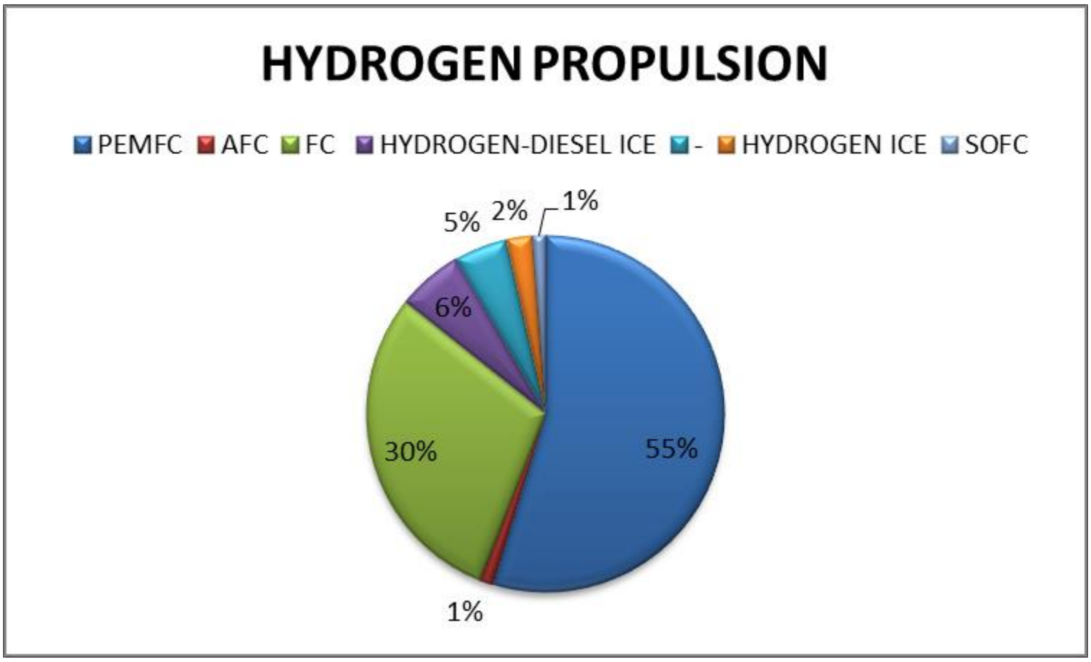


Chart 4.2 Type of hydrogen propulsion.

From Pie 4.2, it can be observed that 87% of the vessels that use hydrogen as a marine fuel are powered with FC systems of which 55% use PEMFC, 1% AFC and 1% SOFC. On the other hand, ONLY 6% of the projects use dual fuel (hydrogen-diesel) ICE and 2% hydrogen ICE. Finally, 5% of the projects do not clarify what is the exact propulsion type that they use.

According to table 4.1, the hydrogen storage onboard mainly focuses on compressed GH_2 at pressures between 200-500 bar with commonly use the 350 bar or storing hydrogen in the liquid form with a liquefied cryogenic hydrogen storage system or in solid form with metal hydrides like the $NaBH_4$. Storage location either can be in mobile or stable tanks, cylinders, type C tanks, or containerized, located on the deck or below the deck.

The vessels with hydrogen as a marine fuel are different types for many uses. The use of hydrogen in ships has been used to power submarines or AUV, water taxis, water-bus, ferries, ROPAX, RO-RO, passenger vessels, passengers and cars ferry, car ferry, crew-boat catamaran, shuttles, canal boat, tourist boats, cargo vessels, container vessels, fast vessels (fast ferry (HSC), high-speed passenger ferry, etc.), tugs, push boat, test boat, research vessels, yachts, leisure boats/sport boats. Hydrogen as a fuel has been also used for whale-watching ship, cruise ship, hydrofoiling trimaran, rescue boat, inland river self-unloading ship, supply vessel, offshore construction vessel, jack-up vessel (WTIV), trailing suction hopper dredgers.

Most of the 84 hydrogen-powered vessels are small size vessels. The only exception is about four vessels, which are a cruise vessel with 900 passengers capacity and a crew of 500 people, a potential ship with 1800 passenger capacity and 2300 lane meters car/truck capacity, a ferry of 600 passengers and a car ferry with a truck capacity of 30-96 and passenger capacity of 1150-1500. The passengers capacity of the rest vessels is ranking between 6-300 passengers.

5. Conclusions and recommendations

According to the findings, from 2000 onwards, the Netherlands, Norway, and Germany appear to have the most hydrogen-powered vessels with 19%, 18%, and 14% respectively. The preferred hydrogen propulsion system is fuel cells. More specifically, it is used PEMFC in most cases and hydrogen is stored either as compressed gas at 350 bar or in liquid form with a liquefied cryogenic hydrogen storage system or in solid form with metal hydrides. The vessels are small size ships with some exceptions and around 6-300 passengers capacity. The types of vessels that are powered with hydrogen are many with most of them to be ferries.

Therefore, hydrogen as a marine fuel seems to be a very promising method to power the vessels in order to reduce GHG emissions and meet the IMO's targets for the 2050 (reduce GHG emissions from international shipping by at least 50% by 2050). Many countries have already begun to deploy such vessels. Unfortunately, there are currently no regulatory requirements for hydrogen as a maritime fuel, so it is urgent to be implemented such rules as soon as possible since hydrogen as a marine fuel is very potential and has begun to expand fast, particularly in 2021.

Furthermore, it is known that the most abundant chemical element in the universe is hydrogen. Nonetheless, on Earth, hydrogen is created by the use of energy from other hydrogen-containing sources like nuclear sources, carbon sources or renewable sources, and it can power an entire economy. When the source of power is renewable, there are no CO_2 emissions from hydrogen (green hydrogen). A decrease in hydrogen production costs and an increase in hydrogen availability have the potential to make hydrogen the preferred fuel alternative choice for marine vessels. The cost of marine hydrogen will decline as more countries create hydrogen from renewable sources.

Hydrogen poses no more or lesser risk than other combustible fuels such as gasoline and natural gas. It is critical that the crew of a hydrogen-powered ship is taught on how to maintain a hydrogen system on board a ship as well as how to manage fire safety. Storage and availability are the two most expensive aspects of converting a vessel to hydrogen as a marine fuel vessel. Finally, it is worth noting that in 2021, MF HYDRA was announced as the ship of the year (Fig. 5.1) (Norled LinkedIn official page).

Figure 5.1 MF HYDRA (Norled)-Ship of the year 2021 (Norled LinkedIn official page).

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