HYDROGEN AS A MARITIME FUEL AND DESIGN OF A ZERO EMISSIONS PROPULSIVE SYSTEM

Joan Tardio Capdevila

Thesis to obtain the Bachelor's Degree in

Naval Architecture and Ocean Engineering

Examination Committee

Chairperson:	Prof. Ângelo Manuel Palos Teixeira
Supervisors:	Prof. Dr. Manuel Filipe Simões Franco Ventura
Members:	Prof. Tiago Alexandre Rosado Santos
	Prof. Dr. Manuel Filipe Simões Franco Ventura

September 2022

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DECLARATION

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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ACKNOWLEDGMENTS

I dedicate this Thesis to my family, which are my emotional support, especially my parents who have always helped me reach all I want in life and have given me unconditional love.

I want to express my gratitude to Prof. Dr. Manuel Ventura for being my supervisor, and the IST for being my home for these past months and giving me the best experience of my life. I would also like to thank the Facultat Nàutica de Barcelona for making me the person I am today, individually and professionally, and for giving me the opportunity to be a Naval Architect.

ABSTRACT

The recreational craft sector has seen an exponential growth in this past decade, but this market expansion is also seen in the impact on the environment, as this sector is not as regulated as others such as maritime shipping or automotive, thus giving us the responsibility to take action to shift towards more sustainable practices, innovation and to give rise to new technologies.

With this in mind, the need to have new solutions is imminent, and for this reason, in this master thesis it is addressed the use of hydrogen as an alternative fuel. Firstly, a study on the current situation regarding hydrogen on the recreational boat sector will be made. Later, features and characteristics of hydrogen as a fuel will be gathered as well as fuel cell specifics. Also, a hull will be designed in order to study the possible zero-emissions configurations for its propulsion.

To determine the power required, the calculation of the drag is needed. Once the power is known, a study will be made to determine the best way to propel the yacht without emissions, with electric motors and batteries, plus hydrogen fuel cells.

Finally, the results will be evaluated, in order to draw a conclusion regarding the power plant installed and hydrogen as an alternative fuel.

Keywords:

Hydrogen, Fuel cells, Ship design, Zero-emissions, Pleasure craft.

RESUMO

O sector das embarcações de recreio registou um crescimento exponencial na última década, mas esta expansão do mercado é também vista no impacto no ambiente, uma vez que este sector não é tão regulamentado como outros, tais como a navegação marítima ou automóvel, dando-nos assim a responsabilidade de tomar medidas para mudar para práticas mais sustentáveis, inovação e para dar origem a novas tecnologias.

Com isto em mente, a necessidade de ter novas soluções é iminente, e por esta razão, nesta tese de mestrado é abordada a utilização do hidrogénio como combustível alternativo. Em primeiro lugar, será feito um estudo sobre a situação actual relativa ao hidrogénio no sector das embarcações de recreio. Mais tarde, serão reunidas as características do hidrogénio como combustível, bem como as especificidades das células de combustível. Também será concebido um casco a fim de estudar as possíveis configurações de emissões zero para a sua propulsão.

Para determinar a potência necessária, é necessário calcular a resistência ao avanço. Uma vez conhecida a potência, será feito um estudo para determinar a melhor forma de propulsão do iate sem emissões, com motores eléctricos e baterias, além de células de combustível de hidrogénio.

Finalmente, os resultados serão avaliados, a fim de tirar uma conclusão sobre os sistemas propulsivos instalados e o hidrogénio como combustível alternativo.

Palavras-chave:

Hidrogénio, Células de combustível, Projecto de embarcações, Zero-emissões, Embarcações de recreio.

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ACRONYMS

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
BV	Bureau Veritas
CO_2	Carbon Dioxide
DMFC	Direct Methanol Fuel Cell
DNV	Det Norske Veritas
EBA	European Boating Association
GH_2	Compressed gas hydrogen
GHG	Greenhouse Gases
GL	Germanischer Lloyd
H_2	Hydrogen
HFO	Heavy Fuel Oil
IEC	International Electrotechnical Commission
IGF	International Gas Fuel
IMO	International Maritime Organization
ISO	International Organization for Standardization
LH_2	Liquefied Hydrogen
LiFePO4	Lithium Iron Phosphate
Li-ion	Lithium Ion
LNG	Liquefied Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MCFC	Molten Carbonate Fuel Cell
NO_x	Nitrogen Oxides
PAFC	Phosphoric Acid Fuel Cell

ACRONYMS

PLC	Programmable Logic Control
QRA	Quantitative Risk Analysis
R&D	Research and Development
SOFC	Solid Oxide Fuel Cell
SO_x	Sulfur Oxides
TWh	Terawatt Hour

SYMBOLOGY

Δ	Displacement
B	Beam
DC	Direct Current
DWL	Design Waterline
ft	Feet
h	Hours
hp	Horse Power
K	Kelvin
kHz	Kilohertz
kWh	Kilowatt Hour
Lh	Length of the Hull
LOA	Length Overall
LPM	Liter per Minute
m	Meters
mA	Milliamperes
min	minutes
MJ	Mega Joules
mm	Millimeters
T	Draft
t	Tons
wt%	Weight Percent
ºC	Degree Celsius

1. INTRODUCTION

1.1. Motivations

Recreational boating, being a very broad concept, can be defined as the activity of sailing on the water for pleasure either with a boat or through related nautical activities. This has been practiced in Europe throughout the centuries since it is such a contributing activity for everyone. Lately, the recreational craft sector has seen significant growth, as it is gaining popularity among society, and in consequence the sector has become an important economic source worldwide, and especially to the European Union, since it generates roughly €20 billion of annual revenue. Furthermore, there is no discussion in the fact that the recreational boat market has a lot of potential, but one of the major challenges to its bright future is the environmental impact connected with the greenhouse gasses (GHG) emissions footprint. In order for this sector to evolve towards a greener scenario, the need of focusing in the transition to low emission crafts is essential for its success.

Since the term sustainability appeared in the equation, the marine sector has focused its attention into producing a lower impact on the environment, so organizations such as the International Maritime Organization (IMO) have watched over and created requirements for the reduction of carbon emission for the maritime shipping industry, so companies have started to take action, for instance introducing scrubber systems to their fleet, which remove harmful materials from exhaust gases before they are released into the environment, or by transforming their power plants in order to reduce the emissions. Though, the organizations responsible of crating this requirements for the reduction of emissions have not taken into account the recreational sector whatsoever. For this reason, while the reduction of emissions from recreational crafts is key to eliminate impacts on coastal areas, the decarbonization of this sector will rely on further policy and legislation, since there are no clear GHG emissions targets yet. Nevertheless, it is clear that the future is green and it is important to act as soon as possible, for this reason more and more companies have opted towards this change, and alternative propulsion systems are being tested and added to the market, for instance electric, solar or wind power, and hydrogen. These alternatives help directly in reducing GHG emissions, and in consequence downsize one of the most concerning current issues, global warming.

Currently, the main problem with alternative fuels, regardless of fossil fuels, is the short autonomy plus the elevated prices of the systems. It is therefore, difficult for the market itself to raise the demand of this type of boats and systems, so in consequence, shipyards do not find it interesting to invest in these types of propulsions yet. Moreover, as there is not a high demand, the industry does not adapt, since the industry supply chain is dependent on consumer demand, furthermore there is no investments dedicated to infrastructure and technology availability to boost these alternatives fuels systems. Thus, it is crucial to create a good product, with great and innovative technology, to then increase the demand and draw attention to the industries for them to invest in these incoming technologies. Though, more research overall needs to be done previous to achieve the application of innovative technology, as systems for alternative fuels such as hydrogen are not as studied as they should be if the idea is to implement them in a short-medium term.

Of all the alternative fuels, hydrogen seems to be the most interesting solution to these problems presented, due to its great characteristics, and above all the solution with the highest potential for zero emissions, since to produce electricity from hydrogen, only water is created, which obviously does not cause any harm to the environment. For this reason, this thesis will present a substantial research on hydrogen as a maritime alternative fuel.

1.2. Objectives

The aim of this MSc Thesis is to design a propulsive system for a 40 feet yacht. In this case, the combination of hydrogen and electricity will be enough to provide energy for propulsion and other systems, which will generate zero emissions to the atmosphere, which is the main goal with this thesis, the propulsion with no emissions.

Regarding the propulsive plant, a hydrogen fuel cell will provide enough electricity to power the yacht at low speeds, in addition to recharging the batteries if necessary. To do this, hydrogen tanks will be installed inside the hull, as well as a battery bank. Therefore, the yacht will need a hydrogen and electricity connection in order to fill the tanks and charge the batteries. With the combination of the electricity stored in the batteries plus the electricity generated by the fuel cell, the yacht should be able to reach high speeds, and moreover to have a large autonomy. The objective in this case will be to create the best configuration of systems possible in order to reach a good performance in terms of speed and autonomy.

The yacht's hull design needs to be optimized in order to reduce as much as possible the drag of the boat, which can lead to a reduction on the fuel consumption and an improvement of the range, so this objective will be taken into account throughout the thesis. In addition, an optimization of the hull can facilitate the installation of alternative propulsive systems that require heavier storage or power systems, such as hydrogen-electric systems.

Also, in order to know about the current situation of hydrogen as an alternative marine fuel, a study needs to be made to fully understand the potential of this element. So with this objective in mind, different criteria will be researched, for instance its intrinsic characteristics and behavior, its safety requirements, the different storage systems in existence, its regulatory framework and also, its potential and barriers as an alternative fuel. In addition, a brief study on the current situation of fuel cells will take place as well.

The final objective is to draw significant conclusions regarding the propulsive systems designed, and compare them against traditional systems. Are alternative systems feasible and viable? Is hydrogen far away from conventional fuels? This are some questions that need to be answered at the end of this thesis, which will help to understand deeper the hydrogen current situation.

1.3. Structure of the Thesis

This thesis will be organized in six chapters and respective appendices.

Chapter 1 is the introduction of the thesis matter to be discussed, which includes the motivations, the main objectives of the work and its structure.

Chapter 2 contains a literature review or state of the art, in which several papers related with the main topics of this thesis are analyzed to display the current situation of the market regarding the technology of hydrogen as a fuel. The chapter also contains a study of hydrogen as an alternative fuel, where different topics are presented, such as its intrinsic characteristics and behavior, its safety requirements and risks, its forms of storage, its current regulatory framework and finally its potential and barriers as an alternative fuel. Also, a fuel cell technology study is presented, where its operation is explained, plus the different types in existence on the market and its regulatory framework.

Chapter 3 describes the basic steps of the hull's design process, such as the initial dimensioning, plus the generation of the hull shape and stability analysis with specific software.

Chapter 4 presents the selection of the yacht's propulsive system, with the different systems chosen.

Chapter 5, the study of the different configurations is made.

Finally, chapter 6 presents the main conclusions of the thesis and provides some recommendations for further work.

2. STATE OF THE ART

2.1. Background

Environmental challenges are set to be accomplished in the next decades for all sectors and industries. At this time, alternative fuels and energy sources are key as solutions for the reduction of GHG such as CO_2, NO_x or SO_x emissions. In the maritime domain, IMO, as a maritime organization, has taken the lead on the regulatory targets, regarding the emissions in the Annex VI (Regulations for the Prevention of Air Pollution for Ships) of MARPOL, the International Convention for the Prevention of Pollution from Ships (IMO, 2005). Currently, most of the commercial fleet converts chemical energy of fuels into thermal energy through combustion, which at a later stage is converted again into mechanical energy, which transferred by the shaft to the propeller, generates thrust, and so it creates the movement of the ship. The systems commonly used for this process are diesel and gasoline engines, or gas and steam turbines (Andersson et al., 2016). This marine propulsion systems have an impact to the environment due to their high GHG emissions produced by the combustion process. As seen in the Figure 1, in the initial stages of the maritime industry, ships were propelled by steam engines and turbines using coal as a fuel, which later on they were replaced with marine engines using fossil fuels, such as diesel, heavy fuel oil (HFO), or more recently, low sulfur heavy fuel oil. Nevertheless, marine propulsion systems have changed and are currently adapting to the new global requirements. Although HFO is the dominant shipping fuel, and diesel inboard and gasoline outboard engines are the most common for recreational craft, some alternative fuels have gained relevance, for instance liquefied natural gas (LNG), biodiesel, methanol, ammonia, biofuel, electricity and especially hydrogen (Andersson et al., 2016). In fact, many governments and energy professionals throughout the world feel that hydrogen has the potential to change the global energy landscape. The United Nations Energy Program is also keeping a close eye on developments in hydrogen-energy technology, as it has the potential to help the transportation industry transition to a more sustainable energy future (Al- Enazi, 2021).

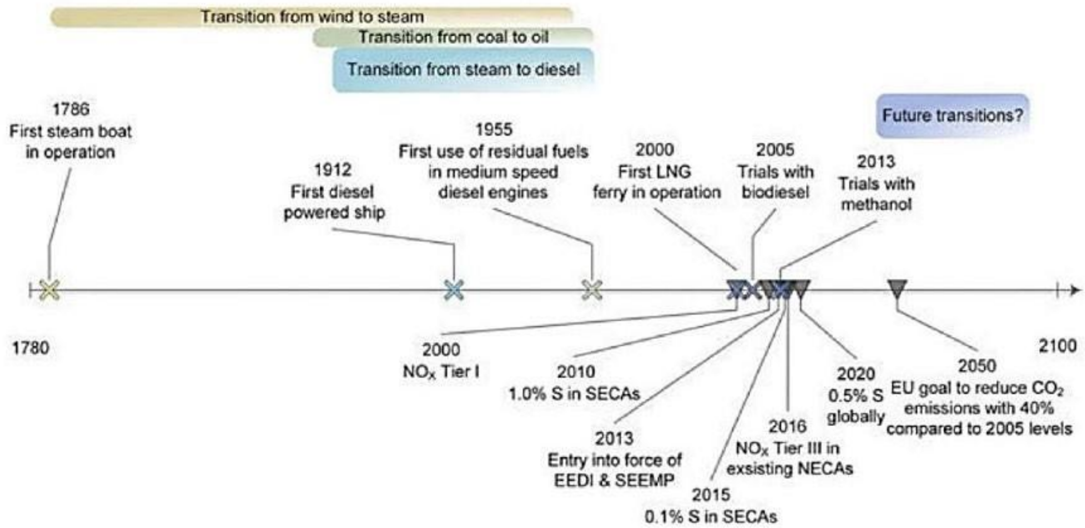


Figure 1. Transition of marine fuels from 1780 to 2100 (Andersson, 2016)

According to DNV (2021), hydrogen has the potential to become a popular solution in a variety of industries, since hydrogen technologies are gaining traction, and industries are expanding their investment in hydrogen solutions across the spectrum of expected hydrogen value chains. Actually, current global public spending on low carbon energy technologies, such as carbon capture and storage, renewable, nuclear, hydrogen, and fuel cell research and development amounts to $18.5 billion a year (Birol, 2019). The commercialization of hydrogen technologies is being accelerated by the European Union. Production related programs aim to enhance research in order to build a large-scale factory for demonstration purposes. This plant can produce hydrogen fuel as well as electricity on a large scale while also separating and storing CO_2 produced as a byproduct of the process. This will aid in the development of centralized and decentralized hydrogen infrastructure for both production and distribution; autonomous or grid connected hydrogen power systems; a large number of hydrogen-powered vehicles; and fuel supply infrastructure (Al-Enazi, 2021).

Because hydrogen is primarily in the form of water, it is not considered a primary source of energy like fossil fuels or solar, hydraulic, or wind energy, but rather a medium for storing and transporting energy, therefore an energy vector (Morante, 2020). While hydrogen as a fuel can help to ensure a sustainable global future, it is worth noting if hydrogen is not produced with green energy, since H_2 can only be classified as a clean fuel if the technology used to produce and consume it are powered by clean energy as well. In fact, hydrogen is divided into four categories; grey hydrogen, which is created from fossil fuels and natural gas processing, implying CO_2 emissions; blue hydrogen, when grey hydrogen is accompanied by carbon capture technology which reduce the CO_2 emissions; green hydrogen, where hydrogen is generated from renewable energy sources with zero emissions; and finally brown hydrogen which is produced by coal processing (Al-Enazi, 2021; ABS, 2021). Therefore, it is necessary in order to solve the GHG emissions problem, to decarbonize the whole process, from its production, to its transport, to finally its application for power generation. It is worth mentioning that some papers include brown hydrogen as part of the grey hydrogen, dividing hydrogen in only three categories. Though, in this thesis, only two types of hydrogen will be considered, the blue and green hydrogen.

Hydrogen's importance is increasing, since it is the only combustible that does not produce CO_2 during combustion, as it only produces water when combined with oxygen. Plus, several other reasons, such as its regenerative character as a fuel, considering the reserves are unavoidable; also, it is possible to store physical items in a relatively simple manner, such as compressed gas or liquid. These unique characteristics make it significant to overcome the challenges that exist, in order to build a renewable energy economy (Morante, 2020). Nevertheless, hydrogen's main purpose as an alternative fuel is the generation of electric power. The use of fuel cells is a solution to produce that power. Fuel cells are devices that allow electricity to be generated from the chemical energy of hydrogen and oxygen without the need for combustion. Instead, the electrochemical oxidation of hydrogen reaction is produced, which has a significant advantage over combustion in terms of efficiency. Innovative systems and technologies for the reduction of the percentage of emissions in traditional engines using fuel cells are being currently presented on the market. According to Ching et al (2021), fuel cell power systems are a good and attractive option due to their high energy efficiency compared to marine combustion engines. In fact, the use of fuel cells and hydrogen for marine applications have been recorded since the 1960s. McConnel (2010) registers 28 demonstration projects, most of them experimental but a few of them, which were applied to large ships such as offshore supply ships, ferries and submarines, including *Hydra*, the world's first electric fuel cell boat, which constructed around 2000, was powered by an electric motor and a 5 kW AFC system (Moraiti, 2022). Though it was in 2006, when the first hydrogen-powered leisure boat was constructed to participate in the Frisian Nuon Solar Challenge race on Netherlands; the *NX Hydrogen* gets its electricity from a 1.2 kW PEMFC and has four 200 bar tanks (FC, 2006). In 2007, in Germany, a hybrid boat named *Solgenia*, in which the hydrogen is produced by stationary photovoltaic cells, and the boat has 3x1.2 kW PEMFC plus 350 bar tanks for hydrogen storage (Moraiti, 2022). Later on, the *Nemo H2*, which was launched in December 2009 was the world's first canal boat powered by a hydrogen fuel cell. This prototype is powered by 2x30 kW PEMFC. The hydrogen is stored in 6 cylinders at 350 bar (Vogler and Sattler, 2016). During 2015, the *Kamine boat project* was developed in order to create safety guidelines for hydrogen fuel cell powered boats. The boat has 2x30 kW PEMFC, 60 kWh lithium-ion battery and 2x50 kW IPM motors (Moraiti, 2022).

More recently, in 2016 a hydrogen powered pleasure craft was created by Cheetah Marine; the 9.95 m catamaran did not use fuel cells, instead it featured a hydrogen internal combustion engine, which they called HICE (Pratt and Klebanoff, 2016). The boat has two Honda outboard motors, which burn hydrogen instead of petrol producing zero emissions, and twin tanks that hold 15 Kg of hydrogen at 350 bar. In the end, the project was a success since the boat completed the predefined route in less time than expected (Cheetah, 2016). Also in 2016, a hydrogen yacht from Germany called *Tuckerboot* was built. The yacht has 2x1.2 kW PEMFC, plus an electric motor and a battery. The hydrogen is stored on board in metal hydride containers (Moraiti, 2022).

Later, in April 2017 another hydrogen-powered vessel was launched by CEA-Liten, the *Energy Observer*, whose mission was to travel around the world with fully green energy autonomy. To do so, the boat includes 2 vertical axis wind turbines, solar panels, 2 electric motors plus lithium ion (li-ion) batteries, an electrolyzer and compressor, and finally a 22 kW proton exchange membrane fuel cells (PEMFC) and high pressure hydrogen (H2) tanks which can store 62 kg of hydrogen (Guilbert and Vitale, 2021). According to the designers, this vessel was created as a laboratory for ecological transition, and to advance and produce clean energy solutions (EO, 2017). The vessel was able to complete every tour, which was a success, until Covid-19 appeared and stopped the program.

During recent years, other hydrogen-powered boats have been developed, but in this case, their mission is sustainable luxury. The catamaran designed by the Swiss company *AQUON*, is a 19.5 m vessel with a combination of hydrogen fuel cells and Li-ion batteries; the compressed hydrogen stored in the tanks serve as a long-term energy storage, whereas the use of batteries provides with short-term electricity storage used for propulsion and onboard activities. Due to its length, the production of hydrogen on board is feasible, so with the energy produced by solar panels, an electrolyzer is able to generate green hydrogen which can be stored in the tanks, this way the vessel does not have the need to refuel hydrogen on port, giving it more autonomy (AQUON, 2020).

HYNOVA 40 is another interesting project. It is a 40 ft yacht propelled by two electric motors fed by the electricity stored in lithium iron phosphate (LiFePO4) batteries, and the electricity produced by the 80 kW Toyota PEMFC "REXH2", a solution developed by Toyota and Energy Observer Developments. This yacht has a cruise speed of 15 knots, but with the combination of the electricity stored in the batteries plus the production of the fuel cell it can reach a top speed of 25 knots (Hynova, 2020). Since the length of this yacht is 40ft, an installation of hydrogen production is not possible, as there is a lack of space for the machinery to be installed, furthermore the need of stopping at port and refueling is a must, which in addition with the low autonomy makes this a boat for day-time navigation only.

Finally, TU Delft Solar Boat Team, built the first flying hydrogen powered boat, the hydro foiling trimaran *Hydro Motion Project*. The boat has 30 kW PEMFC and the H_2 is stored at 350 bar tanks (Moraiti, 2022).

Table 1 presents a summary of the different boats mentioned is made, in order to analysis the similarities and differences between the different projects:

Table 1. Hydrogen boat projects review

Project	Year of Construction	Propulsive System	Storage System	Type of boat
Hydra	2000	Electric motor 5 kW AFC	Metal hydride	Ferry
NX Hydrogen	2006	1.2 kW PEMFC	200 bar tanks	Leisure boat
Solgenia	2007	3 x 1.2 kW PEMFC Photovoltaic cells	350 bar tanks	Research hybrid boat
Nemo H2	2009	2 x 30 kW PEMFC	6 x 350 bar cylinders	Canal boat
Kamine	2015	2 x 30 kW PEMFC 60 kWh lithium-ion battery 2 x 50 kW IPM motors	-	Test boat
HICE	2016	2 x Honda outboard motors that burn H2 instead of petrol	Twin tanks of 15 kg of H2 at 350 bar	Catamaran
Tuckerboot	2016	2 x 1.2 kW PEMFC Electric motor, battery	Metal hydride container	Yacht
Energy Observer	2017	2 vertical axis wind turbines Solar panels 2 x Electric motors Lithium ion batteries 22 kW PEMFC	High pressure tanks at 350 bar	Catamaran
AQUON	2020	Solar panels Li-ion batteries PEMFC	300 bar carbon tanks	Catamaran
HYNOVA 40	2020	LiFePO4 batteries 80 kW PEMFC	350 bar cylinders	Yacht
Hydro Motion	2021	30 kW PEMFC	350 bar cylinders	Hydro foiling trimaran

As seen in the existing hydrogen-powered projects, the combination of PEMFC and Li-ion or LiFePO4 batteries for ship applications is the most common. According to Markowski and Pielecha (2019), since 2000 most of the fuel cell projects for ships have used PEMFC, since they are powered with pure hydrogen and they have a high electricity production efficiency up to 65%. Regarding fuel cells systems, a fuel cell is an electrochemical device that generates electricity by utilizing the energy generated by the chemical reaction of hydrogen and oxygen. Because it is only involved with the generation of water and heat, this energy conversion is environmentally friendly. There are two types, high and low temperature, which are used in stationary systems and in transport respectively, for this reason, low temperature fuel cells, such as PEMFC, are the best candidates for naval applications related to hydrogen (Al-Enazi, 2021). High temperature fuel cells, for instance phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC), were seen back in the day as a promising option for the future, however, nowadays the PEM fuel cells are the more mature technology for these naval applications and also the ones in use (Vloger and Würsig, 2010). According with Hart et al. (2020) fuel cell activities increased in 2020, and there are now more marinized fuel cell options available, with higher range for smaller vessels. Cold ironing is being tested in shipyards, and ports are ideal cluster places for hydrogen. For hydrogen-based shipping applications in 2021, Ballard, CMR Prototech, Nedstack, PowerCell, and Proton Power obtained a lot of attention. Also, Toyota created a maritime fuel cell technology, which is currently being tested aboard the Energy Observer green catamaran. EODev (Energy Observer Developments), currently offers portable fuel cells, 1 MW range extenders, and a floating platform for H2 delivery in marinas (Hart et al., 2020).

Regarding hydrogen storage systems, they are divided into two categories, hydrogen-based and incorporated into other products. Hydrogen can be stored in a gaseous or liquid state, on the surface and inside of solids, or in hydrogen-carrying chemical compounds. The storage of hydrogen as a gas generally require high-pressure tanks at 350-700 bar, whereas the storage of hydrogen as a liquid requires cryogenic temperatures, as the point of ebullition of hydrogen at atmospheric pressure is -252,8 °C (Morante, 2020). As seen in the previous mentioned existing hydrogen powered boats, high-pressure tanks at 350 bar are the most commonly used within the analyzed projects, since this storage system is less complex, cheaper and less energy intensive than liquefied storage (IMO- Norway, 2021).

Overall, in the existing literature, hydrogen and fuel cell technology is seen as a potential solution to the GHG emissions produced by traditional engines, though it is still seen as an immature technology, specially applied to ships and moreover to recreational crafts. Some current barriers for hydrogen in recreational boats are the unfeasible option of carrying large quantities of H_2, the elevated prices compared to traditional fuels either with H_2 or the capital cost of the laborious installations, plus the power to weight issues caused by the low power and autonomy that gives such a heavy machinery (Burke et al, 2021). These are also safety barriers, since hydrogen is a dangerous gas due to its risk of explosion, and there is not enough safety studies about the safety of hydrogen on ships (Chen and Guan, 2021). In addition, for hydrogen-powered ships, neither the IMO, Flag States, nor Class Societies have satisfactory rules or requirements yet. For instance, DNV has Class rules, but none of them apply to hydrogen storage. Nevertheless, the IMO has started a process to create fuel cell regulations in the IGF Code. Also, the IMO's international regulation base points to a rigorous approval process equivalent to the DNV Technology Qualification process, which approval process is essential in order to show an equivalent level of safety when compared to traditional methods (DNV, 2021).

Nevertheless, a recent study from Mylonopoulos et al. (2022) affirms that if all the requirements, such as ventilation and gas detection, are considered, hydrogen systems can be used on ships safety wise.

Apart from the barriers on board, currently there is also a limitation of hydrogen refueling infrastructure, which needs to be considered for this technology to thrive. In fact, "*The decarbonisation of the recreational craft sector addresses not only the vessels but the wider infrastructure. This includes ports, harbors and marinas which will need upgrades to support electric charging and storage of alternative fuels*." (Burke et al, 2021). Furthermore, in the future years to come we will see if countries invest in this technology with the construction of refueling facilities. According to EBA (2015), Europe is expected to have 3,700 hydrogen refueling stations by 2030, which means that Europe is aiming towards an energetical change with hydrogen as a leading alternative fuel.

Currently, the construction of hydrogen powered vessels in a large scale is seen as a long term solution, since according to the literature, hydrogen technology still has a long way to go in order to be fully implemented, especially in the recreational craft sector, as it needs more research and development (R&D) overall to ensure the safety on the installations, plus the development of safety standards for handling H_2 onboard and also on land. Although hydrogen appears to be an ideal alternative fuel for power generation, there are several challenges to overcome such as advanced storage requirements and fire risk mitigation. In addition, for hydrogen to become a competitive alternative marine fuel, it may also face the challenges of availability and the high costs of production at scale and transportation infrastructure. Green hydrogen production needs to be more dominant as well. So, in order for hydrogen to be a clean alternative fuel, its production needs to be decarbonized, and more investment in clean solutions for hydrogen production must be made for hydrogen to thrive.

Finally, as of now, there are not enough systems available in the market for this type of technology, and the ones already commercialized are not as advanced as other conventional systems. In fact, in all the projects presented of hydrogen-powered boats, their power delivery is not even close to the power delivered by traditional engines. For this reason, it is currently difficult for shipyards to compete with the current models and give to the client the same performances. Furthermore, much effort on research need to be made in order to implement new zero emission solutions that can compete with conventional engines, in terms of performance, capital cost and commodity, otherwise, it is very difficult for these systems to thrive in a world where conventional engines are evolving in an exponential way.

2.2. Hydrogen as a Net-zero Carbon Alternative Fuel

Regarding the type of fuel, it has been decided that hydrogen fuel cell technology will be used for the study of the design. As seen in the literature of previous chapters, hydrogen has a great potential as an alternative to fossil fuels, so in this chapter a further study on why hydrogen as an alternative fuel can be the best option will be discussed.

Hydrogen can be found as a molecular form most of the time, for instance as a compound of either water or methane, being the ninth most abundant element on earth. To acquire pure hydrogen the element must be separated from these compounds. Its properties help this element to be a good replacement for traditional fuels, since hydrogen produces zero emissions plus it is harmless and non-toxic; in addition, hydrogen is characterized by having the highest energy content per mass at 120.2 MJ/kg, compared to other marine fuels, for instance outperforming marine gas oil by 2.8 times. As a result, hydrogen as a fuel can boost the efficiency of an engine and help reduce the fuel consumption. Also, its low density makes it an easily dissipated molecule in case of a leakage. However, its high flammability and potential for combustion can raise unease regarding safety, and due to its lower volumetric energy density, liquid hydrogen requires four times more space than MGO and twice as much space as liquefied natural gas (LNG) for an equivalent amount of energy transported (ABS, 2021). In fact, the volumetric energy density of the H_2 varies depending on the storage form, for instance, liquefied hydrogen (LH_2) has a volumetric energy density of 8.5 MJ/dm^3, which is 4 times lower than HFO (35 MJ/dm^3); compressed hydrogen (GH_2) at 700 bar has a volumetric energy density of 4.5 MJ/dm^3, 8 times lower than HFO, while GH_2 compressed at 300 bar is 12.5 times lower than HFO (2.8 MJ/dm^3), so overall, hydrogen has a much lower volumetric energy density than HFO no matter the form of storage (IMO- Norway, 2021).

Hydrogen, as an energy vector, can be commercially produced by a variety of processes, though, hydrogen cannot be seen as a clean alternative fuel if not obtained from renewable sources or with low GHG emissions. Furthermore, the best way to do so is by obtaining it from electrolysis, which is an electrochemical process based on the dissociation of the water molecule by direct current into hydrogen in the cathodic zone and oxygen in the anodic zone (Nikolaidis and Poullikkas, 2017). The process of electrolysis needs energy, and this energy must be from renewable sources in order to ensure a sustainable production of hydrogen.

Depending on how the low emissions hydrogen is produced two types of hydrogen can be described:

Table 2. Types of low emissions hydrogen (Mathey, 2022)

Blue Hydrogen	Green Hydrogen
Natural gas	Renewable electricity
Advanced gas reforming (CCS)	Electrolysis

Blue hydrogen is produced from natural gas, by a process called steam methane reforming, which releases CO_2, although the carbon released is captured and stored (Brunel, 2021).

Green hydrogen is made by electrolysis, which must be powered by renewable energy sources. Green H_2 production is not yet very widespread, hence hydrogen has great potential as a net-zero carbon alternative fuel but it needs a wide investment regarding its production, as in order to fulfill the GHG emissions requirements, the hydrogen production needs to be from renewable energy sources so at least the majority of the hydrogen production could be green hydrogen. Solar, wind or nuclear electricity generation could be the energy renewable sources that produce the sufficient energy for this process.

More and more countries are betting for hydrogen as the future fuel. Over 200 projects have been announced by over 30 countries, with a total investment of $300 billion. For instance, the European Union, has established a clean hydrogen alliance and is creating the so-called hydrogen valleys, which utilize the North Sea's offshore wind potential to power electrolyzes. The longer-term strategy calls for transporting hydrogen throughout the continent via the network of natural gas pipelines already built (Brunel, 2021). Other countries like Australia or Saudi Arabia have shown their interest to enter this market, therefore this shows a clear intention worldwide for hydrogen as a global fuel.

Figure 2 shows the number of blue and green hydrogen projects in Fitch Solutions Hydrogen Projects Database over 2021.

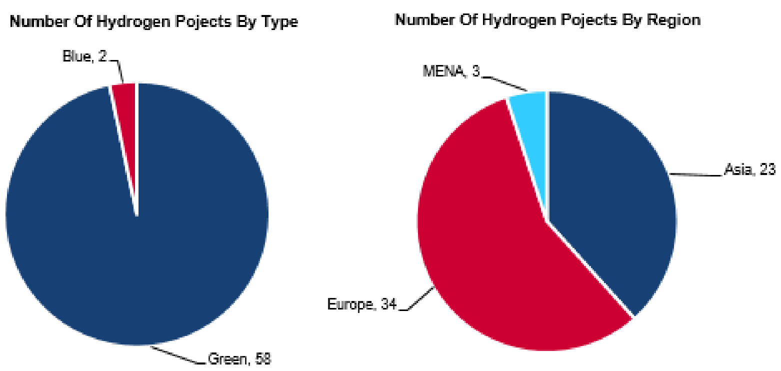


Figure 2. Green and blue hydrogen projects.
Source: https://www.offshore-energy.biz/green-and-blue-hydrogen-investments-to-jump-in-2021/

2.2.1. Hydrogen Safety

One of the main issues regarding hydrogen as a fuel source is its safety issues due to its natural behaviors. The primary safety concerns for this element are its flammable properties and range which also increases when mixed with pure oxygen. In addition, these characteristics cause a potential of combustion when the conditions are met (ABS, 2021).

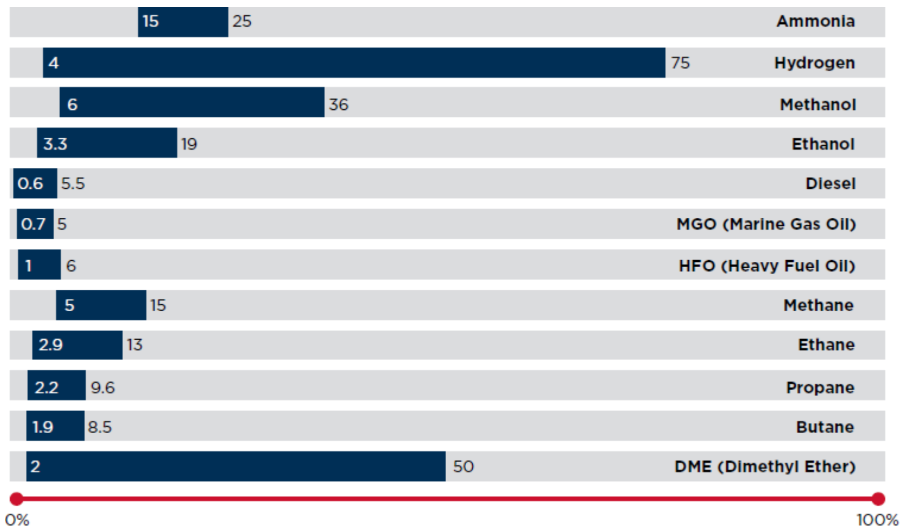


Figure 3. Flammability range in % of volume of gas in air (ABS, 2021)

As seen in Figure 3, which shows the gas flammability ranges in % volume with air, hydrogen has a large flammability range compared to other fuels. For instance, diesel has a range of 0.6- 5.5% in air, while hydrogen presents the largest range of them all from 4% to 75%, which means a quick formation of flammable gas mixture. Though, hydrogen leaks in open areas are expected to dissipate rapidly due to its low density, but if leaked in enclosed spaces it can be a serious fire hazard because of its flammable character and its low activation and ignition energy, which also makes hydrogen burn extremely quickly compared to other gasses.

With this in mind, the best thing to do is to eliminate the possibility of hydrogen concentration, that can be accomplished with a correct management of the gas and a proper ventilation. In addition, it is important to ensure that all hydrogen handling equipment is protected against the accumulation of electrical charges and potential sparks to prevent the ignition of hydrogen, since the flow of hydrogen can create electrostatic charges that can cause sparks and ignition of flammable concentrations of hydrogen; furthermore, all electrical systems used in the fuel cell area must be certified explosion-proof in order to mitigate any ignition possibility inside this hazardous area (Morante, 2020).

In case of a fire produced by the initial concentration of hydrogen, the best options are dry chemical extinguishers or carbon dioxide extinguishers (ABS, 2021). Also, in case of the spreading of the fire, the need of a water cooling system for the contained hydrogen is required, in order to prevent the hydrogen tanks of heating up and reach the explosive temperature limit, plus a pressure relief system, which should be also installed to protect the contained hydrogen from over-pressurization. However, the areas carrying hydrogen in tanks should be insulated so the fire can't get easily in contact with different compartments. Other solution would be to storage the high-pressure hydrogen tanks in the open deck, this way, leaks can be dispersed rapidly in the air. Although, this can bring some problems such as an increase in difficulty in detecting gas leaks, a reduction of the boat's stability, due to a heavy weight at a higher position, and finally a lack of protection from weather, corrosion and possible impacts (ABS, 2021).

2.2.1.1. Gas Detection

Regarding the detection of hydrogen leakages, according to ABS (2021) the best option would be to implement leak detection strategies within the hardware, for example a pressure monitoring system which could analyze the gas flow parameters indicating a possible leak. The detection of hydrogen gas in the hazardous areas by sensors is also a good option but can be not as practical as the previous mentioned since hydrogen could move away from the sensors in a area of transient airflow.

In small vessels where the fuel cell enclosed area is relatively small, sensors could be the best option in order to detect any H_2 leakage. Point gas detectors could be a good solution, its function is to detect gas concentrations and give an alarm or a signal for automatic shutdown in case of hydrogen concentration. Also, another solution could be line gas detectors, which detect a change in the gas density along a line between two sensors, and in case of a difference in the common density, an alarm is set as well as the previous sensors (ABS, 2021). However, for small leaks of gas in well ventilated zones, point gas detectors may not detect a hydrogen leak due to the low concentration. For this reason, acoustic gas detectors could be the best option as they are able to detect small concentration of gas, detecting a small leak that can develop into a serious risk, therefore it is important to detect leaks at early stages in order to mitigate the problem fast. These elements should be located in the ceiling and close to possible leak locations (ABS, 2021).

2.2.1.2. Ventilation

It has been mentioned that the best way to reduce the possibility of gas concentration is by having a proper ventilation system that is able to create an elevated airflow to dilute any H_2 leak and produce the extraction of the gas. Any space with circulating hydrogen must have a ventilation system, for instance the fuel cell space, where the ventilation of such space is key to prevent any formation of flammable gas consequent of a pipe leakage. According to DNV (2021) the ventilation rate in the room should be specified according to the possible leakage scenario that may occur in the room, thus it can be ensured that a dimensioned leakage scenario should be diluted by ventilation so that an explosive atmosphere could not be possible. Since in this particular boat the room with ventilation needs is a small space, the exchange of air needs to be at a greater rate than a large room, since small rooms can develop a dangerous cloud of gas with less of it, so provided the same amount of leaked gas, the smaller room will need to change the air at a greater rate.

Other thing to keep in mind is the ventilation arrangement, as the air flow created by the ventilation system should provide a circulating air with as few dead zones as possible and also without the recirculation of air (DNV, 2021). Considering that hydrogen is lighter than air, in case of a small leak, a concentration of gas can be trapped at the ceiling. For this reason, it is beneficial to have the extraction in the ceiling and the inlet close to the floor. Furthermore, with a strong airflow inside the room, hydrogen can be ejected or at least more distributed across the room reducing this way the risks (DNV, 2021).

Hence, a well distributed inlet and outlet ducts are keys for a well designed ventilation system, reducing the explosion risk and increasing the gas dilution efficiency. However, these systems need to be reliable to avoid any danger in case of any leaks, so good inspections and maintenance needs to be carried out to ensure its good operation. Broadly, as long as the outlet guides the gas to a non-hazardous area and the inlet is in a location where uncontaminated air can flow properly, the ventilation system would have a optimized distribution (DNV, 2021).

2.2.1.3. Fire Control

As seen so far, working with hydrogen entails several risks, especially due to its high flammability range, for this reason a fire control and protection strategy is a must when handling this gas, in order to prevent the fire from speeding up and reach other parts of the boat.

In case of small hydrogen fires, which would be the potential situation in a 40 feet recreational boat, the best way to extinguish the fire is by dry- chemical extinguishers or with CO_2 (Pratt and Keblanoff, 2016). However, an optimal strategy would be to stop the ventilation when a fire is detected, this way the airflow of the room would be stopped and the fire eventually extinguished (DNV, 2021). Fire control systems and manual firefighters, such as water sprays or sprinklers, is a good option to cool down the heated area and minimizing the risk of explosion, especially when the ventilation of the room cannot be shutdown. However, the best thing to do in a fire, is to shut off the H_2 supply first, so generally the fire should be extinguished after the hydrogen flow can be stopped. In addition, water sprays could be used to extinguish any derived fire and prevent it to spread across other areas of the boat (DNV, 2021).

According to DNV (2021), preventive measures for fire control and protection can include automatic or manual hydrogen flow and ventilation shutdown systems, as well as sprinklers, water sprays systems and dry-chemical extinguishers.

In conclusion, proper fire detection and suppression systems for hydrogen installations should be provided. The best protocol is to have an strategy plan which in case of a fire can be followed by the people onboard. An optimal strategy to follow would be to first cut the hydrogen supply to ensure no H_2 is circulating through the pipes; afterwards, the best thing would be to stop the ventilation in order to suffocate the fire and use a dry- chemical extinguisher to extinguish any fire on the installation plus manual firefighters to cool down the affected area by the fire. Hydrogen as a fuel can be dangerous and present several risks, but with a proper safety plan and the proper equipment, it can be handled properly.

2.2.2. Hydrogen Storage

Most hydrogen fuel applications store H_2 gas in tanks under pressures between 350 and 700 bar (Morante, 2020). In order to increase the density of the gas, an insulated pressure vessel can be used between ambient and cryogenic temperatures and between atmospheric pressure and high pressure, depending on the technology or material used for the insulation and resistance of the container. Since hydrogen has a small molecular size, gas can disperse through materials, including the walls of the containment systems, and also certain liquids or other solid materials over time to achieve center of gravity. Furthermore, hydrogen must be stored in suitable materials to minimize permeability and reduce the loss of hydrogen contained in (DNV, 2021).

There are a few hydrogen storage systems, which allow practical, long-term energy storage without loss over time. However, the main challenge of this storage comes from the low density per unit volume. For this reason, different methods are used to increase the volumetric density, such as compressing, liquefying or incorporating hydrogen on the surface or inside other chemical compounds (Morante, 2020). Storage techniques are divided into two main groups, in the form of hydrogen or incorporated into other compounds. Hydrogen can be stored in a gaseous or liquid state, on the surface and inside solids, or in hydrogen-bearing chemical compounds (synthetic methane, methanol, ammonia, etc.). Storing hydrogen in a gaseous state normally requires a high-pressure vessel (350-700 bar), while storing it in a liquid state requires freezing temperatures, since the boiling point of hydrogen at atmospheric pressure is - 252.8°C (Morante, 2020).

2.2.2.1. Compressed Hydrogen Storage

Compressed hydrogen is mainly used for storage in vehicles, where refueling stations have high-pressure tanks. For example, liquid hydrogen has a volumetric density of 8 MJ/L compared to 32 MJ/L for gasoline. This implies that a larger volume of hydrogen is required for gasoline- like energy storage. Hydrogen storage remains a challenge, especially for transportation applications where the available volume is limited compared to stationary applications where large volumes of compressed gas cylinders may be of little importance (Pratt and Keblanoff, 2016).

Compressed hydrogen gas tank storage is the most mature technology according to Morante et al (2020). It includes compressed hydrogen tanks at nominal operating pressures of 350 and 700 bar. Compressed hydrogen is typically stored at room temperature, while other types of storage, such as cold compressed hydrogen at temperatures above - 123 °C, are being studied to obtain higher hydrogen densities at lower temperatures. Similarly, compressed hydrogen tanks are classified according to material of construction and maximum allowable pressure and Table 3 provides a summary of the features for each type of compressed hydrogen storage:

Table 3. Types of compressed hydrogen storage

Type	Materials	Typical Pressure (bar)	Cost (€/kg)	Gravimetric Density (wt%)
I	All-steel	300	80	1.7
II	Fiberglass hoop wrap steel liner	200	83	2.1
III	Composite full wrap (all carbon), metallic liner	350 - 700	670	4.2
IV	Fiberglass/carbon full wrap, plastic liner	350 - 700	605	5.7

Below, the configuration of each type of high pressure cylinder can be seen in detail:

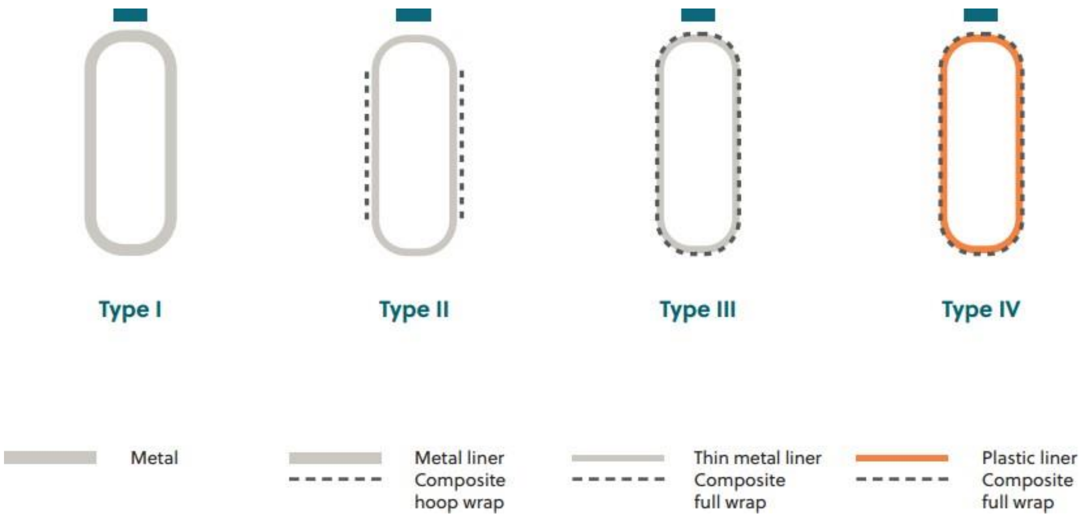
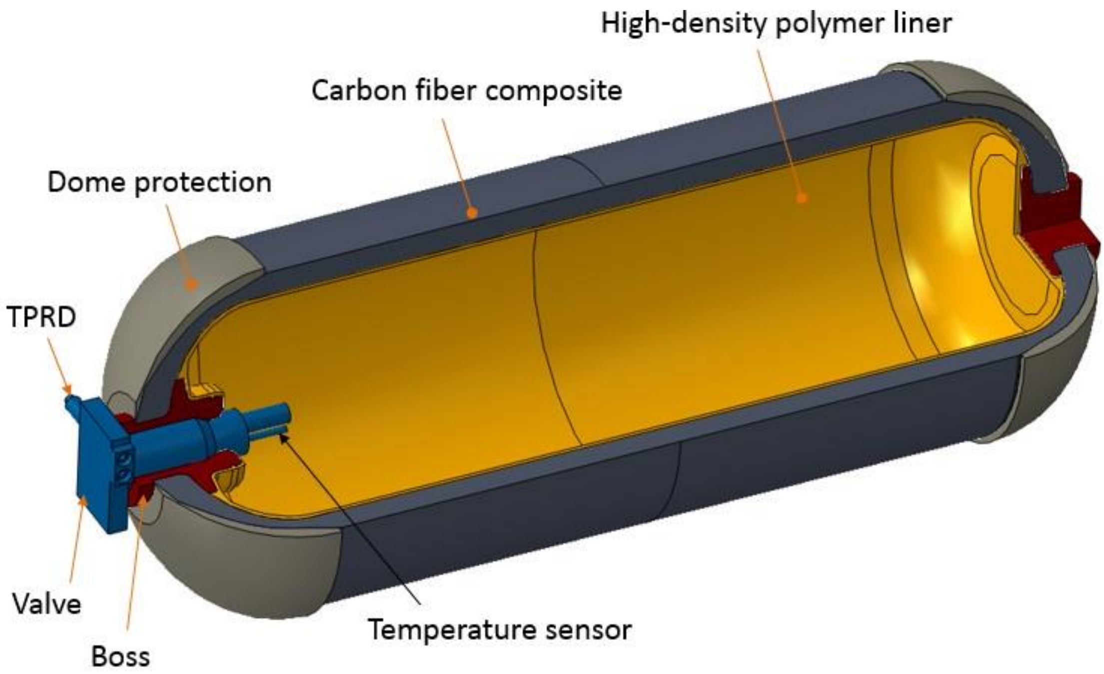


Figure 4. Types of high-pressure cylinders (Su & al, 2021)

As seen in Figure 4, both type III and IV tanks, are lighter and have thinner walls compared to the other types, thus they main application is mobility and H_2 transportation.

The type IV composite overwrapped compressed hydrogen tank has the following elements shown in Figure 5:



TPRD = Thermally Activated Pressure Relief Device
Credit: Process Modeling Group, Nuclear Engineering Division. Argonne National Laboratory (ANL)

Figure 5. Components of a pressurized hydrogen storage tank

2.2.2.2. Liquefied Hydrogen Storage

Liquefied hydrogen or LH_2 needs to be stored at a cryogenic temperature (-253 ºC), for this reason its application as a fuel for vehicles is still under development. This option of storage is seen as the most efficient one in terms of energetic density per volume (Morante, 2020), hence low pressure liquid hydrogen is used mainly for storage applications and large scale transportation.

Hydrogen liquid tanks are designed with the purpose to retain a cryogenic liquid, furthermore the tanks needs to be properly sealed and isolated in order to prevent the transfer of heat with the exterior, since if a transfer of heat existed, the internal pressure could increase and consequently the hydrogen could escape, inducing to the known boil- off phenomenon (Morante, 2020). Also, according to Pratt and Klebanoff (2016), when LH2 is stored in metallic tanks, hydrogen atoms can diffuse into the bulk of the material, and accumulate at defect sites in the presence of material strain and form brittle metal hydrides such as FeH_2 and CoH_2, which can lead to small cracks on the surface and eventually a material failure.

The liquid hydrogen storage tanks have the elements shown in Figure 6:

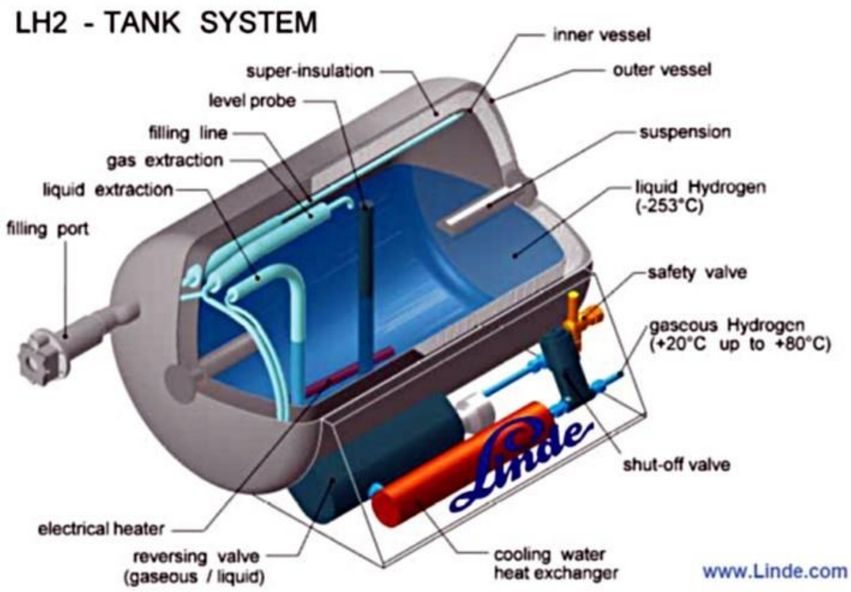


Figure 6. Liquid hydrogen tank
Source: Linde Group

In conclusion, according to Rivard (2019), liquid hydrogen's thermodynamic properties make it less appealing for movement, since its low storage temperature of 253ºC is a problem due to the boil-off losses, plus, although liquid hydrogen tanks are not required to resist high pressure, they must be well insulated, resulting in reservoirs with thick walls. Finally, the expense of liquefied hydrogen is high, both in terms of energy and equipment.

2.2.2.3. Storage of Chemical Materials

The storage of chemical materials refers to the covalent bonding, either solid or liquid, of compounds which contain a high density of hydrogen. It is similar to how the nature stores and uses hydrogen through biochemical processes in which hydrogen is liberated and recombined to generate chemical compounds. Dehydrogenation of hydrogen in chemical materials can be done either by reacting with water or by adding heat to the mixture. For instance, the ammonia borane (NH3BH3) has attracted a lot of attention as a chemical hydrogen storage material due to its high hydrogen density, environmental stability, lack of toxicity, and high solubility in common solvents (Morante, 2020).

Diverse metals and alloys, such as magnesium, titanium, iron, manganese, nickel, and chrome, create metal hydrides in the presence of hydrogen. Hydrogen atoms are encapsulated within a metal structure, resulting in higher volumetric densities when compared to compressed and liquid hydrogen. As a result, metal hydrides can absorb and release hydrogen in a reversible manner without causing significant damage. However, these hydrides are sensitive to substances such as oxygen and carbon monoxide, both of which reduce the hydrides ability to absorb hydrogen (Morante, 2020).

Other more novel methods are based on carbon nanotubes, which are made up of hexagonal carbon networks that are curled and closed forming tubes. These are light, porous, and highly resistant systems that allow the storage of large amounts of hydrogen. In terms of hydrogen storage capacity, carbon nanostructures can store up to twice the amount of hydrogen as liquid tanks. However, the majority of hydrogen evaporates at room temperature, but nano tube storage is possible at extremely low temperatures, below -196°C (Morante, 2020).

At the moment, the main advantage of using hydrides or carbon nanostructures, is its greater storage security, though it has not compensated for their disadvantages, such as the lower storage density in the case of hydrides, the potential degradation with time in both cases, higher costs, or a lack of long-term reliability. As a result, the use of these options is still in its early stages, and the various industries involved have chosen compressed or liquefied hydrogen as the hydrogen storage system (Morante, 2020).

2.2.2.4. Overview

Table 4 shows an overview of all the existing hydrogen storage methods, plus its basic characteristics (Rivard, 2019).

Table 4. Hydrogen storage methods overview

Method	Gravimetric Energy Density (wt%)	Volumetric energy density (MJ/L)	T (K)	P (bar)	Remarks
Compressed	5.7	4.9	290	700	Current industry standard
Liquefied	7.5	6.4	20	0	Boil off issues
Cold/cryo compressed	5.4	4.0	40-80	300	Boil off issues
MOF	4.5	7.2	78	20-100	Great densities only at low temperatures
Carbon nanostructures	2.0	5.0	289	100	Possible at extremely low temperatures
Metal hydrides	7.6	13.2	260-425	20	Requires thermal management system
Metal borohydrides	14.9-18.5	9.8-17.6	130	105	Thermal management required
Kubas-type	10.5	23.6	293	120	-
LOHC	8.5	7.0	293	0	Not suitable for mobility
Chemical	15.5	11.5	298	10	Requires SOFC fuel cell

2.2.3. Regulations for Hydrogen as a Maritime Fuel

According to DNV (2021), maritime regulations and rules exist on three levels, which are international regulations developed by IMO, national regulations and class rules. The main objective of the codes and standards presented is to assist and support the approval process for hydrogen-fuelled vessels. The use of some of these standards may be requested by a Class Society or the Flag State, and some may be required as part of the approval process for specific components.

The safe use of any fuel depends on the prevention of situations where all three elements of combustion are present: ignition source, oxidizer agent and fuel. Some properties of hydrogen require additional control systems to ensure its safe use. The International Association for Hydrogen Safety (Hysafe, 2021) has established itself as a reference for all these issues. Its mission is to facilitate international coordination and provide support to organizations, industry and governments. Safety standards for hydrogen use vary depending on whether they are open spaces or enclosed spaces. Regulations and standards serve different purposes, while regulations are legally restrictive and compliance is mandatory, standards are voluntary and based on technical safety criteria, agreed upon by the industry. With emerging technologies, standardization may precede regulation, once there is substantial knowledge of the technology. However, nowadays there is no regulatory requirements available specifically for hydrogen as a marine fuel according to IMO- Norway (2021).

Regulations, standards and guidance about hydrogen can be seen in Table 5:

Table 5. Hydrogen regulations, standards and guidance (IMO- Norway, 2021)

Organization	Documentation	Status/Comment
IMO	IGF Code	Current edition does not cover neither H_2 storage or as a fuel. This must follow the design approach in accordance with SOLAS Regulation II-1/55. IGC and IGF Codes cover only LH_2 storage.
ISO	ISO/TR 15916:2015	Guidelines for the use and storage of GH_2/LH_2. Safety concerns, hazards and risks, H_2 safety relevant properties description.
ISO	ISO 20519	H_2 bunkering and port regulations for H_2 bunkering. Under preparation for its final publication.
ISO	ISO 14687	H_2 purity regulation.
DNV GL Rules for Classification	Ships- Part 6 Chapter 2 Section 3- Fuel Cell Installations	This can be used to classify ships with fuel cell technology.
Bureau Veritas	NR 547	Requirements for the arrangement and installation of fuel cell power systems on board ships
Bureau Veritas	NR 529	Incorporates text from the IGF Code regarding ships using low-flashpoint fuel

As said, there are no regulatory requirements for hydrogen as a marine fuel. However, SOLAS, has begun to address this topic with a structured design process, known as the *Alternative Design*, which is based on risk assessments, for instance a hazard identification study or HAZID, technology qualification, quantitative risk analysis (QRA) and explosion risk analysis, in such cases where a vessel deviates from the prescribed rules (DNV, 2021). The *Alternative Design* approach tries to include alternative fuel regulations even though they are not specifically in the International Gas Fuel (IGF) Code, since it does not contain specific requirements for fuels other than LNG; so alternative fuels like hydrogen could be used if its safety levels are proven at the same level that with traditional fuels. According to DNV (2021), the IGF Code Part A states that a low- flashpoint fuel, such as hydrogen, can be used as a maritime fuel, as long as the systems are designed in accordance with the *Alternative Design* approach, which means that the systems are as reliable and safe the systems used in a conventional ship. 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) (Moraiti, 2022).

According to Moraiti (2022), the risk equivalence compared to conventional vessels must be demonstrated by the SOLAS regulation II-1/55, and later it must be approved by the administration. SOLAS regulation II-1/55 refers to the process specified in MSC.1/Circ 1455 (MSC.1/Circ 1455, 2013; DNV, 2021). This process is based regarding risk and safety, and is split in two phases, the preliminary design and the final design, which are displayed in the following figures (7 and 8) by (DNV, 2021).

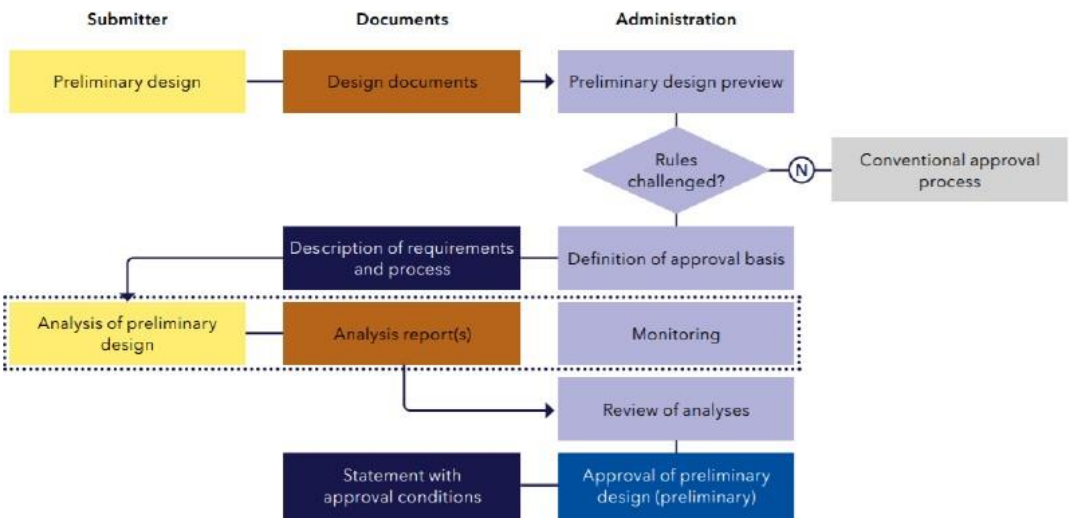


Figure 7. Overview of the approval procedure for preliminary design required according to the Alternative Design approach (DNV, 2021)

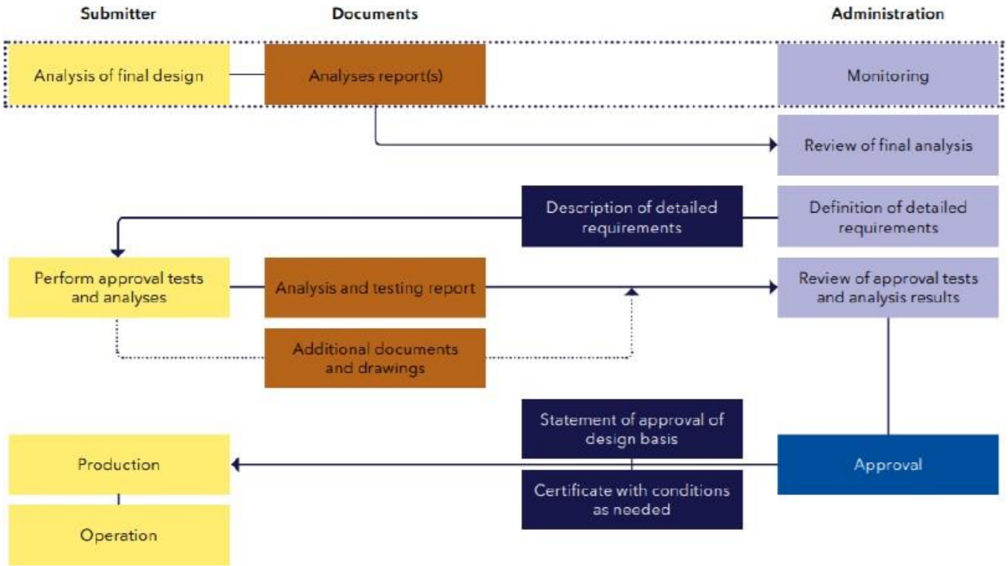


Figure 8. Overview of the approval procedure for final design required according to the Alternative Design approach (DNV, 2021)

According to DNV (2021), the main purpose of the IGF Code Part A and the *Alternative Design* approach is for hydrogen systems to present the same level of safety, reliability and dependability as new conventional power systems. As mentioned in previous chapters, hydrogen as a fuel can present several risks, therefore, since current hydrogen fuel systems are immature for maritime applications and there is no adequate regulatory framework, a quantitative risk analysis is needed in this kind of installations. In fact, DNV (2021) has proposed the steps to follow in the process towards the final approval for hydrogen-fuelled ships, which can be seen in Figure 9:

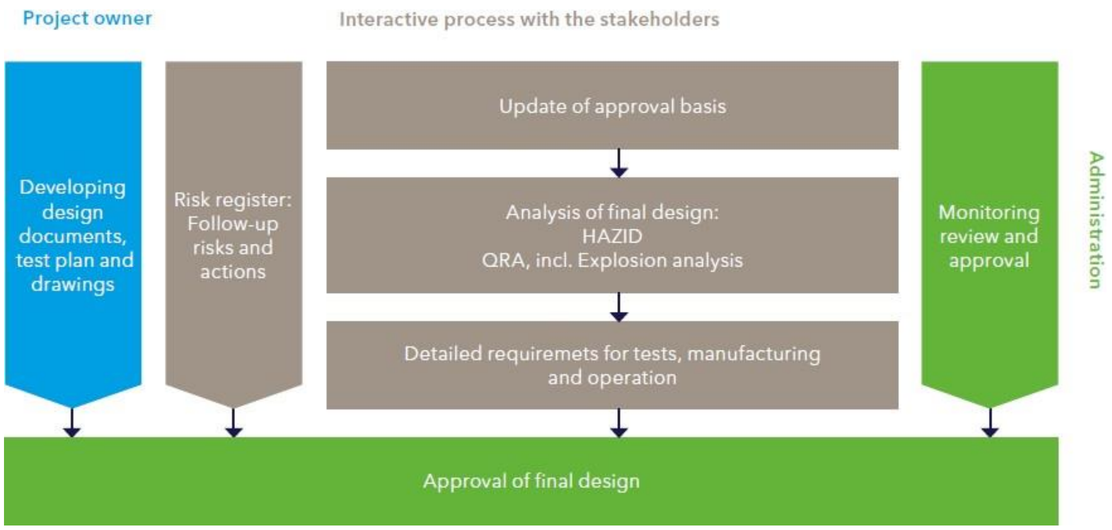


Figure 9. Proposed steps in the process towards final approval for hydrogen-fuelled ships (DNV, 2021)

For a long time, hydrogen has been employed all over the world as an industrial. Hence, there are standards and rules in place for the industrial use of hydrogen, and some of them may be applicable to the use of hydrogen as a fuel for the maritime sector. The American Society of Mechanical Engineers (ASME) and the American Petroleum Institute (API) are the most widely utilized standards in the maritime industry. Other standards, such as EU directives and standards, may be employed based on geography. EU directives and standards, for example, may be applied within the EU. The use of ISO and IEC standards in the introduction of hydrogen as a ship fuel is equally important, since these two organizations focus on the development of global standards and generic protocols (DNV, 2021).

A resume of the international hydrogen standards is given by DNV (2021), which is presented in Table 6:

Table 6. International hydrogen standards (DNV, 2021)

Organization	Documentation	Comment
ISO	ISO/TC 197- Hydrogen technologies (TC)	Standardization in the field of hydrogen generation, storage, transportation, measurement, and usage systems and equipment
	ISO/TC 220	Standard for cryogenic insulated storage tanks used to store and transport refrigerated liquefied gases on land. It also covers vessel design and safety, gas/material compatibility, insulation performance, and equipment operational requirements.
	ISO 19880-3:2018	Gaseous hydrogen and fuelling stations
	ISO 26142:2010	Hydrogen detection apparatus for stationary applications.
	ISO 19885 series	H_2 gas fuelling protocols for hydrogen fuelled vehicles. Some parts can be applied to the bunkering of maritime vessels.
	ISO 19886	LH_2 fuelling protocols.
	ISO/TR 15916	Safety properties and related considerations for hydrogen.
	ISO15649:2001	H_2 piping network.
	ISO 19882:2018	Pressure relief devices for compressed hydrogen gas.
IEC	IEC/TC 105 Fuel Cells	H_2 energy and fuel cell technology.
	IEC 60079-10-1:2015	Standard that covers the classification of areas where flammable gas concentrations may cause an ignition hazard.
ASME	ASME B31.12	Hydrogen piping and material compatibility

CGA	CGA G-5-2017 Hydrogen	Proper handling and use of hydrogen.
	CGA G-5.4-2019 Standard for Hydrogen Piping Systems at User Locations	Principles recommended for compressed hydrogen gas and liquefied hydrogen piping systems.
	CGA G-5.5-2014 Hydrogen Vent Systems	Design guidelines for hydrogen vent systems for compressed gas H_2 and liquefied H_2 systems.

In conclusion, as seen in the Table 6, there are a variety of rules regarding hydrogen matter, such as storage, transportation, usage of the systems and equipments, fuelling stations and so on. However, regulations about hydrogen applications on vessels are not yet developed, since there is not a proper legal framework, and the organizations responsible for standardizing have not yet introduced hydrogen as a fuel in its documents, for this reason in order for this technology to thrive, this global organizations must introduce regulatory requirements for hydrogen as a marine fuel to its rules and standards.

2.2.4. Hydrogen Implementation Potential

Hydrogen's promise as a future energy vector depends on its ability to mass produce hydrogen using renewable sources such as water electrolysis or biomass gasification. When considering the future of renewable hydrogen generation, other concerns or challenges exist, such as generation and supply capacity, transportation, and the ability to integrate intermittent production, such as renewable energy sources, into continuous processes, like industrial processes, which require a continuous supply of energy. Because of these factors, hydrogen storage is also a significant factor to consider (Morante, 2020).

Studies show that the potential of the European Union to produce green hydrogen using electrolysis technology may be calculated by taking into account the EU's renewable energy potential, as well as the demand for electricity and the losses associated with the conversion of electricity to hydrogen (Morante, 2020). In order to use this estimate, it is estimated that the technical potential of renewable energy is, according to Van Nuffel et al. (2019), 14,000 TWh/year. As a result, despite the fact that energy projections for 2050 are highly uncertain, it is possible to assert that renewable hydrogen could contribute a significant portion of the total primary energy consumed in the European Union (Morante, 2020). Tough, the European Union will need a more aggressive investment strategy in the next decades in order to boost its technical capacity for renewable energy production, if it wants to replace nuclear power plants and reach 100% renewable energy generation.

In the report by Undertaking (2019), an ambitious scenario for hydrogen deployment in the European Union is presented, based on the perspective of different organizations, such as the Hydrogen Council, Hydrogen Europe and 17 hydrogen- related companies. In the report is concluded that there is a potential for producing 2,250 TWh of hydrogen in 2050, which represents approximately a quarter of the European Union's total energy demand. By 2050, if this ambition is fulfilled, the EU will have reduced CO2 emissions by around 560 Mt, accounting for about half of the required reductions to meet the 2-degree scenario, as part of the well known Paris agreement. CO2 emissions in the EU must be reduced from 3,500 Mt now to 770 Mt in 2050 (Undertaking, 2019). Using modern technologies and existing energy and climate commitments from European countries, around 60% of the gap could be closed (approximately 1,700 Mt in the Reference Technology Scenario). End-of-life hydrogen could help to reduce half of the remaining 1,100 Mt and attain the 2-degree scenario (Undertaking, 2019).

Below, it can be seen in Figure 10, the ambitious scenario where hydrogen could provide up to 24% of the total energy demand in the European Union, which is up to 2,250 TWh of energy by 2050, plus the several benefits these would bring for the European Union (Figure 11), such as the CO_2 reduction, the annual revenue of this new industry that would come, the reduction of the local emissions, for instance in ports, lakes or rivers, and finally the amount of jobs this industry would create.

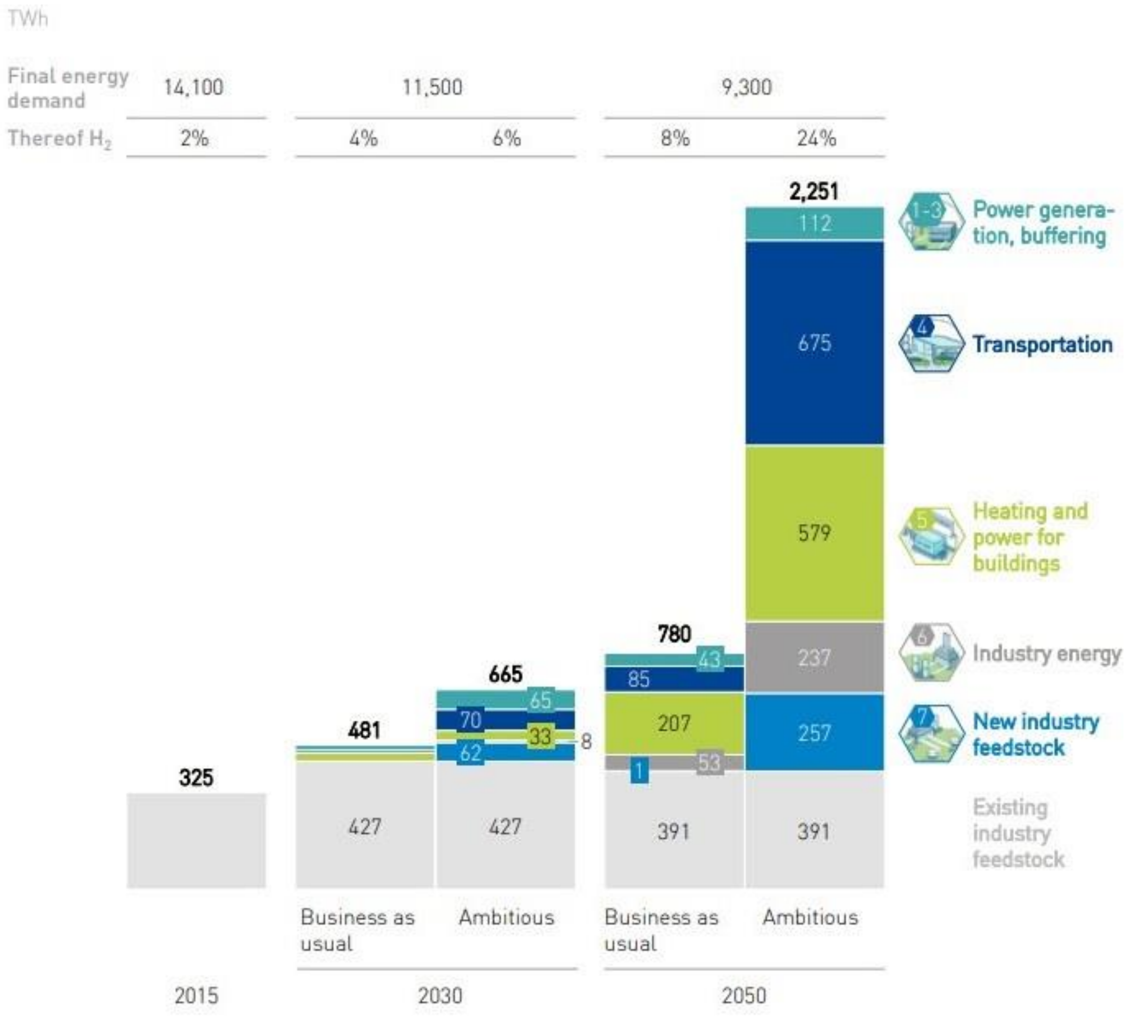


Figure 10. Ambitious scenario for Hydrogen deployment (Undertaking, 2019)

Figure 11. Benefits of Hydrogen for the European Union (Undertaking, 2019)

It is worth mentioning that the potential of using hydrogen in combination with natural gas cannot be underestimated as European policies progress in the economy's decarbonization. In total, it is feasible to estimate, based on the path laid out by the European Parliament in the Pacto Verde, that the global potential for hydrogen production could be greater than 11,000 TWh/year (55 percent of primary energy consumption), allowing for the gradual implementation of hydrogen as an energy vector in the transition to a more sustainable society (Morante, 2020). Despite the uncertainty of future energy models, there is no doubt that the technical potential of low-carbon hydrogen is enormous, as well as the chance for economic and social development. According to the European Commission, the gas that will be transported in the European Union in 2050 will be very different from what is currently being transported, so there are many scenarios that could be played out above the table, and in each of them, the proportion of natural gas decreases while the proportion of hydrogen increases dramatically (Morante, 2020).

2.2.5. Hydrogen Barriers and Risks

The barriers and risks of hydrogen as an alternative fuel for the maritime industry can be divided in four categories (IMO- Norway, 2021).

The first category is the commercial, where the high hydrogen production cost is the biggest concern, especially green H_2, since an excessive fuel cost is a strong barrier to widespread the adoption of hydrogen as a fuel. Also, the high cost of engine replacement or conversion needs to be taken into account, due to the lack of existing stock of this type of technology plus the complexity on the installations makes it another barrier. No current bunkering infrastructure is another barrier to commercial operation. Finally, the low volumetric energy density of hydrogen leads to the need of large tanks, which in consequence reduce the cargo or passenger space on the ship.

Policy matters is the second category, since a lack of regulations for bunkering and storage on board and on land are such a big barrier for this new technology to evolve and expand. Currently, hydrogen as a fuel is not included on the IGF Code.

The third category is sustainability, since as mentioned earlier, nowadays hydrogen production is mainly supplied from natural gas or coal, which does not resonate with the GHG emission targets. Furthermore, in order to see hydrogen as a clean fuel, its production needs to be supplied from green energy sources, such as renewable, in order to obtain green hydrogen.

Finally, the technical criteria is another barrier to take into account. The lifetime of stacks and reformer units need to be proven, so a scale up of electrolyzers and fuel cell components can be made. Also, safety challenges from high flammability range and low ignition temperature need to be solved for hydrogen installations, with increased ventilation, gas detection and a sever control on sources of ignition, which can be a technical challenge for the design of the boat. Finally, there are insufficient current methods for safely and effectively storing and transporting hydrogen, thus this is a big barrier for hydrogen installations on board.

2.3. Fuel Cell Technology

Hydrogen fuel cell technology has followed an interesting path in recent years as their optimistic applications give them a lot of attention across all the sectors trying to reduce the GHG emissions in their activities. Fuel cells are generally known for the generation of electrical power from the chemical energy of hydrogen and oxygen, without the need of combustion. In fact, inside the fuel cell, an electrochemical reaction takes place, where electrons are release and captured by the external circuit and used as electric current (Xing, 2021); moreover, the hydrogen molecules react with the oxygen atoms by forming water, which of course does not pollute whatsoever, and so is a great advantage for this technology. The cell in which this process takes place is composed of two electrodes, the anode and the cathode, which are separated by an electrolyte in either solid or liquid form (Morante, 2020). In the process, the hydrogen, which acts as the fuel, is supplied to the anode, where the oxidation reaction will take place, and on the other hand, oxygen is supplied to the cathode, in which the reduction reaction will happen. The flow of electrons created from the electrons released at the anode to those obtained at the cathode generates an electric current, which later can be used as electricity to power any system (Morante, 2020).

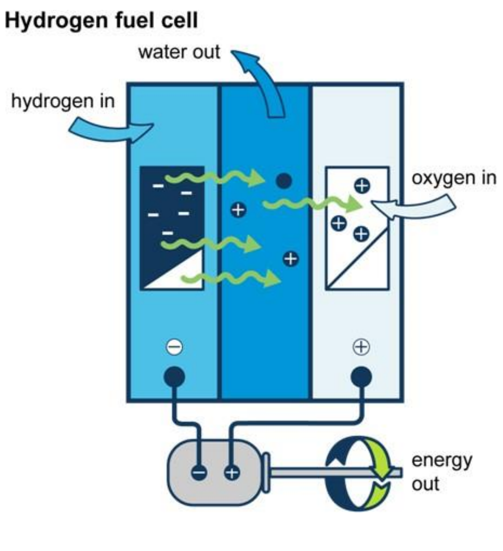


Figure 12. Fuel cell operation scheme
Source: National Energy Education Development Project

The use of fuel cells brings several advantages, for instance they contribute to the reduction of GHG emissions and atmospheric pollutants, since only water is emitted during the process; also, fuel cells give high efficiency to the process compared to combustion processes, and in addition this technology is quite and safe, since the devices have no moving parts. Finally, in accordance with Morante et al (2020) fuel cells are versatile, since the cells can be adapted to produce energy, either in the form of electricity or heat or in different quantities, and can be used in a wide variety of applications, ranging from vehicles to power generation or cogeneration plants.

2.3.1. Types of Fuel Cells

In the current market there exist 6 types of fuel cells (EMSA, 2017), which according to Pratt and Keblanoff (2016) are divided into two regimes of operating temperatures, the low- temperature fuel cells, which operate between 50ºC and 220ºC, and on the other hand the high- temperature fuel cells that operate above 650ºC. Within the low- temperature fuel cells, there are four different types, the PEMFC, DMFC, PAFC, and alkaline. The SOFC and MCFC are high-temperature fuel cells. Table 7 presents the different types, their operating temperatures and applications according to Larminie (2003) plus other properties according to Xing (2021):

Table 7. Data for different types of fuel cell

Fuel cell type	Operating Tº (ºC)	Efficiency (%)	Power capacity	Fuel	Relative Cost	Size	Applications
AFC	50 - 200	50 - 60	< 500 kW	High purity H_2	Low	Small	Used in space vehicles
PEMFC	30 - 100	50 - 60	< 120 kW	H_2	Low	Small	Vehicles and mobile applications
DMFC	50 -120	20	< 5 kW	Methanol	Moderate	Small	Delivers a small amount of electricity over a prolonged time
PAFC	220	40 - 80	100-400 kW	LNG, Methanol, Diesel, H_2	Moderate	Large	Large number of 200 kW CHP systems in use
MCFC	600 - 700	50 - 80	120 kW- 10 MW	LNG, Methanol, Diesel, H_2	High	Large	Medium to large scale CHP systems
SOFC	500 - 1000	60 - 85	< 10 MW	LNG, Methanol, Diesel, H_2	High	Med	Large scale power production on shore up

According to Welaya (2011) all of the above fuel cell types, except the alkaline fuel cell and the DMFC, are suitable for producing electric energy and for propulsion systems on surface ships. These fuel cells consume hydrogen, hydrogen-rich gases such as methane, or liquid hydrocarbons like methanol or diesel fuel, which must be adequately reformed for use in fuel cell systems. As an oxidizing agent, pure oxygen or air can be utilized (Sattler, 2000).

Regarding PEMFC, its low operating temperature allows a flexible and safe operation, however it lacks of waste heat recovery options and water management, and also it needs pure hydrogen to function (Xing, 2021). However, PEMFC has a high power-to-weight ratio, plus it is a suitable system for transportation (EMSA, 2017). PAFC has an acceptable cost and works with fuels other than pure hydrogen, plus it can reach efficiencies up to 80% with a proper heat recovery (EMSA, 2017), but its reforming process generates CO_2. MCFC has a higher cost compared to the others and it operates at very high temperatures, which allows several fuels to be used, such as LNG or methanol; it is a highly efficient fuel cell but, especially with a functional heat recovery system, but it has a slow start-up and is less flexible than low temperature fuel cells. MCFCs are commercially available but they struggle with high cost, short lifetime and low power density (Xing, 2021). Finally, SOFCs are relatively high cost and operate at temperatures of 500-1000ºC. If combined with batteries, a more flexible operation can be accomplished (Xing, 2021).

The key obstacles in using fuel cells in the maritime environment are meeting the demands for high power density in relation to weight and size, salt air tolerance, shock resistance, and quick start and load response characteristics. Due to hydrogen's low volumetric energy density, its application in fueling fuel cells in commercial transportation is expected to be confined in the future to interior waterways and coastal waters (Yousri, 2011).

Table 8 compares the properties of MCFC and PEMFC with those of diesel and gas turbine technologies, which are the two main competitive propulsion choices. Specific values may change as technology improve and knowledge is gained, but the core principles will remain vital (Yousri, 2011).

Table 8. Comparison between fuel cells and marine power technologies (Alkaner, 2006)

Criterion	MCFC	PEMFC	Diesel	Gas Turbine
Response to load change	Slow start-up	Fuel/reformer dominated	Good	Fast
Life cycle	5 years	5 years	20+ years	20+ years
Noise and vibration	Low	Low	High	Medium
Power range	500 - 2,500 kW modular	20 - 2,500 kW modular	Up to 68 MW	Up to 50 MW
Emissions	Zero	Zero	Medium	Medium, no CO_2 benefit

MCFC and PEMFC are the most promising possibilities for maritime applications among the currently available fuel cell technologies since they have a large market, most of the materials needed in their manufacturing are readily available, and their efficiency is rapidly improving. Furthermore, while SOFC has the greatest theoretical potential, it is currently underdeveloped (Yousri, 2011).

2.3.2. PEMFC

The proton exchange membrane fuel cell is one of the most conceptually simple, and it feeds the anode with gaseous hydrogen and the cathode with pure oxygen or oxygen present in the ambient air. A basic unit (cell) is made up of an electrolyte lamina, two electrodes (anode and cathode), a catalyst, bipolar plates, and gas diffusion layers. Its operation begins when hydrogen is supplied to the anode and oxygen to the cathode. Both gases pass through the canals of their respective electrodes and are distributed across their entire surface area through gas diffusion layers (Mayandia, 2009). Once the reactive gases have passed through the diffusion layer, they get in contact with the catalyst, which in the case of PEMFC is formed by metal-based alloys. This catalytic cap is located between the gas diffuser and the electrolyte layers, and in the case of the anode, it has the mission of separating the hydrogen molecule into protons and electrons. When a combustible molecule is separated, the protons travel through a polymeric membrane to reach the cathode, while the electrons travel through an external electrical (Mayandia, 2009). The catalyst, is responsible for combining the electrolyte's H+ ions with oxygen from the air and electrons from the outside circuit to produce water. The surface area of contact between the catalyst and the reactive gases is what matters, not its size or weight (Mayandia, 2009).

In conclusion, PEMFC work if they are feed with pure hydrogen and oxygen. Thus, a hydrogen storage installation for the supply of gas to the fuel cell is required. PEM fuel cell is a mature technology that has been successfully used both in marine and other high energy applications. The technology is available for a number of applications. The maturity of the technology is the main reason why this is one of the most promising fuel cell technologies for marine use, this also leads to a relatively low cost (EMSA, 2017).

2.3.3. Fuel Cells Regulatory Framework

Fuel cells have started to be incorporated in the IGF Code, and they are expected to be included as a new section of the IGF Code in the future, in addition to be covered under interim guidelines in the meantime. The goal is to gather more experience with fuel cells before including regulations into an update of the IGF Code during the four year cycle of SOLAS adjustments. As a modification to the IGF Code, the final fuel cell specifications will be incorporated in Chapter E. As a result, Chapter E will almost certainly become a new chapter of the IGF Code in 2028 (DNV, 2021). In 2003, Germanischer Lloyd (GL) published the first rules for the use of fuel cells, in addition to the IGF Code. Other classification societies, such as DNV (Det Norske Veritas) and BV (Bureau Veritas) are working on standards for the use of fuel cells in the maritime sector (DNV, 2021). In fact, the classification society Bureau Veritas has published on January 2022 a rule note with requirements for fuel cell power systems used as auxiliary or main electric power systems on ships. It covers design and installations of fuel cell power systems and the spaces containing such installations (Bureau Veritas, 2022)

The IMO standards for fuel cell installations are still being worked out, thus acceptance of such systems will have to follow a different design procedure. For fuel cell installations, several classification societies have set their own rules. These regulations do not apply to the storage and delivery of low-flashpoint fuels such as hydrogen, but they do establish standards for fuel cell power installations (DNV, 2021).

The international standards or relevant class rules considered applicable for FC installations in ships are (DNV, 2021; EMSA, 2017):

- IEC 62282-3 Fuel Cell Technologies- Part 3-100: Stationary Fuel Cell Power Systems- Safety- The test program may be based on this standard, but also needs to take the ship-specific environmental and operational conditions into account.
- IEC 60079-10 Electrical installations in hazardous areas- This standard outlines the principles for how hazardous areas are divided into zones 0, 1, and 2 and is needed for selection of electrical apparatus and design of electrical installations.
- IEC 60092-502 provides guidance and informative examples for tanks.
- NR547 R01 from Bureau Veritas. Ships using fuel cells.
- ABS. Fuel cell power systems for marine and offshore applications.
- Lloyd's Register. LR Technical Papers: Development of requirements for fuel cells in the marine environment.
- Korean Register of Shipping Guidance for Fuel cell Systems on Board of Ships GC-12CE.
- DNV GL rules for classification of ships: Part 6 Ch. 2 Sec. 3: Fuel cell installation.

Additional fuel cell standards used for design of land-based fuel cell installations that may be relevant are:

- ANSI/CSA America FC1-2014 Stationary Fuel Cell Power Systems.
- IEC 62282-1 Fuel Cell Technologies- Part 1: Fuel Cell Terminology.
- IEC 62282-2 Fuel Cell Technologies- Part 2: Fuel Cell Modules.
- IEC 60079-10-1 Electrical Apparatus for Explosive Gas Atmospheres.
- IEC 60068-2-6 Environmental Testing- Part 2-6: Tests- Test FC: Vibration.
- ISO 14687-3:2014. Proton exchange membrane (PEM) fuel cell applications for stationary appliances.

3. HULL DESIGN

3.1. Initial Dimensioning

In this chapter the main dimensions of the hull will be obtained through a data base of similar existing models of what is tried to be accomplished. Later, a regression curve will be computed in order to obtain the main dimensions.

3.1.1. Database

Nowadays, in the recreational sector, yachts with full forms are trendy, shipyards such as De Antonio, Pardo, Fjord or Austin Parker are getting more demand, as their yachts are very spacious for the daytime necessities.

For the design of this yacht, it has been taken by example all the models that resemble with the type of boats mentioned. Different models from different shipyards with similar dimensions will be compiled in a database in order to obtain the main dimensions of the yacht that is being designed.

The database with all the models compiled can be seen in "APPENDIX 1- BOAT DATABASE". Though, for the computation of the regressions, the following dimensions have been chosen from the models of the database, since these dimensions are the most adequate for the dimensions that are need to be accomplished:

Table 9. Database for the regressions computations

Lh [m]	B [m]	T [m]	Δ [kg]
10.95	3.60	0.90	7,000
12.80	4.20	1.05	9,870
14.95	4.96	1.23	14,900
11.63	3.64	0.94	8,225
11.99	3.99	1.00	9,800
12.15	3.99	1.17	11,560
11.99	4.25	1.04	9,570
11.99	4.25	1.14	11,250
14.50	4.79	1.37	17,800
11.30	3.64	1.00	9,000
12.50	4.21	1.10	15,000
15.50	4.60	1.27	15,500
9.63	3.35	1.00	5,688
9.90	3.40	0.80	5,723
9.90	3.40	0.97	6,148
13.50	4.15	1.20	11,214
11.50	3.85	0.94	7,959
11.28	3.48	0.90	7,276
9.36	3.32	0.90	5,377
12.77	4.42	1.15	12,200
12.52	4.20	1.15	11,040
11.95	3.82	0.94	9,800
14.25	4.33	1.17	13,500
11.85	3.53	1.00	8,500
13.82	4.06	0.96	10,900
12.65	3.81	1.02	10,145
12.90	3.94	1.20	14,000

3.1.2. Regressions

To obtain the principal parameters of the yacht that is being dimensioned, the next relations will be used in order to create the following regressions:

- B = f (Lh)
- Δ = f (Lh)
- Δ = f (T)
- T = f (B)
- Δ = f (B)

1st Case:

The beam is related to the length of the hull.

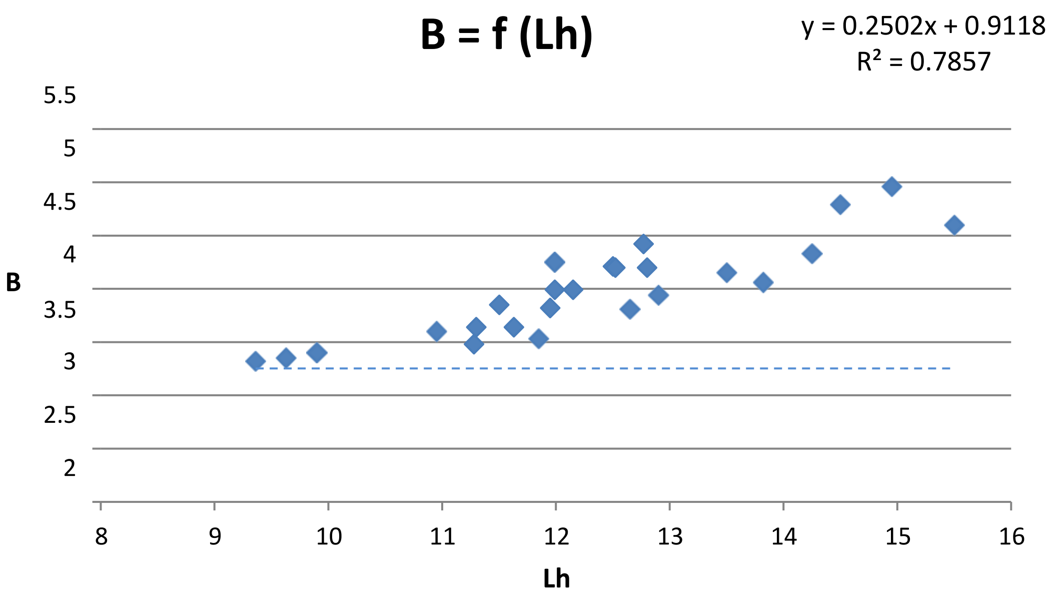


Figure 13. Beam/Length regression

The following equation is obtained:

$$y = 0.2502x + 0.9118 \quad (3.1)$$

2nd Case:

The displacement is related to the length of the hull.

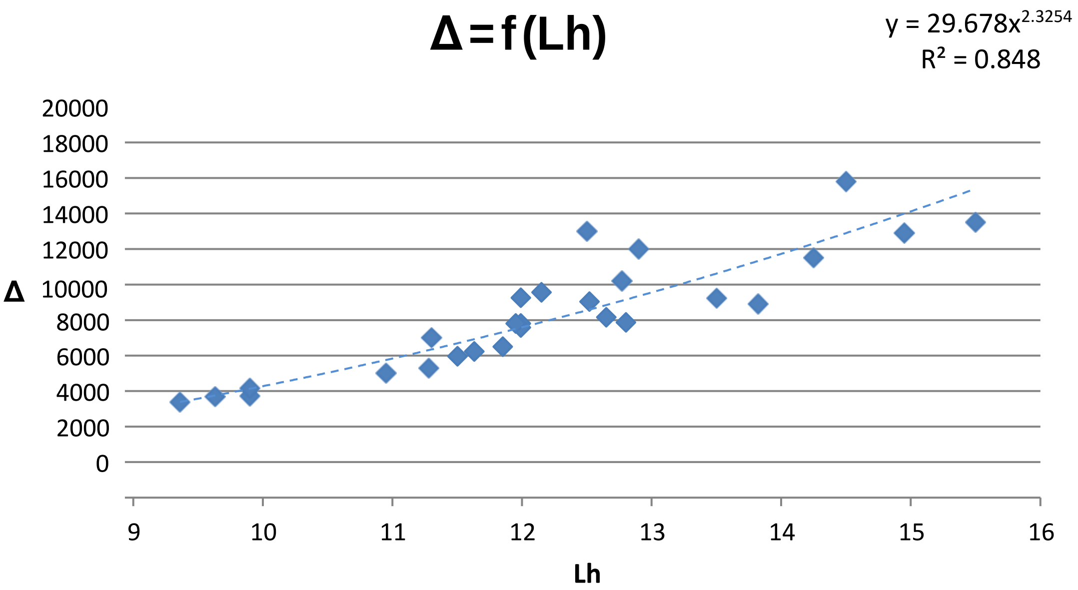


Figure 14. Displacement/Length regression

The following equation is obtained:

$$y = 29.678x^{2,3254} \quad (3.2)$$

3rd case:

The displacement is related to the draft.

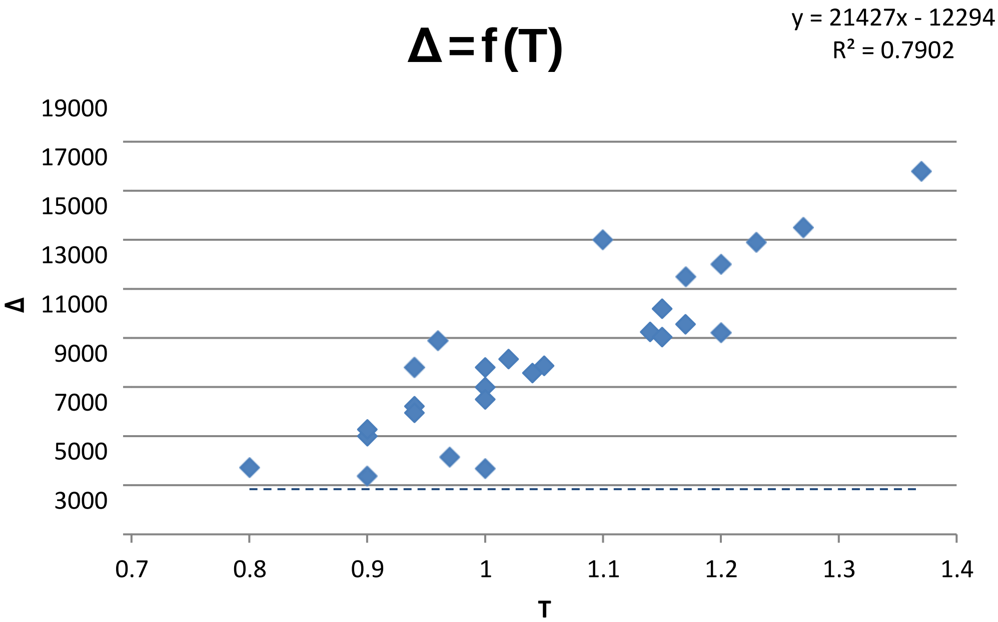


Figure 15. Displacement/Draft regression

The following equation is obtained:

$$y = 21,427x - 12,294 \tag{3.3}$$

4th case:

The draft is related to the beam.

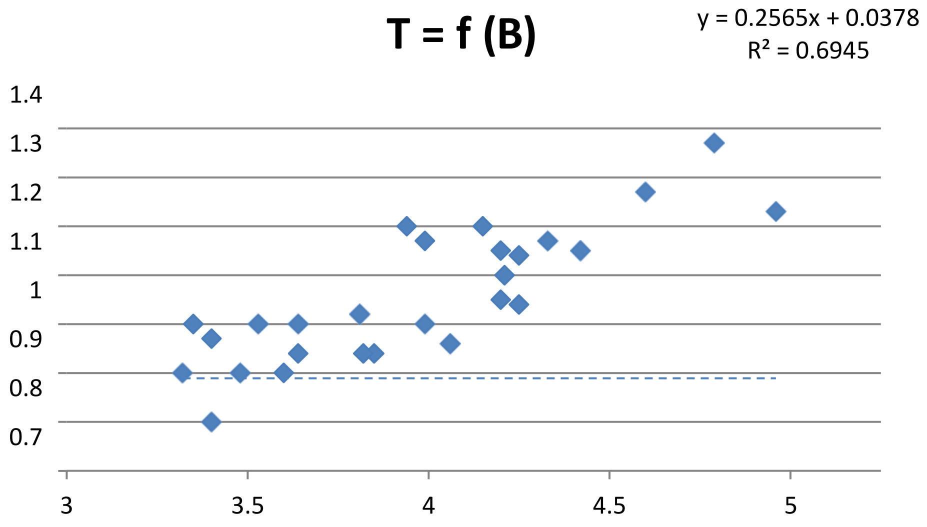


Figure 16. Draft/Beam regression

The following equation is obtained:

$$y = 0.2565x + 0.0378 \quad (3.4)$$

5th case:

The displacement is related to the beam.

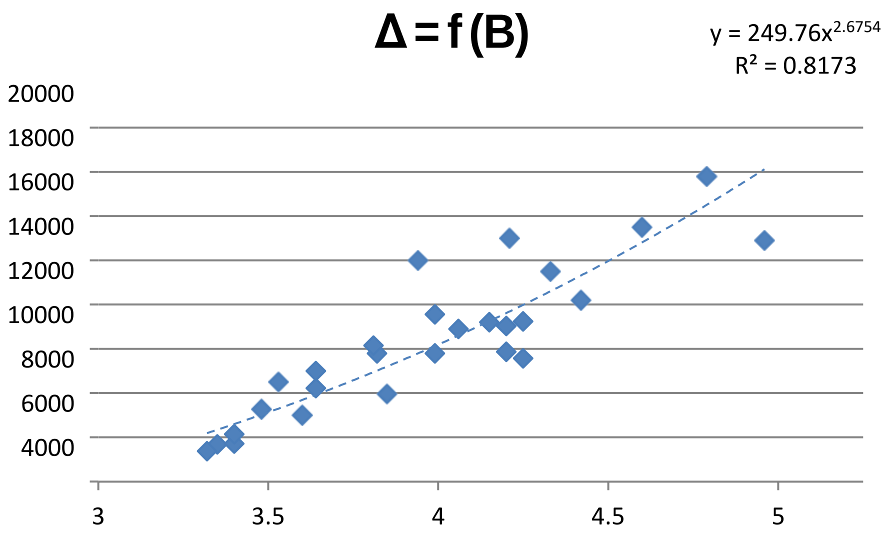


Figure 17. Displacement/Draft regression

The following equation is obtained:

$$y = 249.76x^{2,6754} \quad (3.5)$$

To do the study of the dimensions through regressions, the regressions with a correlation coefficient closest to 0.8 will be used, as this will ensure a certain reliability of the calculations.

In order to do the calculations, a Lh of 40 ft (12.2 m), will be taken into account, since it is the length of the ship by design. For the calculations, the following relations will be used:

- Δ = f (Lh)
- Δ = f(T)
- Δ = f (B)

Table 10. Final parameters

Parameter	Function		Result		Final Result
Lh	-	-	12.2	m	12.2 m
Δ	Δ=f(Lh)	$y = 29.678x^{2,3254}$	9,969.09	kg	10 t
B	Δ = f (B)	y = 1,865.6x - 12,472	3.967	m	4 m
T	Δ=f(T)	y = 21,427x - 12,294	0.945	m	0.95 m

The final dimensions of the hull will be a length of 12.2 meters, a 4 meters beam, and a draft of 0.95 meters; the depth, in reference to the distance between the waterline and the deck, will depend on the needs of the interior spaces.

The displacement of the hull will be around 10 tons, which can oscillate depending on the final draft and needs of the hull.

3.2. Hull Shape

The generation of the hull form is key for further phases of the design, as it has a direct influence on the stability, power, the position of the center of gravity and so on. Optimizing the hull design has such importance, since it can reduce the vessel's drag which as a result can lead to a reduction on the fuel consumption and an improvement in range. In addition, this optimization can also facilitate the installation of alternative power plants that require heavier storage systems.

Since a spacious but fast yacht is the objective, a planning hull design is the best option to do so, as in order to reach high speeds on the water, a hull design that has a quick transition to the planning regime is necessary.

Thus, to have a planning hull we need to consider V- shaped frames on the bow, instead, on the aft it is required a flatter form with straight buttock lines to avoid unnecessary vibrations. It also needs sharp hard chines, which are longitudinal edge lines that extend from the bow to stern which generate a flow separation from the side of the boat, throwing the spray away from the sides of the hull and this way reducing the drag. Finally, a sharp wide transom is recommended as well for a planning hull.

In addition, for planning hulls it is recommended to use lifting strakes, also known as spray rails, which are tapered surfaces with a particular triangular section which its mainly use is to deflect the spray caused by the movement and increase the lift raising the boat out of the water and consequently reducing the drag. The spray rails run longitudinally along the hull bottom, below the waterline.

3.2.1. Generation of the Hull

To generate the hull of the yacht, first, the curves from a previous yacht model were exported from the *DELFTship* software to the design software *Rhinoceros 7*, which was the tool used in order to shape the final hull form with the objective to create a planning hull. The final design will be exported to the naval analysis program *Maxsurf Modeller*, *Maxsurf Resistance* and *Maxsurf Stability* with the purpose of studying the hydrostatics and the resistance of the hull, plus the stability tests.

The final curves of the hull can be seen on the Figure 18:

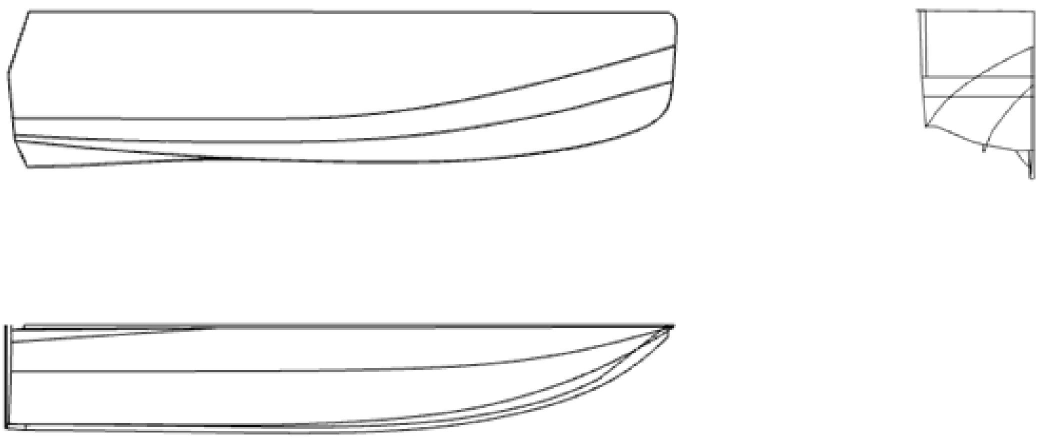


Figure 18. Hull Curves

Once the curves are drawn, NURBS surfaces can be created by joining the curves designed. In the following figures, different perspectives of the hull surfaces can be seen with the *Rhinoceros*'s render view (Figure 19):

Figure 19. Hull form views

Figure 20. Fore body and transom perspectives

As mentioned before, the idea was to create a planning hull which is the best hull type for adapting to the goals of the project. To achieve this, several specifications have been taken into account in the design. For instance, as seen in the different perspectives, on the bow area a V- shaped frames have been designed, which will reduce the displacement of the boat and also help to reach the planning regime and consequently reducing the drag. On the other hand, as seen in the transom perspective (Figure 20), on the aft a more U- shaped or flat forms have been achieved. This will help the boat to avoid unnecessary vibrations caused by the propeller, plus a more uniform wake, which will also help on the vibration situation and lift the boat earlier into the planning regime.

Also, a keel has been added to the hull's design. This will have a crucial behavior on the yacht, as the keel will give a better stability on the turns, since this element will prevent the boat from drifting on high speed close turns. This way, the yacht will have a better maneuverability and stability while navigating at higher speeds.

Finally, as seen in the different views (Figure 19), spray rails and hard chines have been added to the design. As mentioned earlier, both details help to reduce the drag of the yacht because of their behavior, as they deflect the spray from their respective hull zone. Also, they both have been added along the length of the hull.

3.2.2. Hydrostatics

The hydrostatic data obtained with the naval architecture program *Maxsurf* will be presented and further conclusions about the design will be discussed.

Table 11. Hydrostatics at DWL

Measurement	Unit	Value
Length WL	m	12.05
Beam max WL	m	3.72
Immersed Depth	m	0.81
Prismatic Coefficient	-	0.72
Block Coefficient	-	0.30
LCB	m AP	4.85
LCF	m AP	4.76
LCB	%Lwl	39.77
LCF	%Lwl	39.03
KB	m	0.58
Length/ Beam Ratio	-	3.05
Beam/ Draft Ratio	-	4.88

As seen in the hydrostatic data from Table 11, most of the main parameters have been fulfilled. The draft and the displacement will be analyzed later.

From the beginning of this chapter, one of the goals has been to design a planning hull, so either if it is a planning hull or not will be discussed. In order to be considered a planning hull, certain parameters must be between some specific values, for instance:

- Cp of [0.70 - 0.78]
- V /(Lwl^(1/2)) >= 2.5

As seen in Table 11, the prismatic coefficient (Cp) is 0.72.

30 kn / (40 ^(1/2) ft) = 4.74 ; which is higher than 2.5.

In conclusion, by the facts shown, it seems that the designed hull has conditions to be a planning hull as all the values comply with the given specifications. Nevertheless, based on empirical computations it cannot be assured that it is actually a planning hull. Therefore, several hull elements, such as spray rails, hard chines, a wide transom, have been considered to facilitate the entrance in the planning regime.

3.2.3. Lightship

The lightship of the hull must be computed for further calculations, such as the stability analysis. In this case the weight of the hull's structure is going to be computed. To do so, two laminate sequences are presented, which will be the sequences that must be followed to construct the different parts of the yacht. The two laminate sequences can be seen in Table 12 and Table 13:

Table 12. Laminate sequence 1

Layer	Type	Thickness (mm)	Weight per area (kg/m2)
1	Gelcoat	3	4.667
2	MAT	1.042	3.224
3	WR	1.372	5.739
4	MAT	1.042	3.224
5	WR	1.372	5.739
6	PVC	3	4.224
7	MAT	1.042	3.224
8	WR	1.372	5.739
9	MAT	1.042	3.224
10	WR	1.372	5.739
TOTAL		15.656	44.743

Table 13. Laminate sequence 2

Layer	Type	Thickness (mm)	Weight per area (kg/m2)
1	Gelcoat	3	4.667
2	MAT	1.042	3.224
3	WR	1.372	5.739
4	PVC	3	4.224
5	MAT	1.042	3.224
6	WR	1.372	5.739
7	MAT	1.042	3.224
8	WR	1.372	5.739
TOTAL		13.242	35.78

The first laminate sequence, shown in Table 12, is thicker than the other laminate sequence, and for this reason, this sequence is going to be used for structures that need more resistance, such as the exterior parts in contact with the water, which are the bottom, the sides and the transom of the hull. On the other hand, the second laminate sequence, shown in Table 13, will be applied to interior structures, for instance the bulkheads, the deck plus the compartments.

Table 14 shows the structure weight computations:

Table 14. Lightship computations

Structures	Area (m^2)	Thickness (m)	W/A (kg/m^2)	Density (kg/m^3)	Weight (kg)
Bottom	44.91	0.01566	44.74	2,857.88	2,009
Sides	41.27	0.01566	44.74	2,857.88	1,847
Transom	3.97	0.01566	44.74	2,857.88	178
Bulkheads	10.5	0.01324	35.78	2,702.01	376
Deck + Comp	46.72	0.01324	35.78	2,702.01	1,672
				TOTAL	6,081
				Margin (5%)	304
				TOTAL	**6,385**

The final weight of the hull's structure, applying a design margin of a + 5%, is 6,385 kg, which represents the lightship. For further analysis in this thesis, this lightship plus the weight of other systems will compute the lightweight of the ship, which will be used for the stability analysis.

4. PROPULSIVE SYSTEM SELECTION

The objective of this chapter is to find a propulsive system which provides the amount of energy in order to supply enough power for the different systems of the boat and the propulsion of the motors. Since the project aims for a zero emissions configuration, it is intended to study a system for obtaining energy from clean sources.

4.1. System Components

The propulsive system is formed by different systems. First, a fuel cell will be installed, which will produce electricity to feed an electric motor. In order for the fuel cell to produce electricity, a hydrogen and oxygen supply is required, so an installation for storing the H_2 is also required. For the supply of oxygen, an air inlet is sufficient to feed the fuel cell with oxygen. In addition, a bank of batteries will be installed in order to give extra power to the electric engine and also a better autonomy to the boat. Therefore, a hydrogen and electric connection is required in order to fill the hydrogen tanks and the bank of batteries.

Figure 21 shows a hydrogen fuelling station, where boats can fill the tanks with blue or green hydrogen.

Figure 21. Hydrogen fuelling station

The operation of the propulsive system or power plant is the following. The batteries will feed the electric engine at low speed, while the fuel cell can recharge the energy consumed by the batteries to power the engine. When aiming for higher speeds, the fuel cell can provide the enough power for the electric motor, but if top speeds are to be reached, the idea is to have a combination of the power delivered by the fuel cell plus the power by the batteries, which should produce the sufficient power for the electric engine to reach its peak power. This, will be organized by a programmable logic control (PLC), which will be the responsible for making the decisions of either powering the electric engine with only the batteries at low speeds, or only the fuel cell at higher speeds, or even both at top speeds. Also, when the H2 cylinders do not have enough hydrogen to provide the operation pressure, the PLC must decide to stop the H_2 flow, and power the motor with the remaining energy on the batteries.

Figure 22, shows a basic scheme of the propulsive system:

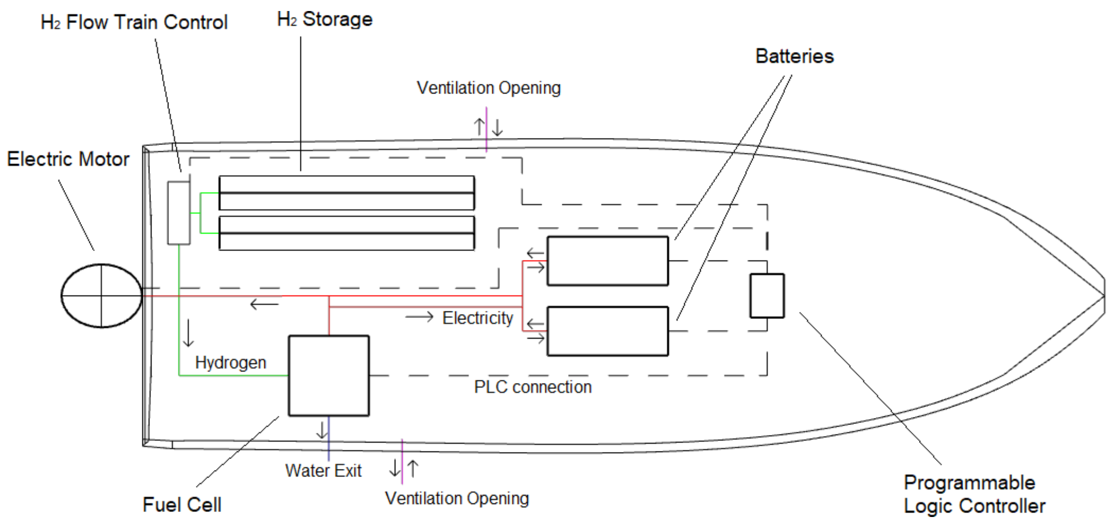


Figure 22. Propulsive system scheme

4.2. Hydrogen Storage Selection

The hydrogen storage system function is to store as much hydrogen as the vessel's energy utilization profile requires. Compressed hydrogen cylinders are huge and expensive, but for practical reasons, they are the industry's current choice. Compressed hydrogen is significantly more developed than the other possibilities because it is the industry standard. For this reason, compressed hydrogen is the option chosen for the storage of H_2 onboard of the yacht. Even though, LH_2 has better gravimetric and volumetric characteristics in general compared to compressed gas, its technology is too complex for a 40 feet yacht, since the need to store the hydrogen at cryogenic temperature makes it difficult. Also, problems related with boil-off losses and embrittlement phenomenon makes GH_2 storage a better option for this project.

Table 15. Gravimetric and volumetric storage specifications for hydrogen storage method (Pratt and Klebanoff, 2016)

Tank Type	Gravimetric Specifications (Empty tank mass/ H_2 stored mass) (kg/kg)	Volumetric Specifications (Outer tank volume/ H_2 stored mass) (l/kg)
150 bar, Carbon steel	103.4	105.7
140 bar, Aluminum	72.4	130.0
350 bar, Composite	17.9	54.9
700 bar, Composite	23.5	42.1
LH_2 tank	8.7	24.8

Table 15 shows that non-composite tanks, such as carbon steel and aluminum have much worse gravimetric specifications than composite tanks, and also their volumetric characteristics almost double the composite characteristic, since non-composite tanks store the GH_2 at lower pressures (150 bar) compared to composite tanks (350 - 700 bar). In addition, metallic tanks are too heavy compared to composite tanks, though they have a lower cost.

In conclusion, even though composite tanks are expensive, these are the best option compared to metallic tanks. Their characteristics makes them better, but also, since this project is for a 40 feet yacht, spaces and weights need to be as reduced as possible, and since metallic tanks are way too heavy compared to composite tanks, for a pleasure craft, the lightest option is the best, and if they also have better gravimetric and volumetric specifications, they seem to be the perfect fit for this type of boat and installation. Composite storage solutions offer high durability and high fatigue strength, as the carbon-fiber construction reduces impact, damage and fatigue; also, they are non-corroding.

Regarding the type of chosen compressed hydrogen tank, the selection is a type IV, composite (fiberglass/carbon) full wrap, with plastic liner. As seen in Table 15, different pressures can be applied for composite tanks. Since increasing the pressure from 350 bar to 700 bar do not decrease as much the volumetric specifications (from 54.91 to 42.12), and it is preferable to have lower pressures safety-wise and to make the installation less complex, 350 bar composite tanks should be enough for the installation required. Moreover, as shown on the state of the art, other projects have used this solution for the storage of hydrogen, furthermore this gives a clue for the correct selection.

To place the compressed hydrogen cylinders inside the hull, the cylinders must be inside a block, divided by compartments where each cylinder can be fitted and fixed to the surface of each block compartment. In order for the cylinders to be secures, the block must be weld to the hull's structure to prevent any damage to the cylinders in case of pitching due to a rough sea.

For space and capacity purposes, Hexagon Purus 350 bar type IV cylinders have been chosen. The tanks will be placed in the port side of the aft area, where within a compartment the cylinders will operate. The type IV cylinder from Hexagon Purus have the following characteristics as seen in Table 16, taken from the specifications shown on "APPENDIX 3- HEXAGON PURUS CYLINDERS SPECIFICATIONS":

Table 16. H_2 storage tank specifications

Nominal working pressure (15ºC)	Outside diameter	Overall length	Tank weight	H_2 capacity	Weight ratio (H2 / tank)
bar	mm	mm	kg	kg	%
350	430	3190	101	7.5	7.4

4.3. Hydrogen Flow Train Control

Figure 23 shows the connections between the hydrogen storage system and the fuel cell, where all the valves can be seen.

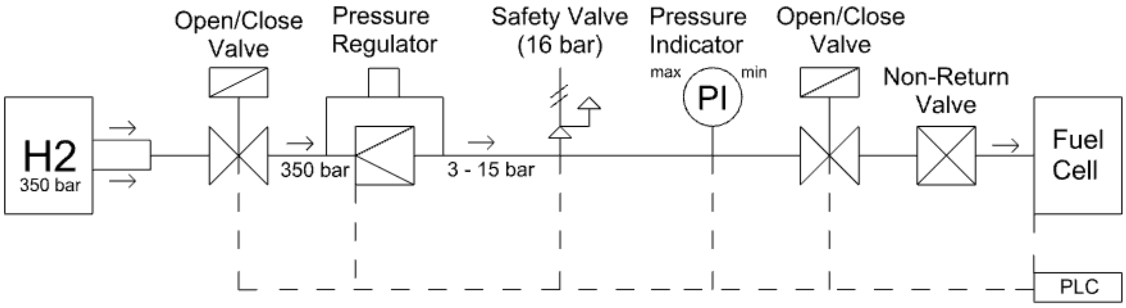


Figure 23. Hydrogen fuel supply system

The hydrogen stored at the cylinders at 350 bar, where a collector interconnects the different compressed gas cylinders, flows through a high pressure pipe, passing through a high pressure open/close valve, which permits the hydrogen gas to flow when needed. Later, the hydrogen is decompressed, inside the pressure regulator, from 350 bar to the operational pressure range, which is between 3 and 15 bar. If a failure occurred during the decompression, the safety valve, activated by the PLC, would take the gas out to the atmosphere. The pressure can be measured in the pressure indicator, in order to know if the operational pressure is the one needed. Finally, the hydrogen gas pass through another open/close valve and a non-return valve before arriving to the fuel cell.

As mentioned in previous chapters, hydrogen leaks can be dangerous. For this reason, a hydrogen detector is required within the installation. In this case, since small leaks could happen, is possible that with a proper ventilation, point gas detectors may not detect the small hydrogen gas leak. Acoustic gas detectors is the best option for small leaks, so an acoustic gas detector will be part of the safety installation of the hydrogen storage system.

Figure 24. Acoustic gas detector

The electronic acoustic detector with an output of 4-20 mA, is made to identify certain ultrasonic frequency content associated with events like gas leaks. When a pressurized gas leak occurs, the frequency content of the sound that is produced crosses over into the ultrasonic area of the spectrum, above 20 kHz. Pressure, leak rate, gas viscosity, and distance from the leak source are some of the variables that affect the intensity of the sound generated by a leak. Acoustic detection is less vulnerable to environmental conditions that can affect the effectiveness of conventional sensing technology based on gas concentration to identify the presence of a leak, such as high winds from ventilation, hence an acoustic gas detector is the best option for the installation.

The acoustic gas detector must be in continuous communication with the PLC. If a hydrogen gas leak is detected by the sensor, an immediate communication may occur between both systems, so the PLC can take action and immediately close the high pressure open/close valve, in order to cut the H2 flow. In parallel, and alarm would show the presence of gas in the installation, so proper safety and fire controls could be taken into account. Once the hydrogen flow was cut off by closing the high pressure valve, the ejection of the remaining hydrogen inside the room through the ventilation opening, situated at the highest point of the compartment, will occur, since hydrogen dissipates rapidly due to its low density. The same acoustic gas detector must be installed in the fuel cell compartment, since the operation of the fuel cell requires a hydrogen flow. In this case, the same process will be followed. If the sensor detects hydrogen in the fuel cell room, the hydrogen flow would be cut off, same as the other case, and the remaining gas would dissipate through the ventilation opening.

If a fire due to hydrogen was initiated, once the hydrogen flow was stopped, the best solution is to stop the movement, in order to cut off the ventilation and therefore, the flow of oxygen, and use a dry-chemical extinguisher to extinguish the fire and prevent to reach other installations.

4.4. Fuel Cell System Selection

In this chapter, several fuel cells currently available in the market will be analyzed. Later, the best option will be discussed to be chosen to be part of the boat's propulsive system.

Because PEMFC were designed primarily for lower-scale mobility power applications, such as car power plants and auxiliary power, they have a higher power density, less weight, and smaller volume than conventional fuel cell systems. PEM fuel cells have a high-power density, high efficiency, and the ability to work well in cold and transient conditions, plus they are one of the lightest and smallest fuel cells available. Furthermore, the PEM fuel cell is a commercially accessible product with a proven track record of performance. These benefits are compounded by the fact that it is a zero-emission source. For all these reasons, PEMFC are the type of system that will be used for the propulsion of this yacht.

Table 17 shows the currently available PEMFC applicable to this project, that are currently available on the market .

Table 17. Fuel cell models

Model	Rated power [KW]	Type	Fuel supply pressure [bar]	Weight [kg]	Dimensions l x w x h [mm]
Ballard FCMove-HD	70	GH_2	8	250	1,812 x 816 x 415
Ballard FCveloCity-HD100	100	GH_2	8	280	1,200 x 869 x 487
Ballard FCwave	200	GH_2	3.5 - 6.5	1,000	1,209 x 741 x 2,195
NEDSTACK FCS 13-XXL	13.6	GH_2	0.15 - 0.3	41	604 x 196 x288
PowerCellution Marine System 200	200	GH_2	3 - 8	700	700 x 900 x 2,000
Proton Motor-Hyship (PM400 modules)	Up to 213	GH_2	3 - 7.5	-	954 x 436 x 279
Genevos HPM-40	40	GH_2	3 - 8	160	155 x 65 x 35
EODev- REXH_2	Pn 70 Pmax 90	GH_2	11 - 15	400	1,000 x 1,000 x 1,000
EODev- REXH_2 V2 Next generation	From 70	GH_2	11 - 15	630	1,600 x 1,000 x 1,000

Large vessels such as ferries or canal boats, normally use a stack of fuel cells which can give high rated power in combination. Though, since this yacht is only 40 feet, a PEMFC stack system cannot be considered due to the lack of space. At most, the combination of two fuel cells can be possible with the space available on the yacht.

Before selecting the fuel cell system for this yacht, first we have to consider the amount of energy that needs to be supplied in order to propel the boat at specific speeds. The data from "APPENDIX 2- RESISTANCE RESULTS" shows the different powers needed for each speed. Since the yacht is expected to reach speeds between 10 and 30 knots, the system should supply a power of at least 50 kW.

Consequently, for the propulsive system of this yacht, the EODev- REXH_2 fuel cell have been chosen. This decision has been made for two main reasons; its cubic form gives this system a lot of facilities in terms of system organization. Since the system is a 1 meter cube, it makes it easy to store it inside of the hull along with other systems, and it enables to create a lot of different configurations. Moreover, its rated power of 70 kW (60 kW continuous and 90 kW peak power) is higher than the other systems in relation with its size, plus it provides the minimum supply of 50 kW mentioned. In addition, the system includes an integrated cooling system, several security sensors, like H_2, smoke and ventilation sensors, plus an accelerometer. Finally, an air compressor is installed within the system, which its function is to compress the atmospheric air into the operation pressure, which is around 11 bar. Therefore, an air inlet close to the fuel cell is required in order to supply the sufficient oxygen for the fuel cell to work.

In conclusion, Toyota fuel cells are currently the most compact and efficient range extender on the market in terms of power delivered. Table 18, shows some important characteristics of this system taken from the specifications shown in "APPENDIX 4- REXH$_2$ SPECIFICATIONS".

Table 18. REXH2 specifications

Output Voltage (Range and Current type)	600V DC
Estimated end of cycle (nominal power)	13,000 hours
Max sea water temperature and flow requirement	32ºC / 200 LPM
Consumption at nominal power	4.6 - 5.4 H_2 Kg/h
Pure water production	< 50 L/h
Ambient air temperature	-15ºC to 40ºC
Required inlet air & ventilation flow	8,000 nL/min

Figure 25 shows the Toyota REXH$_2$ PEMFC.

Figure 25. Toyota REXH$_2$ EODev PEMFC

4.5. Electric Motor and Battery Selection

The electric motor is the system which function is to propel the yacht with the help of the other systems of the power plant, which have the function to supply electricity to the motor, including the batteries. Regarding the selection of the motor the resistance analysis shown in "APPENDIX 2- RESISTANCE RESULTS" are considered. The range of speeds are between 10 and 30 knots, so a power from 50 kW to 250 kW need to be consumed by the electric motor, which will be supplied by the batteries and the fuel cell.

With this in mind, the solutions of the Norwegian company *Evoy* will be used, both for the electric motors and the batteries. Currently, *Evoy* have developed the world's most powerful outboard electric motor. Also, its range in inboard electric motors is also interesting. The batteries present great characteristics as well; each 63 kWh battery gives an extra 17 nautical miles of autonomy to the boat, with a weight of 380 kg. They have an energy density of 166 watt-hours per kg based on 2,170 cells and have about 3,000 recharge cycles.

Figure 26. Evoy electric motors

Regarding the motor range, the outboard electric engine has a nominal power of 90 kW, while its peak power is 150 kW. The weight of the engine is 190 kg and it can be combined with 1 or up to 3 Evoy batteries. The inboard electric engines range, shows two types, the breeze which delivers the same power as the outboard option. Though, compared to the outboard option, it is cheaper and lighter, as its dimensions are 32 cm of diameter and a length of 50 cm. Finally, the other type of inboard electric motor is the hurricane model which is more powerful, since its power is superior than 300 kW. Its weight is 300 kg and is the most expensive option among the others. Specifications can be found in Evoy (2020).

Different configurations can be displayed for the different range of motors:

- 1x 90 kW outboard engine + 2 batteries (126 kWh)
- 1x 90 kW outboard engine + 3 batteries (189 kWh)
- 1x 90 kW inboard engine + 2 or 3 batteries (126 - 189 kWh)
- 2x 90 kW outboard engine (180 - 300 kWh) + 3 or 4 batteries (189 - 252 kWh)
- 1 x 300 kW hurricane inboard engine (300+ kWh) + 2 or 3 batteries (126 - 189 kWh)

Depending on the demands and needs of the yacht, a different configuration will be chosen in order to propel the boat. However, since inside the hull a lot of space and weight is already occupied by the other propulsive system elements, the 90 kW outboard motors will be the best solution, as they will push to the aft the center of gravity. Furthermore, a better trim of the boat could be accomplished and in consequence, a more optimal navigation.

5. PROPULSIVE SYSTEM CONFIGURATION

Typically, in traditional configurations, the boat's speed wanted to be reached is the key to choose the propulsive system configuration. Since there exist a wide range of powers for combustion engines, once the speed is known, the resistance for that speed can be computed and then an engine that supplies enough power to match the resistance can be chosen. Instead, since zero emissions systems are currently very limited, there is not a wide range of powers to choose from once the speed required is known. For this reason, in this case, two configurations that fit with the space available will be presented, and further analysis will be taken, such as the power supplied, plus the range and autonomy. The configurations will be chosen specially taking into account the space available for their installation, the power needed in comparison with the hull resistance results and the feasibility to install them. Once the systems are combined, conclusions about which is the best and optimal way to use this systems will be discussed, and both configurations will be compared in terms of performance.

5.1. Configuration 1

In this first case the configuration used is the following:

- 4 GH_2 storage cylinders
- 1 $REXH_2$ fuel cell (70 kW)
- 2 batteries (126 kWh)
- 1 outboard Evoy electric motor (90-150kW)

Hereinafter, several figures will show the configuration in the yacht model. This way, it can be seen how all the propulsive systems have been displayed inside the hull, plus the separation of the systems with compartments.

Figure 27, shows the basic distribution of the systems components inside the hull. The objective of the distribution is to reach a maximum stability and an optimal weight distribution.

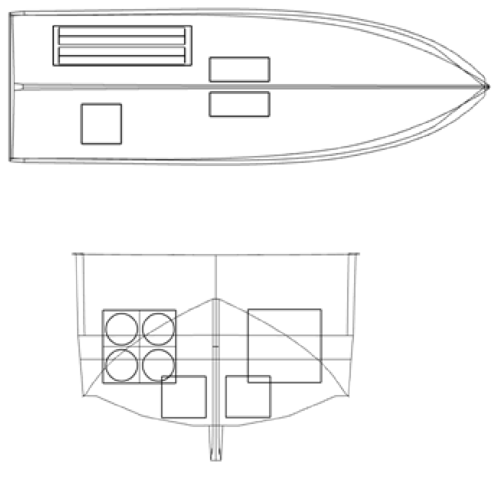


Figure 27. Systems components layout

In Figure 27, it can be seen three types of systems. The fuel cell on the starboard side represents the REXH_2, while the two rectangular parallelepipeds closer to the bow represent the two batteries. Finally, the four cylinders enclosed in a rectangular parallelepiped, on the starboard side, represent the GH_2 storage system.

Once, the distribution has been made, each system needs to be separated from each other through compartments. The compartments increase the safety of the installation and require the needs of each one. For instance, hydrogen storage cylinders need to be very well isolated and ventilated, so in case of a leak this can be detected within the compartment. Also, in the fuel cell compartment, since the oxidant that makes the fuel cell to function is oxygen, an air inlet is required, with it the air compressor will be able to feed the fuel cell with oxygen.

The final layout with each system placed in its respective compartment is shown in Figure 28:

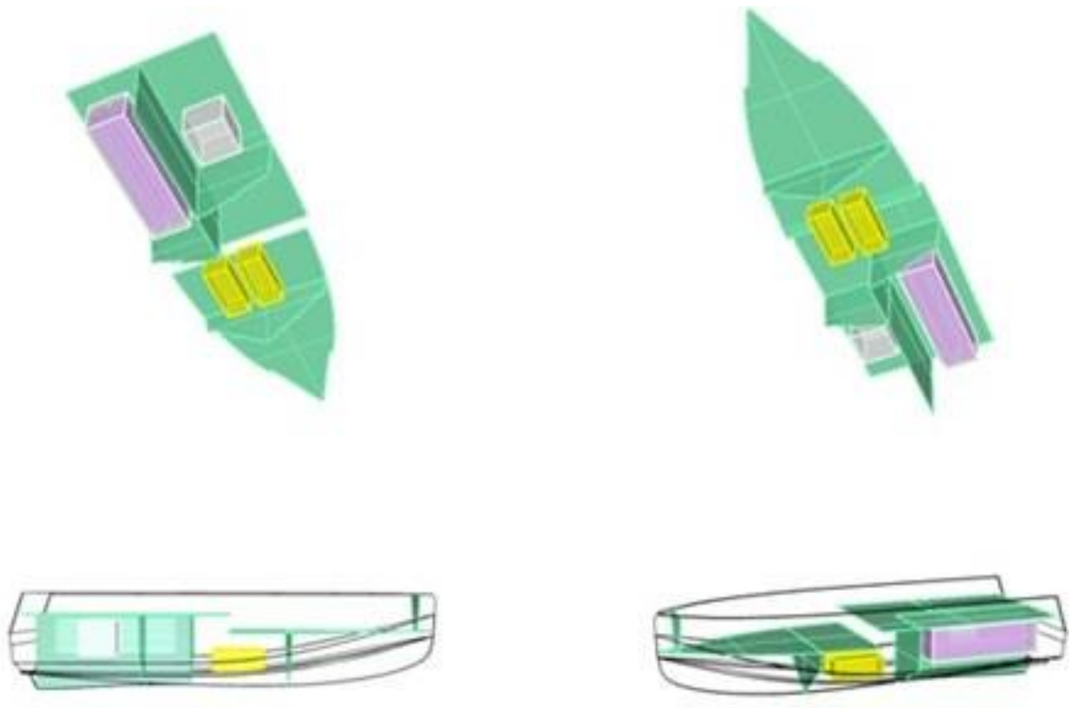


Figure 28. Final distribution layout

As seen in this last compartment layout, a compartment has been added in the furthest point of the bow for the anchoring storage.

Figure 29 shows a sketch of the general arrangement of the boat, its compartments, and the location of the main components of the propulsion system.

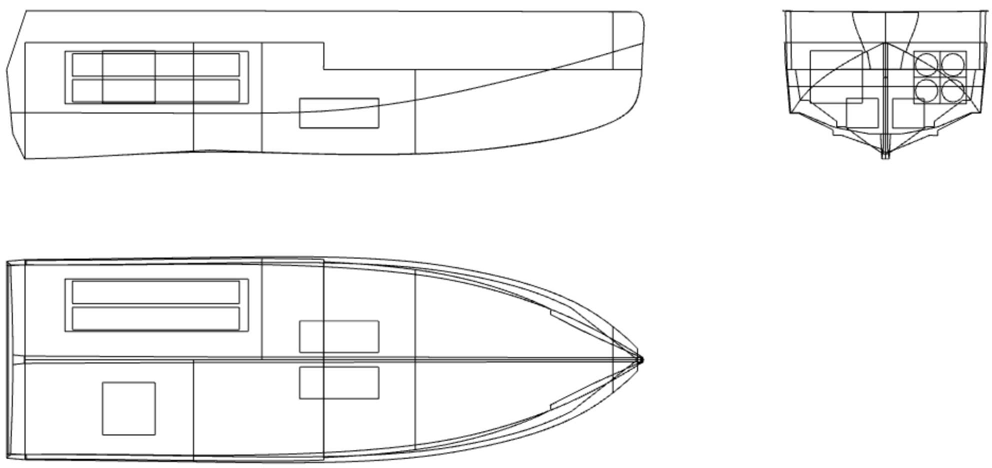


Figure 29. General arrangement

5.1.1. Total Electric Consumption

Table 19 shows the consumption of the different systems:

Table 19. Electric consumption

Element	Electric consumption (kW)
Equipment*	0.3
4000 GPH bilge pumps (x3)	0.5
Electric motor at nominal power	90
Electric motor at peak power	150
Total consumption (nominal power)	90.8
Total consumption (peak power)	150.8

*The equipment refers to the different electronic elements on board, such as VHF radio, automatic pilot, GPS/ chart plotter, navigation lights, on boards lights and engine monitors.

5.1.2. Electric Load Balance

On board of the yacht, the cylinders are the element responsible for the compressed hydrogen storage. As seen in the previous specifications, each cylinder has the capacity to store 7.5 kg of GH_2, which is a total of 30 kg of hydrogen available on board.

The REX H_2 fuel cell has an average consumption of 5 kg of H_2 each hour, in order to supply 70 kW of power during this period of time. Since 30 kg of hydrogen are stored on board, the fuel cell has the capability to function at a nominal power of 70 kW during 6 hours.

Batteries, on the other hand, have a capacity of 63 kW each, which can be used to power the boat in cooperation with the fuel cell in order to reach a higher power.

Table 20. Electric power supply and consumption

System	Power
REX H_2	70 kW
Batteries	63 kWh each (126 kWh total)
Total consumption (nominal power)	90.8 kW
Total consumption (peak power)	150.8 kW

In order to power the electric outboard engine at a nominal power of 90 kW, plus the other electric equipment which totals 90.8 kW, the fuel cell should work along with the batteries to provide this power required. The fuel cell at nominal power, only provides 70 kW, so the batteries in parallel should provide an extra 21 kW to deliver the necessary power. Moreover, with 30 kg of hydrogen on board and with an extra 126 kW on the batteries, the electric needs could be supplied during 6 hours at nominal power.

In accordance with the resistance results of "APPENDIX 2- RESISTANCE RESULTS", the 90 kW power delivered by the electric engine, supports a cruise speed of 14 knots during 6 hours.

The peak power of the electric engine is 150 kW. To supply that, the batteries should deliver an extra 80 kW, along with the 70 kW of the fuel cell. Moreover, this implies an autonomy of just 1 hour, but a top speed of 18 knots could be reached in accordance with the resistance results.

The performance results of this configuration can be seen in Table 21:

Table 21. Configuration 1 performance results

Speed (knots)	Autonomy	Navigation
14	6 hours - 84 nautical miles	Cruise speed
18	1 hour - 18 nautical miles	Top speed

In conclusion, the best option is to work at nominal power, and momentarily increase the power at its peak in order to reach higher velocities. This configuration, even though not being able to reach high speeds, gives a great autonomy to the boat, as with a cruise speed of 14 knots during 6 hours, the boat has a range of 84 nautical miles.

In case of running out of hydrogen on the cylinders, and electricity on the batteries, the best solution is to navigate at low speeds. Furthermore, an extra battery for emergency is the best option in order to give a safety autonomy, which would be equivalent to going on reserve on a car. An extra 63 kW would give the sufficient safety autonomy navigating at low speeds.

Figure 30 shows the final configuration with the extra safety battery.

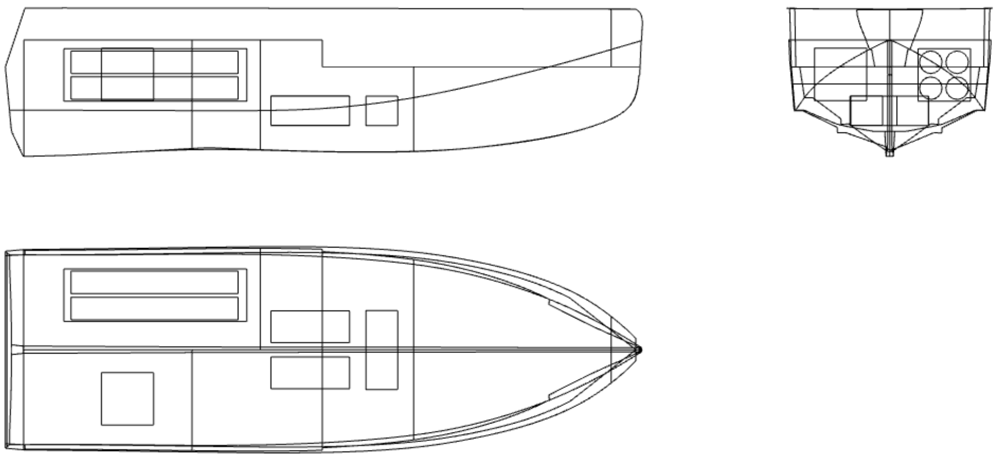


Figure 30. Extra battery distribution

5.1.3. Stability Study

The study of the yacht's stability for this project will be carried out in this section. This study will be evaluated using the ISO 12217-1 criteria (ISO, 2015). To do the stability study, the software *Maxsurf Stability* will be used, since the ISO criteria can be applied to the study.

5.1.3.1. Load Condition

This boat does not contain neither a water tank, fuel tank or slop tank, for this reason, only the maximum load condition will be studied.

The maximum load condition refers to the lightweight of the boat plus their maximum load. Table 22 shows all the elements compiled on the program for this condition.

Table 22. Maximum load conditions

Item Name	Quantity	Unit mass [kg]	Total mass [kg]	LCG [m]	TCG [m]	VCG [m]
Lightship	1	6,385	6,385	5.25	0.0	1.20
Persons	12	75	900	5.0	0.0	1.60
Electric motor	1	190	190	-0.10	0.0	0.82
Fuel cell	1	400	400	2.0	0.95	1.50
H2 storage	1	434	434	2.30	-1.05	1.48
Batteries	3	380	1,140	5.5	0.0	0.80
Total Load case	-	-	9,449	4.71	-0.05	1.20

The maximum weight after these conditions is 9,449 kg. Table 23 shows the main hydrostatics at maximum load.

Table 23. Hydrostatics at maximum load condition

Measurement	Unit	Value
Draft Amidships	m	0.736
Displacement	kg	9,449
Heel angle	deg	-0.3
Draft at FP	m	0.735
Draft at AP	m	0.737
Draft at LCF	m	0.736
Trim (+ by stern)	m	-0.002
Prismatic coefficient	-	0.72

5.1.3.2. Floodable Openings

To demonstrate the level of safety of the boat, an examination of the points where water can enter the vessel is needed, which in this case are the ventilation inlets in both sides, as well as the height at which they are located in relation to the draft of maximum load.

For this study, two flooding points have been defined, being the fuel cell air inlet, plus the H_2 storage ventilation opening, positioned on each side of the yacht. Table 24 shows how they have been defined in the software.

Table 24. Floodable points

Name	LCG [m]	TCG [m]	VCG [m]	Type
H2 storage ventilation	2.30	-1.86	2.0	Down flooding point
Fuel cell ventilation	1.92	1.86	1.85	Down flooding point

5.1.3.3. Flooding Height Test

This test is developed in section 6.1.2. of ISO 12217-1, and is performed on the maximum load condition. Since this yacht is designed with the idea to navigate on coastal zones, its design category is C. Furthermore, according to the standards, the minimum height can be obtained from the next graphic:

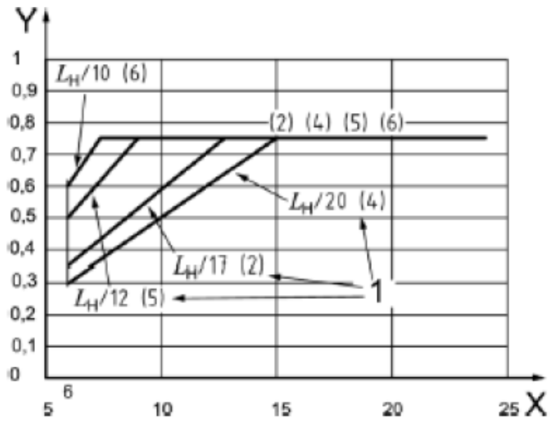


Figure 31. Minimum flooding height for design category C

The height of inundation is the distance between the water line and the first floodable opening. In the normative section 6.1.2, an analysis is carried out to determine what the minimum height should be. To put it another way, no floodable openings can be located closer than the distance specified in section 6.2. The maximum flooding height of a boat with design category C, is determined by the following equation, according to the graphic on Figure 31:

$$\text{MaxFloodHeight} = \frac{Lh}{17} \qquad (5.1)$$

Therefore, the minimum height required is 0.72 meters. The distance between the first floodable opening, which in this case is the fuel cell air inlet, and the flotation line, on the other hand, is 1.114 meters. Furthermore, the requirement is met.

The following figures (32 and 33) show the angle in which both openings would start to flood.

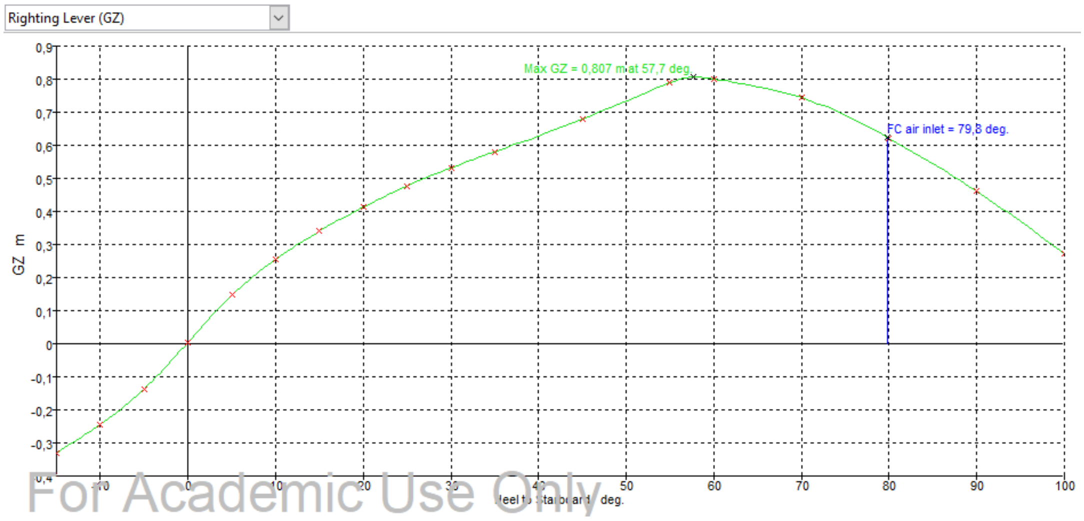


Figure 32. GZ curve at starboard

As seen in Figure 32 the angle of heeling in order for the fuel cell's air inlet to start to flood is 79,8º.

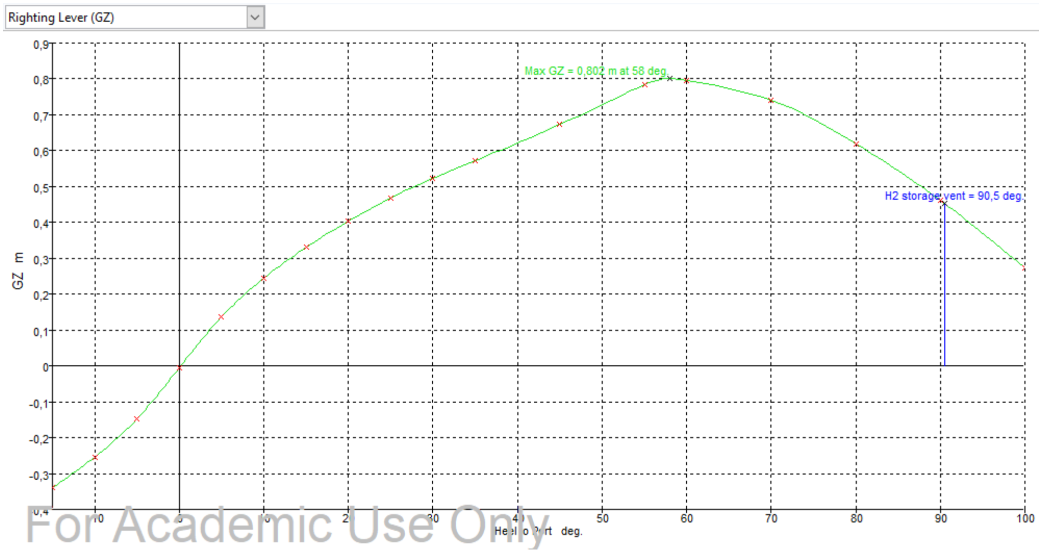


Figure 33. GZ curve at port side

As seen in Figure 33, the angle of heeling in order for the H_2 storage ventilation air inlet to start to flood is 90,5º.

5.1.3.4. Load Compensation Test

The purpose of this test is to check that the boat maintains its stability when the persons on board make a weight change. First the angle of heel must be calculated, this must be less than the one represented by the following equation according to the ISO 12217-1:2017 standard:

$$MaxHeelAngle = 11.5 + \frac{(24-Lh)^3}{520} \qquad (5.2)$$

The maxim heel angle is 14.66º. Also, in accordance with the ISO standards, the minimum freeboard required for the boat category is 0.38 meters.

To do the test analysis, the 12 persons weight computed on the load window will be moved 1.5 meters to the starboard side.

Table 25. Test position of persons

Item Name	Quantity	Unit mass [kg]	Total mass [kg]	LCG [m]	TCG [m]	VCG [m]
Persons	12	75	900	5.0	1,5	1.60

After doing this, the heel angle is 5.2º, which is lower than the required value mentioned previously. In addition, the freeboard is also higher than 0.38 meters, furthermore, all the load compensation requirements by the ISO 12217-1:2017 are fulfilled.

Table 26. Hydrostatics after test

Measurement	Unit	Value
Draft Amidships	m	0.725
Displacement	kg	9,449
Heel angle	deg	5,2

5.1.3.5. Heel Due to Wind

According to the section 6.4 of the ISO standard, the calculation of the heel due to wind only applies to boat's that comply with the following relation:

$$A_{LV} > L * B \qquad (5.3)$$

Where A_{LV} is the area of the hull exposed to the wind, which in this case is 35.093 square meters, much lower than L * B, which is 48,8 square meters. Therefore, since the relation is not complied, this section is not required for the yacht designed.

5.2. Configuration 2

In the second case, the configuration used is the following:

- 6 GH_2 storage cylinders
- 2 $REXH_2$ fuel cells (140 kW)
- 3 batteries (189 kWh) + 1 (safety, 63 kWh)
- 2 outboard Evoy electric motors (180-300 kW)

As well as in the previous section, several figures, will show the propulsive system distribution inside the hull.

Figure 35 shows the basic distribution chosen for this configuration.

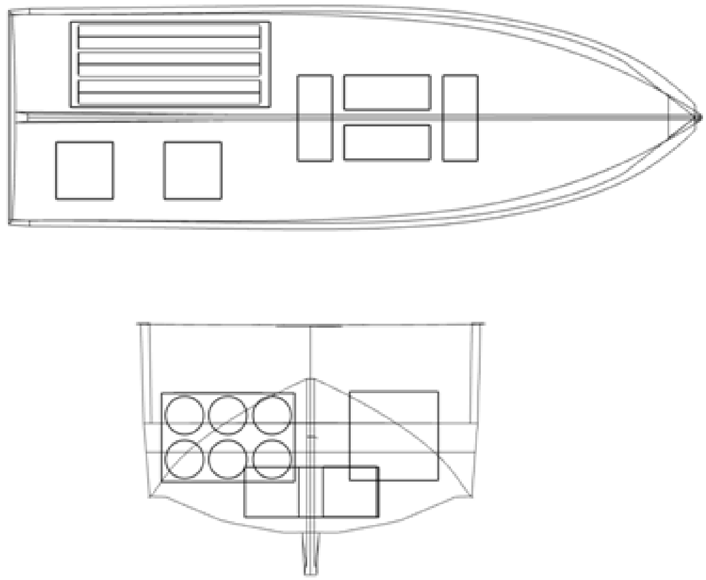


Figure 34. System components layout

Following the same path as previously, after the power plant systems components are distributed, their separation in compartments is a must. For this configuration the separation with compartments is the same. Though, extra room have been added for the two fuel cells to fit.

The final layout with each system placed in its respective compartment is shown in Figure 36:

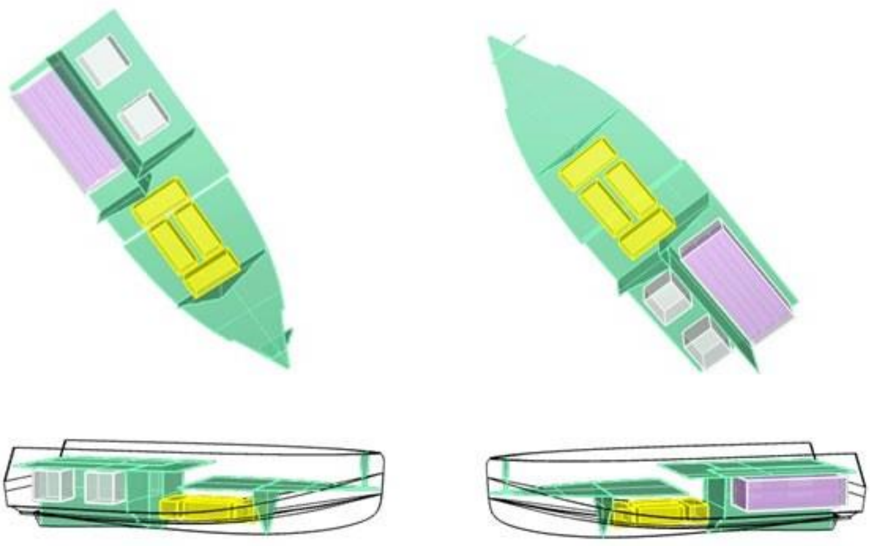


Figure 35. Final distribution layout

Figure 37 shows the general arrangement drawing of the boat and its systems.

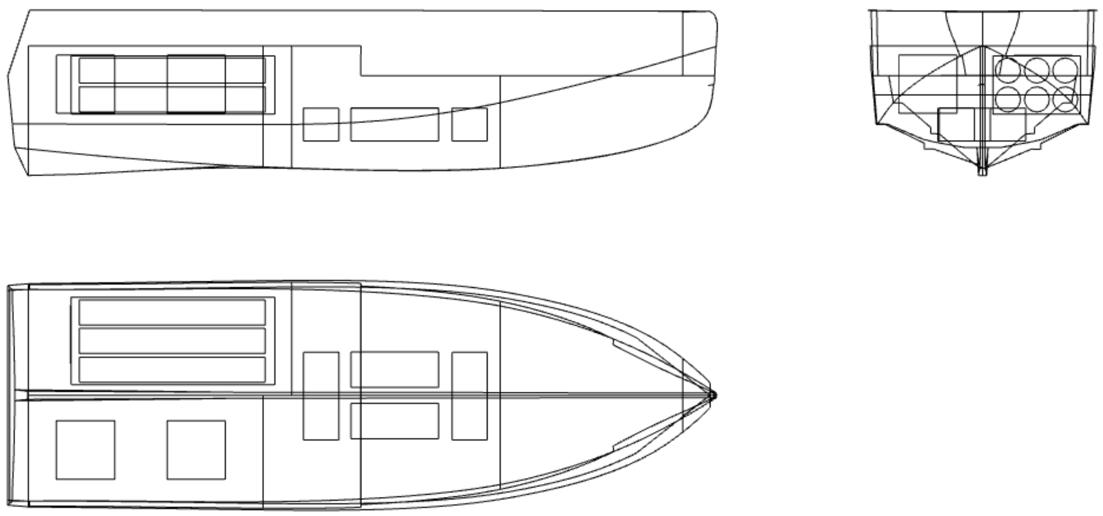


Figure 36. General arrangement

5.2.1. Total Electric Consumption

Table 27 shows the consumption of the different systems:

Table 27. Electric consumption

Element	Electric consumption [kW]
Equipment*	0.3
3 x bilge pumps (4,000 GPH)	0.5
2 x Electric motor at nominal power	180
2 x Electric motor at peak power	300
Total consumption (nominal power)	180.8
Total consumption (peak power)	300.8

*The equipment refers to the different electronic elements on board, such as VHF radio, automatic pilot, GPS/ chart plotter, navigation lights, on boards lights and engine monitors.

5.2.2. Electric Load Balance

For both of the configurations the systems are the same, so the compressed hydrogen storage tank units have the same storage capacity, which is 7.5 kg of GH_2. Since this configuration has 6 tanks, the total hydrogen gas carried on board is 45 kg.

The same calculations as the previous section need to be done. Though, in this case the propulsive system contains two REX H_2 fuel cells, each of one consuming roughly 5 kg of hydrogen per hour. Thus, the total consumption of the fuel cells is 10 kg of hydrogen per hour, which with 45 kg of compressed gas on board, means an autonomy of 4.5 hours of continuous work at a nominal power of 70 kW. Also, in this configuration 3 batteries can give additional power to the system, contributing to 63 kWh each.

Table 28. Electric power supply and consumption

System	Power
2 x REX H_2	140 kW
3 x Batteries	189 kWh
Total consumption (nominal power)	180.8 kW
Total consumption (peak power)	300.8 kW

In order to power the two electric outboard motors at their nominal power of 90 kW, in addition to the other electric equipment which adds up to 180.8 kW, almost the double as the other configuration. Therefore, the fuel cell should work along with the batteries to provide this power required. The fuel cells at nominal power, provide 70 kW each, so the two REX H_2 should provide 140 kW working in parallel. With this in mind, the batteries should provide an extra 41 kWh to supply the necessary power to the systems. Furthermore, with 45 kg of hydrogen on board and with an extra 189 kWh on the batteries, the electric needs could be supplied during 4 hours at nominal power. After that, the fuel cell could provide 140 kW during 0.5 additional hours, or it could feed the batteries and the batteries could power the engines at low speed in order to increase the autonomy. In case of low percentage of H_2, the extra battery could power the engines at a low speed in order to give an extra autonomy.

In accordance with the resistance results of "APPENDIX 2- RESISTANCE RESULTS", the 180 kW power delivered by the electric engines, implies a cruise speed of 20 knots during 4 hours.

The peak power of the two electric engine is 300.8 kW. To supply that, the batteries should deliver 161 kWh, added to the 140 kW delivered by the fuel cells. Therefore, this implies an autonomy of just 1 hour, but a top speed of 30 knots could be reached in accordance with the resistance results, which for a zero emissions boat is a great performance.

The performance results of this configuration can be seen in Table 29:

Table 29. Configuration 2 performance results

Speed (knots)	Autonomy	Navigation
20	4 hours - 80 nautical miles	Cruise speed
30	1 hour - 30 nautical miles	Top speed

In conclusion, unlike the other configuration, in this case we sacrifice autonomy in order to reach higher speeds. This configuration, with a cruise speed of 20 knots during 4 hours, the boat has a range of 80 nautical miles, which in fact is a higher range than the other system disposition. Also, the extra range at low speed given by the extra hydrogen and the extra safety battery need to be also considered. While this configuration seems to deliver a better performance, the weight of the machinery almost doubles, and with it, the cost of the boat also increases.

5.2.3. Stability Analysis

In this case, the same study as the previous configuration will be followed, using the ISO 12217-1 criteria. To do the stability study, the software *Maxsurf Stability* will be used as well, since the ISO criteria can be applied to the study.

5.2.3.1. Load Condition

The maximum load condition refers to the lightweight of the boat plus its maximum load, including the persons and systems on board. Table 30 shows all the elements compiled on the program for this condition.

Table 30. Maximum load condition

Item Name	Quantity	Unit mass [kg]	Total mass [kg]	LCG [m]	TCG [m]	VCG [m]
Lightship	1	6,385	6,385	5.25	0.0	1.20
Persons	12	75	900	5.0	0.0	1.60
Electric motor	2	190	380	-0.10	0.0	0.82
Fuel cell	2	400	800	2.28	0.95	1.50
H2 storage	1	651	651	2.30	-0.86	1.48
Batteries	4	380	1,520	6.50	0.0	0.80
Total Load case	-	-	10,636	4,81	0.019	1.20

The maximum weight in this condition is 10,636 kg. Table 31 shows the main corresponding hydrostatic properties.

Table 31. Hydrostatics at maximum load condition

Measurement	Unit	Value
Draft Amidships	m	0.77
Displacement	kg	10,636
Heel deg	-	0.6
Draft at FP	m	0.76
Draft at AP	m	0.784
Draft at LCF	m	0.775
Trim (+ by stern)	m	0.025
Prismatic coefficient	-	0.721

5.2.3.2. Floodable Openings

For this section, the same characteristics as the previous configuration are provided.

5.2.3.3. Flooding Height Test

The same criteria of the previous configuration will be followed, so the requirements are the same. Therefore, the minimum height required is 0.72 meters.

The distance between the first floodable opening, which in this case is the fuel cell air inlet, and the flotation line, is 1.08 meters. Furthermore, the requirement is met as well.

The following figures (38 and 39) shows the angle in which both openings would start to flood.

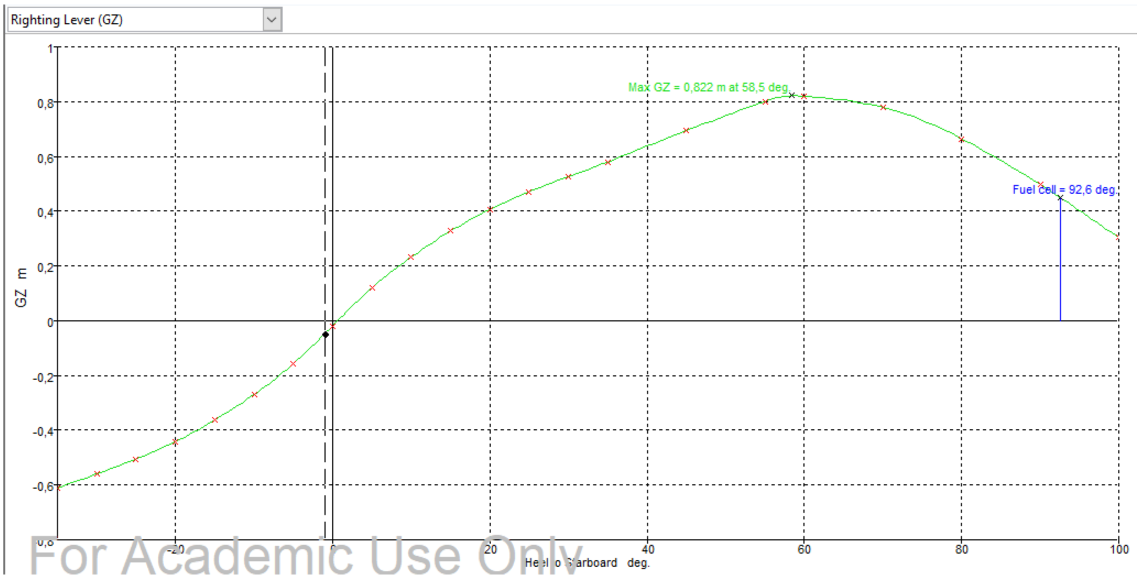


Figure 37. GZ curve at starboard side

As seen in Figure 38, the angle of heeling in order for the fuel cell's air inlet to start to flood is 92.6º.

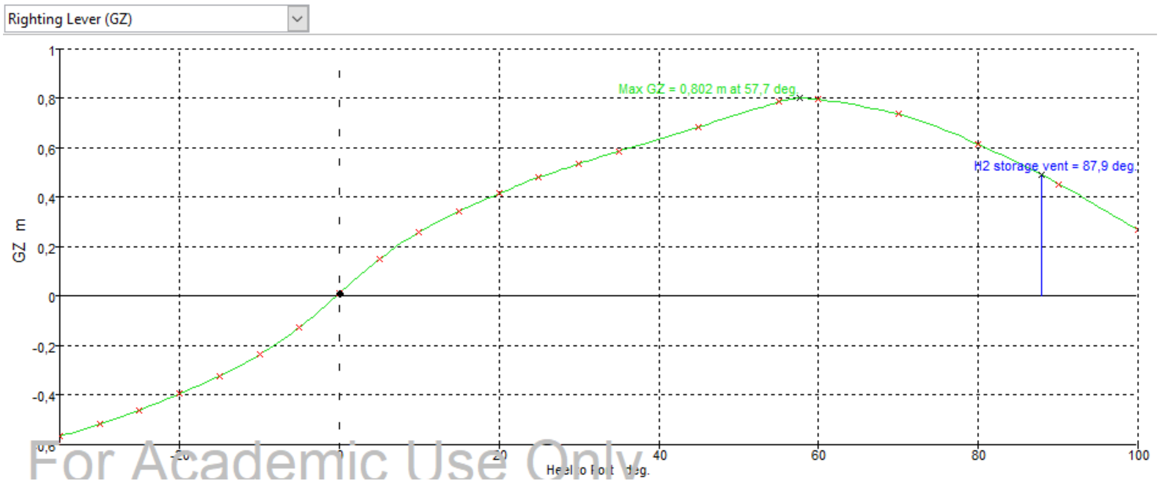


Figure 38. GZ curve at port side

As seen in Figure 39, the angle of heeling in order for the H_2 ventilation air inlet to start to flood is 87.9º.

5.2.3.4. Load Compensation Test

Same criteria and calculations as for the previous configuration are used.

Therefore, the maxim heel angle is 14.66º. Also, in accordance with the ISO standards, the minimum freeboard required for our type of boat is 0.38 meters.

To do the test analysis, the 12 persons weight computed on the load window will be moved 1.5 meters to the starboard side, the same way as the previous configuration. After doing this, the heel angle is 5.4º, which is lower than the required value mentioned previously. In addition, the freeboard is also higher than 0.38 meters, furthermore, all the load compensation requirements by the ISO 12217-1:2017 are fulfilled.

Table 32. Hydrostatics after test

Measurement	Unit	Value
Draft Amidships	m	0.761
Displacement	kg	10,636
Heel angle	deg	5.4

5.2.3.5. Heel Due to Wind

According to the section 6.4 of the ISO standard, the calculation of the heel due to wind only applies to boat's that comply with the relation mentioned in the previous configuration.

In this case, ALV, which is the area of the hull exposed to the wind, is 35.446 square meters, much lower than L * B, which is 48,8 square meters. Therefore, as well as in the first configuration, since the relation is not complied, this section is not required for the yacht designed.

5.3. Performance Results Conclusion

After analyzing both configurations, the final results are presented in Table 33:

Table 33. Summary of configurations

	Propulsive System	Power Supplied	Speed (knots)	Autonomy (h - nm)
Configuration 1 (30 kg of H_2)	Fuel cell (nominal power)	70 kW	12	6 - 72
	Batteries	126 kWh	< 10	Depends on the speed
	Fuel cell + Batteries (cruise speed)	> 90.8 kW	14	6 - 84
	Fuel cell + Batteries (top speed)	> 150.8 kW	18	1 - 30
Configuration 2 (45 kg of H_2)	Fuel cell (nominal power)	140 kW	18	4 - 72
	Batteries	189 kWh	< 10	Depends on the speed
	Fuel cell + Batteries (cruise speed)	< 180.8 kW	20	4 - 80
	Fuel cell + Batteries (top speed)	< 300.8 kW	30	1 - 30

Both configurations are analyzed with the electric motor and the fuel cell working at nominal or peak power. For this particular reason, higher speeds have been reached while the autonomy is poor compared to traditional systems. However, reducing the speed, a larger autonomy could be possible, as the resistance curve is exponential, consequently for higher speeds the power increases in an exponential form. For instance, a good case scenario would be if the fuel cell was working at half of its nominal power, consuming only 2.5 H_2 kg/h, maintaining a speed of 10 knots for the different conditions and configurations. The results would be different, compared as the previous ones at nominal and peak power, as seen on Table 34:

Table 34. Results at half of nominal power

	Propulsive System	Power Supplied (kW)	Speed (knots)	Autonomy (h - nm)
Configuration 1 (30 kg of H_2)	Fuel cell	35	10	12 - 120
	Fuel cell + Batteries	35	10	15.5 - 155
Configuration 2 (45 kg of H_2)	Fuel cell	70	10	18 - 180
	Fuel cell + Batteries	70	10	23.5 - 235

After analyzing the results, in order to get closer to current conventional systems, either speed or autonomy need to be sacrificed, as if a speed of 30 knots is sought, a poor autonomy of 4 hours of navigation is the result. On the other hand, if a large autonomy of almost a day is required, a speed of only 10 knots is the one possible.

Nevertheless, this gives the opportunity to choose between the different options and possible outcomes depending on what is wanted in a particular moment, giving the option to combine these two options of high speed or large autonomy, and to find the optimal option where both of them can meet in a good manner.

In conclusion, as seen in Table 33, working at nominal and peak powers allow the boat to reach high speeds while having a poor but rather acceptable autonomy. On the other hand, working at half of the nominal power, as seen in Table 34, allows the yacht to navigate at 10 knots in accordance with the resistance results, and gives a large autonomy of 23.5 hours or 235 nautical miles for the second configuration.

6. CONCLUSIONS AND RECOMMENDATIONS

The objective with this thesis was to do a substantial research into hydrogen's role as an alternative fuel, and apply it to a boat basic design, especially its propulsive system. Lately, full electric transportation has been the main topic, while hydrogen technology has been on the sideline, although its potential is enormous.

Using hydrogen as a fuel can contribute to a sustainable future, but it is important to remark that its production must be using green energy, decarbonizing the entire process, from production, to transport, to use in power generation. Hydrogen cannot be considered a clean alternative fuel if it is not produced using renewable resources or emits low greenhouse gases emissions, hence only green and blue hydrogen must be used in the maritime domain. Hydrogen does have considerable potential as a net-zero carbon alternative fuel, but its production requires significant investment because it must be produced using renewable energy sources. Renewable energy sources that can generate enough energy for this process include solar, wind, and nuclear power generation.

Regarding the hull design, a yacht with squared forms was the one chosen for the design, so models from shipyards like DeAntonio, Pardo or Fjord were taken as guidance. Also, a planning hull was the goal in order to reduce the vessel's drag which as a result can lead to a reduction on the fuel consumption and an improvement in speed and range. With this in mind, the final design included V-shaped frames on the bow, but more flat forms in the aft plus a sharp wide transom. Also, the implementation of hard chines and spray rails was a must to obtain a planning hull. In the end, once the hull was done, the analysis of certain parameters and relations showed that the hull designed was most likely a planning hull.

For the propulsive system selection, a hydrogen-electric configuration was chosen, as it is the more feasible zero-emissions option in terms of weight and performance. The combination of fuel cells and batteries is seen as the best option for a zero-emissions pleasure craft, since according to the analysis, the installation allows the boat to reach high speeds as high as 30 knots, and overall gives a great autonomy. Specifically, the elements for the power plant are a hydrogen storage system, a fuel cell, a bank of batteries plus a PLC. For the hydrogen storage system, type IV composite cylinders of compressed hydrogen at 350 bar were chosen, due to their great gravimetric characteristics and their light weight. A PEMFC is the type of fuel cell chosen, since they were designed primarily for lower-scale mobility power applications, and they have a higher power density, less weight, high efficiency, and the ability to work well in cold and transient conditions, plus they are one of the lightest and smallest fuel cells available. Finally, an outboard electric motor was chosen in order to gain more space inside the hull.

Once the propulsive system was selected, two configurations were considered. The first one, has four compressed hydrogen cylinders, a PEMFC, three batteries and an outboard electric engine. This particular set-up showed that the systems could be fitted inside the hull easily, and the consumption of the motor could be supplied by the zero-emissions systems on board with no problem whatsoever. In fact, the hydrogen stored plus the electricity in the batteries could propel the boat for 6 hours at a cruising speed of 14 knots at nominal power, which means a range of 84 nautical miles, and a top speed of 18 knots at peak power. Therefore, this configuration affirms one of the main problems with zero-emission craft, which is the low speeds and low autonomies. Though, for a zero emissions yacht, this is a good performance. However, with the fuel cell working at half of its nominal power, the speed was reduced by 4 knots, while the autonomy doubled.

The second configuration was built up with six compressed hydrogen cylinders, two PEMFC, four batteries and two outboard electric engines. Even though a lot of systems were used for this configuration, all of them could be fitted inside the hull and the stability study showed that it did not bring any problem for the stability of the boat. In this case, the presence of two electric engines brought a higher electric consumption, however, the power supplied by the systems was able to supply the sufficient electricity in order to propel the yacht for 4 hours at a cruise speed of 20 knots at nominal power of the electric motor, with a total range of 80 nautical miles. Also, with the combination of the fuel cells and the batteries, a top speed of 30 knots could be attained at peak power, but too much energy is consumed to reach this level. Furthermore, although this configuration implies to double the consumption of the previous one, which means higher operational costs, this set-up brings the zero-emissions design closer to conventional engine yachts. The main problem is that in order to get closer to conventional engine yachts in terms of speed, a lot of machinery is needed, such as in this case, where three different systems were needed to feed the power consumed by the electric engines, instead, on the other hand, for conventional engine crafts, only a fuel tank is required to feed the engines, and currently, can give better performances. In addition, because of the amount of systems required, the total price increases in comparison with traditional systems. For instance, a Mercury 400 hp outboard motor can cost around 40,000 € to 60,000 € and supply a power of 300 kW. On the other hand, the Evoy electric motor itself costs 40,000 €, and being currently the most powerful electric outboard motor in the market, supplies 90 kW of power. So, with the two motors plus the batteries, which can cost around 25,000 € each, and the other systems, the total price of the propulsive systems alone could be from 6 to 10 times more expensive than with a traditional engine. Furthermore, the price of the systems needed in relation with the autonomy and the power delivered in comparison with traditional engines is the biggest current barrier for these types of systems. However, if the fuel cell was used at half its nominal power in this configuration, navigating at 10 knots, an autonomy of 23.5 hours could be accomplished, which is a large autonomy, and is at the same level as traditional engine boats.

To sum up, the main conclusion is that it is feasible to have a hydrogen-electric propulsive system that produces zero-emissions. Pleasure crafts with this system can give good performances with a certain facility of installation, and the main problem in relation with GHG emission can be solved. Though, currently it is not yet as advanced as it should be, as compared to fuel engines, the performances and the commodity is still far away, and different barriers or issues are still presented. For instance, the inability to carry large amounts of hydrogen, the higher costs of either hydrogen or the capital cost of the laborious installations, along with the problems with power to weight brought on by the poor power and autonomy that such heavy machinery provides. Also, there are the safety challenges. Since hydrogen is a dangerous gas due to its risk of explosion, and there are not enough safety studies on the gas's safety on ships. One of the biggest problems with using hydrogen as a fuel is the safety risks associated with its intrinsic characteristics. The primary safety concerns for this element are its flammable properties and range which also increases when mixed with pure oxygen. In parallel to the obstacles on board, the infrastructure for refueling hydrogen is currently limited, which must be taken into account for this technology to advance as well as the non-existing regulations for hydrogen as a maritime fuel. Therefore, hydrogen systems are still far away from traditional fuels, for this reason they need evolution, maturation and innovation if the idea is to replace the current overall propulsive methods for hydrogen systems. However, it is clear that hydrogen as a maritime fuel has great potential, and it is seen worldwide, so with investments in technology and infrastructure, there is no doubt that this technology can thrive and hydrogen can be the fuel of the future if the different current challenges can be overcome.

As a recommendation for further work, the design of the yacht could be adapted to the zero-emissions systems needed, as in this case, the systems have been adapted to the boat previously designed. Hence, if an optimized design is the goal, the best path would be to adapt the hull design to the systems that will form the propulsive system, such as batteries, H_2 tanks and fuel cells. Furthermore, the idea would be to design a hull considering the space and dimensions that those installations would occupy, so a more optimized hull could be designed and in consequence a better performance could be accomplished.

Additionally, if a bigger installation was the case of study, a precise study regarding the safety systems for the hydrogen installation could be added and applied to the design, giving detail on the safety equipment and the respective connection and functions.

Since only green and blue hydrogen can be used for zero-emissions mobility, specific research regarding the production and potential of both of them would be really interesting in order to study hydrogen as an alternative fuel.

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APPENDIX 1- BOAT DATABASE

	Lh	B	T	Δ
DeAntonio				
D36	11,23	3,4	0,6	4500
D42	12,1	3,99	0,7	7600
D46 Open	13,9	4,4	0,7	11000
D46 Cruiser	14,9	4,4	0,7	11500
D50	13,1	4,4	0,7	11000
Pardo Yachts				
P38	10,95	3,6	0,9	7000
P43	12,8	4,2	1,05	9870
P50	14,95	4,96	1,23	14900
Fjord Yachts				
38 Open	11,5	3,64	1,03	6400
38 Xpress	11,63	3,64	0,94	8225
40 Open	11,99	3,99	1	9800
41 XL	12,15	3,99	1,17	11560
44 Open	11,99	4,25	1,04	9570
44 Coupe	11,99	4,25	1,14	11250
Austin Parker				
36 Open	9,94	3,72	1	10700
38 Ibiza	11,3	3,64	1	9000
44 Ibiza	12,5	4,21	1,1	15000
Beneteau				
Flyer 10	9,63	3,35	1	5688
Antares 11	9,9	3,4	0,8	5723
Antares 11 Fly	9,9	3,4	0,97	6148
GT 45	13,5	4,15	1,2	11214
GT 41	11,5	3,85	0,94	7959
GT 36	11,28	3,48	0,9	7276
ST 48	12,77	4,42	1,15	12200
ST 41	12,52	4,2	1,15	11040
Jeanneau				
DB 43	11,95	3,82	0,94	9800
NC 37	9,86	3,59	1,07	6832
Cranchi				
A46	14,25	4,33	1,17	13500
T36	11,85	3,53	1	8500
T43	13,8	4,37	0,9	13700
M44 HT	13,82	4,06	0,96	10900
Princess				
V40	12,65	3,81	1,02	10145
V50	15,35	4,08	1,09	15898
Astondoa				
377- Coupe	11,61	3,56	0,81	11300
Azimut				
Verve 42	12,9	3,94	1,2	14000

APPENDIX 2- RESISTANCE RESULTS

	Speed (kn)	Froude No. LWL	Froude No. Vol.	Savitsky Pre-planing Resist. (kN)	Savitsky Pre-planing Power (kW)	Savitsky Planing Resist. (kN)	Savitsky Planing Power (kW)
1	0,000	0,000	0,000	--	--	--	--
2	0,750	0,035	0,082	--	--	--	--
3	1,500	0,071	0,163	--	--	--	--
4	2,250	0,106	0,245	--	--	--	--
5	3,000	0,142	0,326	--	--	--	--
6	3,750	0,177	0,408	--	--	--	--
7	4,500	0,213	0,490	--	--	--	--
8	5,250	0,248	0,571	--	--	--	--
9	6,000	0,284	0,653	--	--	--	--
10	6,750	0,319	0,735	--	--	--	--
11	7,500	0,355	0,816	--	--	--	--
12	8,250	0,390	0,898	--	--	--	--
13	9,000	0,426	0,979	--	--	--	--
14	9,750	0,461	1,061	5,6	28,137	--	--
15	10,500	0,497	1,143	7,7	41,543	--	--
16	11,250	0,532	1,224	9,8	56,996	--	--
17	12,000	0,568	1,306	11,7	72,110	10,9	67,200
18	12,750	0,603	1,387	12,3	80,514	11,5	75,305
19	13,500	0,639	1,469	12,4	85,910	12,1	83,926
20	14,250	0,674	1,551	12,6	92,336	12,7	92,997
21	15,000	0,710	1,632	12,9	99,907	13,3	102,429
22	15,750	0,745	1,714	13,3	107,553	13,8	112,107
23	16,500	0,781	1,796	13,6	115,019	14,4	121,907
24	17,250	0,816	1,877	13,7	121,886	14,8	131,706
25	18,000	0,852	1,959	14,0	129,507	15,3	141,402
26	18,750	0,887	2,040	--	--	15,6	150,920
27	19,500	0,923	2,122	--	--	16,0	160,217
28	20,250	0,958	2,204	--	--	16,2	169,282
29	21,000	0,994	2,285	--	--	16,5	178,127
30	21,750	1,029	2,367	--	--	16,7	186,784
31	22,500	1,065	2,448	--	--	16,9	195,294
32	23,250	1,100	2,530	--	--	17,0	203,707
33	24,000	1,136	2,612	--	--	17,2	212,074
34	24,750	1,171	2,693	--	--	17,3	220,445
35	25,500	1,207	2,775	--	--	17,4	228,869
36	26,250	1,242	2,857	--	--	17,6	237,393
37	27,000	1,278	2,938	--	--	17,7	246,060
38	27,750	1,313	3,020	--	--	17,9	254,907
39	28,500	1,349	3,101	--	--	18,0	263,973
40	29,250	1,384	3,183	--	--	18,2	273,289
41	30,000	1,420	3,265	--	--	18,3	282,887

APPENDIX 3- HEXAGON PURUS CYLINDERS SPECIFICATIONS

Hydrogen type 4 tank information*

Hexagon Purus

	Nominal working pressure (15°C)	Outside diameter	Overall length	Tank weight	Water volume	Hydrogen capacity	Weight ratio (hydrogen weight/tank weight)	Suitable for neck mount	Approval
	MPa	mm	mm	kg	L	kg	%		
A	25	503	2342	94	350	6.3	6.7	✔	TPED
B	25	654	2413	147	581	10.4	7.1	✔	ABS/US DOT
C	25	653	4419	267	1170	21.0	7.9	✔	ABS/US DOT
D	25	653	5689	342	1544	27.8	8.1	✔	ABS/US DOT
E	30	509	2342	112	350	7.4	6.6	✔	TPED
F	31.8	503	2342	94	350	7.8	8.3	✔	TPED/ADR**
G	35	430	3190	101	312	7.5	7.4	✔	EC79/HGV2
H	35	430	2110	67	193	4.7	7.0	✔	EC79/HGV2
I	35	509	2342	112	350	8.4	7.5	✔	EC79
J	38.1	509	2342	112	350	9.0	8.0	✔	TPED/ADR**
K	50	520	2424	180	347	11.0	6.1		TPED
L	70	332	921	33	36	1.4	4.2	✔	EC79
M	70	440	1050	59	76	3.1	5.3	✔	R-134/HGV2
N	70	530	2154	188	244	9.8	5.2	✔	EC79/HGV2
O	70	705	2078	272	457	18.4	6.8	✔	R-134/ HGV2 planned
P	95	515	2783	365	254	12.4	3.4	✔	PED/US DOT

APPENDIX 4- $REXH_2$ SPECIFICATIONS