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School of Naval Architecture and Marine Engineering



Dissertation

Of

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Techno-economic analysis of a green hydrogen refuelling station for a  
fuel cell powered ferry

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Athens 2022,

Lefteris Epaminonda

## Abstract

Climate change and fossil fuel depletion are the main reasons leading to hydrogen technology. As society and policymakers become increasingly concerned with greenhouse gases and air pollution, shipping emissions are attracting attention. Hydrogen is considered by many as a potential clean fuel for vessels with its ease of production from renewable electricity. This study evaluates the development of zero-carbon marine fuel production, storage, and fuelling for short-distance ferries from a techno-economic aspect. More clearly, the objective is to provide solutions resulting in the reduction of greenhouse gases and air pollution.

The primary purpose of this study is to offer a competitive integrated stand-alone system for zero-carbon propulsion of short-distance ferries employing various plant configurations in terms of hydrogen production capacity and electricity mix. Utilizing the levelized cost of hydrogen and the net present cost for all proposed scenarios, the technical results are used to evaluate economic feasibility. The primary objective is to identify the optimal functioning situation with the lowest levelized cost of hydrogen and perform an Installation example of a standard Ferry Route in Greece by calculating the NPV, IRR, and Payback period.

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# 1. Introduction

## 1.1 Incentive

Since ancient times, mankind has been concerned with innovation and the advancement of new technologies. In some cases, the development was effective, however, the long-term negative effects on the environment have been significantly ignored.

In this day and age, the emission of greenhouse gases (GHG) into the atmosphere has been the result of the uncontrolled use of fossil fuels poses a massive threat to the global environment and, consequently, to climate change (Hites, 2006). In addition, the rising energy demand has necessitated a rise in the pricing of conventional fuels, exposing and declining *import-dependent nations' economies*.

World's energy demand increases significantly because of population growth and industrial evolution. It is important to note that the population has been increased by 2 billion just in one generation and major contribution has been given by developing countries. Preventing an energy crisis in one of the most casual issues of the 21st century. Energy demand is therefore increasing fast in order to meet the requirements of growing population in the world. Different countries in the world have their own strategies, plans, policies, and control measures to establish themselves in the world. As of the population growth and development initiatives, resources available in the world are getting depleted. [Shafiee and Topal 2009].

It is well known that the ecosystem is polluted heavily because of the emission of various gases generated from burning of fossil fuel which are readily available and commonly used for satisfying energy demand in the world. Therefore, by introducing non-renewable energy sources would not definitely meet energy demand since they are exhaustible and limited source of energy [Koroneos, C., Spachos, T. and Moussiopoulos, N., 2003]. All the countries should be able to use the resources to recover energy for setting up an environment conducive for human survival for a long period of time. However, it is not practiced properly to carry out such a task since many countries rely on exhaustible energy sources and avoid renewable energy sources. Furthermore, the continuous use of non-renewable energy sources may contribute negatively to climate change, which will subsequently cause major natural disasters in the ecosystems of the planet [Schou, P., 2000].

It is a known fact that many controversial issues, which lead to disaster, are going among countries because the dominant parties tend to access the places which are abundant in fossil fuel reserves. As a matter of fact, the most recent example has been the ongoing war between Ukraine and Russia, caused due to the constant and growing demand in Energy and Natural Resources. More clearly, the reasons of the war can be justified as *taking Ukraine's energy* would provide Russia the second-largest natural-gas reserves in Europe, worth more than 1 trillion dollars. Also, it is worth mentioning the provision of oil and condensate worth as much as 400 billion dollars, and a significant part *of Ukraine's coal which is the sixth largest reserve* base in the world. Additionally, Russia would consolidate an extraordinary strategic geopolitical advantage with ports on the Black Sea and the Sea of Azov, placing Russia at the centre of global energy supply to the vast European and Asian markets for the foreseeable future [Johannesson, J. and Clowes, D., 2022].

An additional consequence caused by greenhouse gases is in the air temperatures on Earth which have been rising since the Industrial Revolution. While natural variability plays an important role, the preponderance of evidence indicates that human activities particularly

emissions of heat-trapping greenhouse gases are mostly responsible for making our planet warmer.

According to an ongoing temperature analysis led by scientists at NASA's Goddard Institute for Space Studies (GISS), the average global temperature on Earth has increased by at least 1.1° Celsius (1.9° Fahrenheit) since 1880. Most of the warming has occurred since 1975, at a rate of roughly 0.15 to 0.20°C per decade as demonstrated in Figure 4. The maps below show temperature anomalies between the years 1970-1974 and 2017-2021 and we can clearly observe the huge impact human activities have on the planet. These are not absolute temperatures, but changes from the norm for each area [NASA, National Aeronautics and Space Administration Goddard Institute for Space Studies].

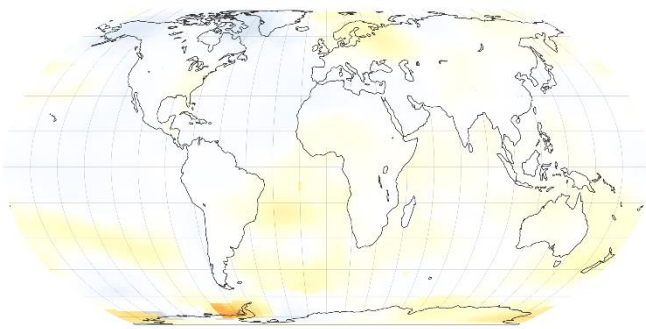


Figure 1 Temperature Anomaly (°C) 1970-1974 The World of Change: Global Temperatures [earthobservatory.nasa.gov]

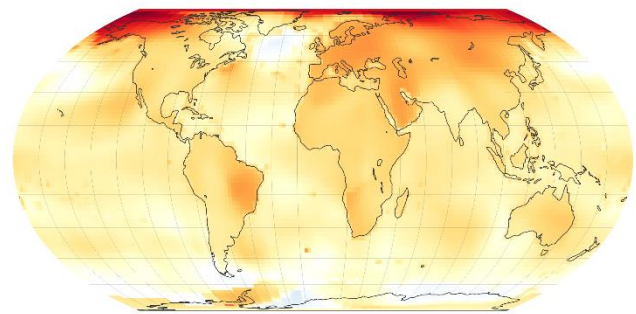


Figure 2 Temperature Anomaly(°C) 2017-2021 The World of Change: Global Temperatures [earthobservatory.nasa.gov]



Figure 3 Temperature Anomaly in °C compared to the average of 1951-1980 [earthobservatory.nasa.gov]

Global warming, which is synonym to climate change, is defined as the drastic change in temperature over the last few years comparatively to the historical trend. This trend will continue and even worsen if policymakers do not adopt the measures necessary to protect the planet, such as limiting gas emission and minimizing its sources as much as possible and introducing preventative solutions. One solution is to develop in further renewable energy technology, expand its use, encourage investment in different and healthier fuels and renewable energy resources and minimize the manufacture of polluting objects. Future energy sources must meet the requirements of being carbon-free and renewable for the long-term mitigation of climate change and reduction in reliance on oil imports [Lund, H., 2007].

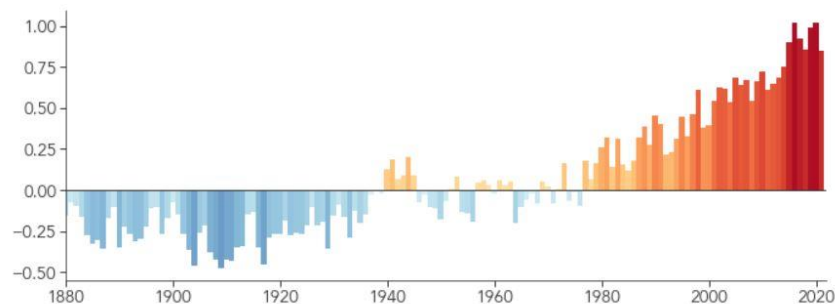


Figure 4 Global Temperature Anomaly from 1880-2021 compared to the average of 1951-1980 [https://earthobservatory.nasa.gov/]

## 1.2 IMO strategy on the reduction of GHG emissions from ships

Countries are now pursuing aggressively GHG (Greenhouse Gas) emission reduction measures because of the 2015 Paris Agreement. More clearly, the Paris Agreement establishes a global framework for preventing dangerous climate change by limiting global warming to well below 2 degrees Celsius and pursuing efforts to limit it to 1.5 degrees Celsius. It also seeks to enhance countries' ability to combat the effects of climate change and to support their efforts. The Paris Agreement is the world's first universal, legally binding agreement on climate change. It was adopted at the 2015 Paris climate conference (COP21). Close to 190 Parties to the Paris Agreement include the EU and its Member States. The EU ratified the agreement formally on 5 October 2016, paving the way for its implementation on 4 November 2016. At least 55 countries representing at least 55 percent of global emissions were required to deposit their instruments of ratification for the agreement to enter into force [European Commission].

Moreover, IMO adopted the initial GHG strategy in 2018 calls for a reduction in carbon intensity of international shipping (to reduce CO<sub>2</sub> emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008) and that total annual GHG emissions from international shipping should be reduced by at least 50% by 2050, compared to 2008. The strategy includes a specific reference to "a pathway for reducing CO<sub>2</sub> emissions consistent with the temperature goals of the Paris Agreement." The initial strategy is a framework for Member States, outlining the future vision for international shipping, the levels of ambition to reduce GHG emissions, and guiding principles. It also includes candidate short-, medium-, and long-term further measures with potential timelines and state-level impacts. Additionally, the strategy identifies obstacles and supportive measures, such as capacity building, technical cooperation, and research and development (R&D) [IMO].

Furthermore, the International Maritime Organization (IMO) continues to contribute to the global fight against climate change in support of UN Sustainable Development Goal, to take immediate action to combat climate change and its effects. IMO has adopted mandatory measures to reduce emissions of greenhouse gases from international shipping, in accordance with IMO's pollution prevention treaty (MARPOL) - the Energy Efficiency Design Index (EEDI) is mandatory for new ships, and the Ship Energy Efficiency Management Plan is mandatory for existing ships (SEEMP). All the measures mentioned above, are explained in depth in the following sub-chapters of this research.

### 1.2.1 The International Convention for the Prevention of Pollution from Ships (MARPOL)

The International Convention for the Prevention of Pollution from Ships (MARPOL) has been initiated by International Maritime Organization (IMO) and it is the main international convention covering prevention of pollution in the marine environment create by the vessels either from operational or accidental causes. They have been developed six technical Annexes to the Convention, all of which have as a main objective to prevent and minimise accidental and routine ship pollution. In many Annexes, there are Special Areas with strict operational discharge controls which are as explained below:



- Annex I Regulations for the Avoidance of Oil Pollution (Entered into force 2 October 1983):

The 1992 amendments to Annex I made it mandatory for new oil tankers to have double hulls and introduced a phase-in schedule for existing tankers to install double hulls. This schedule was subsequently revised in 2001 and 2003.

- The Annex II Regulations for the Control of Pollution by Bulk Toxic Liquid Substances (entered into force 2 October 1983):

Details the discharge criteria and measures for the control of pollution by noxious liquid substances carried in bulk. Approximately 250 substances were evaluated and included in the list appended to the Convention, the discharge of their residues is only permitted to reception facilities when certain concentrations and conditions (which vary by substance category) are met. Within 12 miles of the nearest land, no discharge of residues containing toxic substances is permitted.

- Annex III Preventing Pollution Caused by Dangerous Substances Transported by Sea in Packaged Form (Entered into force 1 July 1992):

Includes general requirements for the publication of detailed standards on packaging, marking, labelling, documentation, stowage, quantity limitations, exceptions, and notifications. Harmful substances are substances identified as marine pollutants in the International Maritime Dangerous Goods Code (IMDG Code) or which meet the criteria in the Appendix of Annex III for the purposes of this Annex.

- Annex IV Preventing Pollution from Ships' Sewage (Entered into force 27 September 2003):

The discharge of sewage into the sea is prohibited unless the ship has an approved sewage treatment plant or is discharging classified and disinfected sewage using an approved system at more than three nautical miles from the nearest land; sewage that is not classified or disinfected must be discharged at a distance of more than 12 nautical miles from the nearest land.

- Annex V Prevention of Pollution by Ships' Waste (Entered into force 31 December 1988):

Deals with various types of waste and specifies the distances from land and the way they may be disposed. The most important aspect of the Annex is the complete ban on the disposal of all types of plastics into the ocean.

- Annex VI Air Pollution Prevention from Ships [Entered into force 19 May 2005]:

Sets limits on sulphur oxide and nitrogen oxide emissions from ship exhausts and prohibits intentional emissions of ozone depleting substances; designated emission control areas set stricter standards for SO<sub>x</sub>, NO<sub>x</sub>, and particulates. The Emission control areas are the Baltic Sea, the North Sea, the North American and the United States Caribbean Sea. In Figure 5 the emission control areas are shown in green.



Figure 5 Emission Control Areas  
[<https://www.egcsa.com/regulatory/>]

Moreover, the control of diesel engine NO<sub>x</sub> emissions is achieved through the survey and certification requirements leading to the issue of an Engine International Air Pollution Prevention (EIAPP) Certificate and the subsequent demonstration of in-service compliance in accordance with the requirements of the mandatory. The NO<sub>x</sub> control requirements of Annex VI apply to installed marine diesel engine of over 130 kW output power other than those used solely for emergency purposes irrespective of the tonnage of the ship onto which such engines are installed.

Different levels (Tiers) of control apply and within any Tier the actual limit value is determined *from the engine's rated speed*. Tier I and Tier II limits tend to be global, while the Tier 3 standards apply only within NO<sub>x</sub> Emission Control Places.

Figure 6 illustrates NO<sub>2</sub> emission limits (gr/Kwh) depending on the nominal speed engine (RPM). Firstly, Tier which is in red is constructed on or after 1 Jan. 2000. Secondly, Tier II in blue is constructed on or after 1 January 2011. Thirdly, Tier III which is in green is constructed on or after 1 Jan. 2016. [NO<sub>x</sub> Regulation 13].

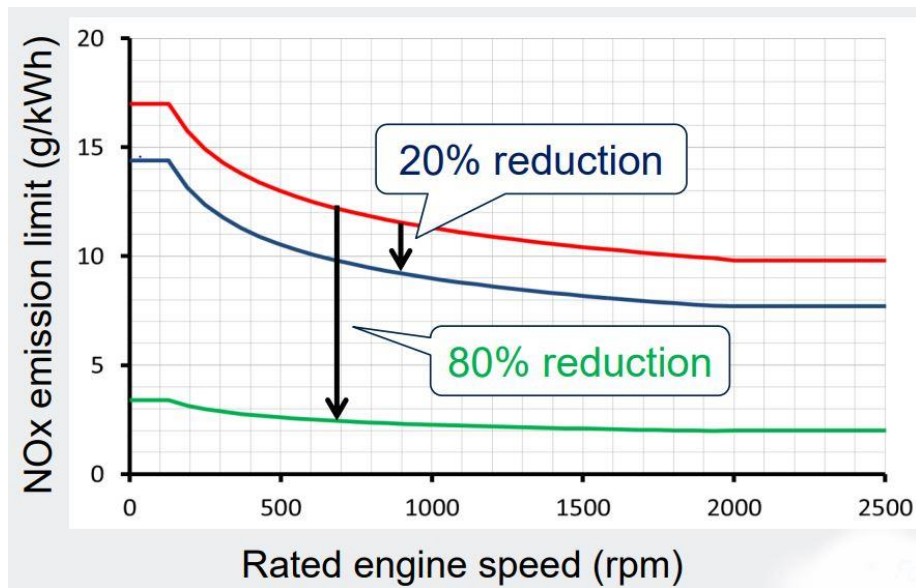


Figure 6 NO, NO<sub>2</sub> emission limits (gr/Kwh) depending on the nominal speed engine (RPM)  
[\[http://www.bergermaritiem.nl/nox\\_tier\\_iii\\_neca\]](http://www.bergermaritiem.nl/nox_tier_iii_neca)

Regarding the SO<sub>x</sub> and particulate matter emission controls apply to all fuel oil, combustion equipment and devices onboard and therefore include both main and all auxiliary engines together with items such boilers and inert gas generators. These controls divide between those applicable inside Emission Control Areas (ECA) established to limit the emission of SO<sub>x</sub> and particulate matter and those applicable outside such areas and are primarily achieved by limiting the maximum sulphur content of the fuel oils as loaded, bunkered, and subsequently used onboard. This is demonstrated in figure 7. These fuel oil sulphur limits (expressed in terms of % m/m – that is by mass) are subject to a series of step changes over the years and are showed in table 1 [IMO SO<sub>x</sub> and PM – Regulation 14].

Outside an ECA established to limit SO <sub>x</sub> and particulate matter emissions	Inside an ECA established to limit SO <sub>x</sub> and particulate matter emissions
4.50% m/m prior to 1 January 2012	1.50% m/m prior to 1 July 2010
3.50% m/m on and after 1 January 2012	1.00% m/m on and after 1 July 2010
0.50% m/m on and after 1 January 2020*	0.10% m/m on and after 1 January 2015

Table 1 SO<sub>x</sub> and PM emissions Limits inside and outside the ECA  
 [IMO]

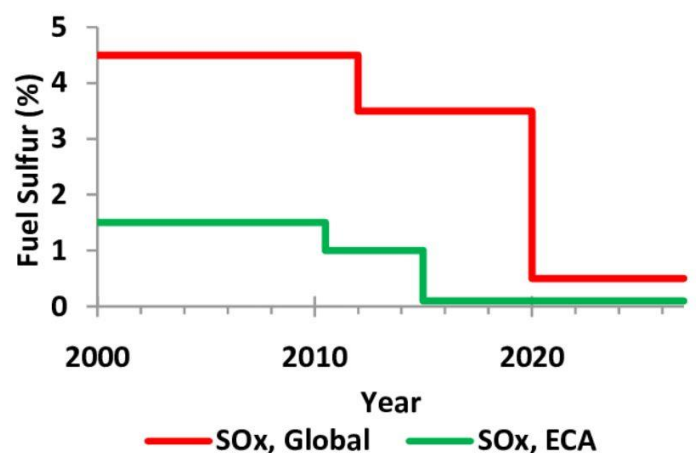


Figure 7 IMO SO<sub>x</sub> and particulate matter limits in and outside Emission Control Areas  
 [Zhu, S., Ma, Z., Zhang, K. and Deng, K., 2020]

### 1.2.2 Energy Efficiency Design Index (EEDI):

The EEDI for new ships is the most important technical measure and aims to promote the use of equipment and engines that are more energy efficient (less polluting). The EEDI mandates a minimum level of energy efficiency per capacity mile (e.g., tonne mile) for various ship types and sizes. EEDI requirements apply to newly constructed, international-voyaging vessels of the following types shown in table 2:

Vessel types	
Bulk Carriers	Combination carriers
Container Ships	Cruise passenger ships
Gas Carriers	General cargo ships
LNG carriers	Refrigerated cargo carriers
Roll on roll off cargo ships	Roll-on, Roll-off passenger ships
Tankers	Vehicle carriers

Table 2

These ship types are responsible for approximately 85% of the carbon dioxide (CO<sub>2</sub>) emissions from international shipping.

Energy Efficiency Design Index (EEDI), formulated for new ships, is an index that estimates grams of CO<sub>2</sub> per transport work (g of CO<sub>2</sub> per tonne-mile). It can be expressed as the ratio of “environmental cost” divided by “Benefit for Society” or in other words “CO<sub>2</sub> Emission” divided by “Transport Work”.

It is a function of:

- Installed power
- Speed of vessel
- Cargo carried

EEDI's guiding principle is that its computation should be simple and easily adapted to widespread application, and that it should encourage efforts by all parties to reduce CO<sub>2</sub> emissions by reflecting a ship's energy efficiency in actual use. It encourages the continued technical development of all ship components that affect fuel efficiency. In addition, it distinguishes between technical and design-based measures and operational and commercial measures.

### 1.2.3 Ship Energy Efficiency Management Plan (SEEMP):

Since January 1<sup>st</sup>, 2013, all the ships over 400 GT operating internationally must have a Ship energy Efficiency Management Plan (SEEMP) on board, in accordance with MARPOL Annex VI Regulation 22. The SEEMP is an operational measure that establishes a mechanism to improve the energy efficiency of a ship in a cost-effective manner.

The SEEMP also provides a method for shipping companies to manage ship and fleet efficiency performance over time utilising monitoring tools such as the Energy Efficiency

Operational Indicator (EEOI). The MEPC.1/Circ.684 guidance on the development of the SEEMP for new and existing ships incorporates best practises for fuel-efficient ship operation and voluntary use of the EEOI for new and existing ships. The EEOI enables operators to measure the fuel efficiency of a ship in operation and evaluate the impact of any operational changes, such as improved voyage planning or more frequent propeller cleaning, or the introduction of technical measures, such as waste heat recovery systems or a new propeller. At each stage of the plan, the SEEMP urges the ship owner and operator to consider new technologies and practises when attempting to optimise a ship's performance [IMO].

### 1.3 Literature review

One of the countermeasures for CO<sup>2</sup>, NO<sub>x</sub>, Sox, and PM emissions from ships is the use of hydrogen as an eco-friendly fuel. Hydrogen is considered a promising fuel especially because of its environmental impact. When it burns it has zero carbon emission and depending on its production route, the amount of carbon dioxide that is released into the atmosphere can be lowered drastically.

Currently, diesel and residual fuel oils represent most of the energy sources for the maritime sector. Increasing fuel consumption efficiency or implementing zero-carbon technologies are some of the potential alternatives to reduce maritime-related GHG emissions [Al-Rousan 2018]. Fuel cell technology is another alternative solution for current fossil fuel combustion-driven ferries.

In the literature, studies are available for hydrogen fuel cell-powered urban transit systems [Haraldsson 2006], marine vehicles [Evrin and Dincer 2019], and rail vehicles [Abbas and Kim 2019]. Various zero-carbon or carbon-neutral fuels can replace fossil-based maritime fuels with different utilization methods. Among the zero-carbon or carbon-neutral fuels, hydrogen receives attention as one of the potential alternative maritime fuels. Klebanoff compared hydrogen and diesel-driven ferries in terms of GHG and pollutant emissions. For the diesel fuel option, both fossil-diesel and biodiesel are considered to calculate GHG emissions. Liquid *hydrogen fuel's emissions are calculated by considering* renewable and non-renewable liquid hydrogen. A current ferry route between Vallejo CA and San Francisco CA, is considered while calculating emissions. Compared to fossil-diesel, renewable liquid hydrogen brought 75.8% GHG emission reduction. [Klebanoff 2017]. They found hydrogen PEM fuel cell technology reduces NO<sub>x</sub> and HC emissions dramatically below the most advanced Tier 4 criteria pollutant emissions requirements regardless of the type of hydrogen (renewable or non-renewable). Madsen investigated the feasibility of a hydrogen fuel cell driven research vessel, Zero- V, from technical, regulatory and environmental. They analysed hydrogen PEM fuel-cell driven vessel with conventional diesel fuel vessel with well-to-waves analysis, therefore, they found 91.4% less GHG emissions for the hydrogen PEM fuel-cell driven vessel, where hydrogen was produced with renewable methods [Madsen 2020].

It is expected that the creative arrangements for hydrogen production will improve the efficiencies, asset usage, resource utilization, ecological protection, and system design [Okonkwo and Bhowmik 2022]. Several groups of researchers have performed a significant amount of work on scientific research, technological development, and Techno-economic analysis in different hydrogen production in a refuelling station.

El Manaa Barhoumi presented an economic assessment and evaluation of PV-HRS producing 150 kg of hydrogen in Tunis, showing that the initial cost and the Levelized hydrogen cost depend mainly on the prices of the PV panels (48.5%), electrolyzers (41%), and storage tanks (3.2%) [Okonkwo and Farhani 2021]. Also, M. Minutillo analysed the levelized cost of

hydrogen in refuelling stations with on-site hydrogen production via water electrolysis in the Italian scenario, using different electric supply management scenarios and H<sup>2</sup> plant capacities [Minutillo 2021]. TM Power (ITM) further demonstrated the feasibility of hydrogen bunkering. ITM is a global leader in the design and manufacture of rapid response PEM electrolyser systems that produce hydrogen using renewable energy to split water. As part of its effort to develop the market in transport, the company has pioneered the roll-out of a network of hydrogen refuelling stations, for a variety of mobility options. Orkney Islands are likely to be receiving a gaseous hydrogen ferry for deployment soon. So, four options for hydrogen production and bunkering were considered based on considerable modelling of the electricity generation from wind, the storage required to achieve an assumed 99% availability, along with the electrolysis generation process [Hyde, K., Ellis, A. and Power, I.T.M., 2019]. Recently, Mert Temiz and Ibrahim Dincer designed a floating PV plant integrated with the electrolyser and grid in Ontario, Canada. The solar driven integrated system is therefore designed in a stand-alone and carbon-free manner. The purpose of the study is to carry out the Toronto Island ferries urban transit system and replace the current fossil fuel- driven ferry propulsion system with the proposed propulsion system with hydrogen fuelling and production station. *The proposed system's overall energy and exergy efficiencies in the grid-connected mode are calculated as 15.35% and 16.19%, respectively. The net present value of the proposed system is found to be 5.06 million Canadian dollars. The investment is paid back in 7.25 years with an 11.75% internal rate of return. The cost of hydrogen production, storage and fuelling for the proposed system is found to be 6.47 Canadian dollars per kilogram at a 26.7 ton/year production rate [Temiz and Dincer 2021].*

An increasing number of Renewable Energy (RE) technologies (such as solar, wind, bioenergy, etc.) are being adopted across the world in an effort toward global decarbonization. However, the Bulk of these RE technology exhibits variability in electricity generation with an associated uncertainty (dropping of the solar output with the sudden arrival of a cloud or falling of the wind energy generation when wind stops blowing) which is the main challenge in the integration of these RE technologies into the grid system.

#### 1.4 Purpose and structure of the dissertation

This study's major purpose is to design a solar-powered hydrogen production, storage, and refuelling system for hydrogen fuel cell-powered ferries in Greece. The suggested system generates hydrogen, electricity, and mechanical propulsion power independently on-site. Figure 4 is a design of a potential system layout.

The present study is structured as follows:

The second chapter concentrates on hydrogen and its qualities, expanding the reasons that hydrogen is the future and elaborating on why it is preferred to other solutions. Also demonstrates IEA's (International Energy Agency) original focus for hydrogen and hydrogen-based-fuels roadmap for the Global Energy Sector, with a Net Zero world by 2050 as its objective.

The third chapter emphasize on the various hydrogen production methods. There are many processes of hydrogen production from both conventional and alternative energy resources such as natural gas, coal, nuclear, biomass, solar, and wind. In this research, a comparative overview of the major hydrogen production methods is carried out. However, it focuses on water splitting methods that can produce eco-friendly and high-purity hydrogen and illustrates the type of electrolysis that is going to be used in the PV-hydrogen marine refuelling station.

The fourth chapter examines the production of electricity from solar energy especially photovoltaic-based hydrogen production. In general hydrogen production which derives from sustainable solar energy and water could have a major crucial role in considering environmentally friendly solutions and consequently reach nowadays energy demands, from a global perspective, and most importantly establish energy security.

The fifth chapter illustrates the main components of the PV-hydrogen marine refuelling station. It analyses in detail all the hydrogen production capacities and calculates the different demands of energy and the different electricity capacities and mixed for the refueling stations.

The sixth chapter indicates the development of a techno-economic assessment of an on-site hydrogen refuelling station based on grid-connected PV plants integrated with electrolysis units. The integrated system mainly consists of four parts: electricity production, hydrogen production, fuelling, and hydrogen-driven propulsion ferries. The current fossil fuel-driven ferry propulsion system is replaced with the proposed propulsion system with a hydrogen fuelling and production station. Different plant configurations, in terms of hydrogen production capacity and the electricity mix (different sharing of electricity supply between the grid and the PV plant), have been analysed in terms of electric energy demands and costs. This study has been performed by considering the Greek scenario in economic terms, for instance, electricity prices, water prices, and solar irradiation conditions. The cost comparison methods are deployed with various criteria, including net present cost. However, the Levelized cost of hydrogen (LCOH), is the most important indicator among the economic evaluation indexes, has been calculated for all configurations by estimating the investment, operational, maintenance, and replacement costs. Finally, it will finalize the most suitable configuration for each situation and a sensitivity analysis is performed on the primary indicators that, if altered, will cause the LCOH to decrease or increase sufficiently.

The seventh chapter states different hydrogen-driven propulsion systems projects and presents the most proper for this project. It is worth mentioning that from 2000 until 2022 around 84 hydrogen-powered vessel projects have been undertaken. The Netherlands, Norway, and Germany appear to have the most hydrogen-powered boats with 19%, 18%, and 14%, respectively. FCS is the preferred hydrogen propulsion method with the most important being the PEMFC. Hydrogen is stored either as compressed gas at 350 bars, or in liquid form using a liquefied cryogenic hydrogen storage system, or in solid form with metal hydrides. Lastly, a case study is conducted for the Piraeus ferries transit system in Aegina and Agistri using an existing High-speed light weight passenger ferry and the most optimal marine refuelling station identified in the preceding chapter. The NPV, IRR, and payback period are determined.

The concluding chapter includes an overview of all significant conclusions and suggestions for future research.



*Figure 8 Proposed Layout*  
*[Hyde, K., Ellis, A. and Power, I.T.M., 2019. Feasibility of hydrogen bunkering. ITM Power]*



## 2. The case for hydrogen

The emission of greenhouse gases (GHG) into the atmosphere as a result of the uncontrolled use of fossil fuels poses a grave threat to the global environment and, consequently, to climate change [Hites, 2006]. In addition, the rising energy demand has necessitated a rise in the pricing of conventional fuels, exposing and declining import-*dependent nations' economies*. Future energy sources must meet the requirements of being carbon-free and renewable for the long-term mitigation of climate change and reduction in reliance on oil imports. In an effort to provide a clean and dependable alternative to traditional fossil fuels, various investigations have focused on hydrogen technology. [Lund, H., 2007].

Renewable energy sources, such as wind and solar, have ephemeral qualities that necessitate the control and storage of energy. Hydrogen is one of the most promising clean and sustainable energy carriers, emitting only water and no carbon as a by-product. Hydrogen has a high energy density (140 MJ/kg), which is more than twice that of conventional solid fuels (50 MJ/kg) [Acar and Dincer, 2014]. In recent years, global hydrogen production has averaged approximately 500 billion cubic metres (bm<sup>3</sup>) per year, with 95% of that production generated from fossil fuels, which also produce carbon dioxide. [Borgschulte 2016].

### 2.1 Hydrogen properties

Hydrogen is the chemical element represented by the symbol H and the atomic number 1. Hydrogen is indeed the lightest element in the world. Hydrogen is a gas containing diatomic molecules with the formula H<sub>2</sub> at ordinary circumstances. It is colourless, odourless, tasteless, non-toxic, highly combustible and has a crystal structure, his flammable gaseous substance that is the simplest member of the family of chemical elements. Although hydrogen is the most abundant chemical element in the universe, comprising around 75% of all normal matter in massive amounts as part of the water in oceans, ice sheets, rivers, lakes, and the atmosphere. Hydrogen is present in all plant and animal tissues, as well as in petroleum, as a component of several carbon compounds. Even though it is commonly believed that there are more known compounds of carbon than of any other element, hydrogen is present in almost all carbon compounds and forms a multitude of compounds with all other elements (except some of the noble gases), so it is possible that hydrogen compounds are more numerous. Although hydrogen is three times as abundant as helium, the next most abundant element, it makes up only 0.14 percent of the weight of the Earth's crust. Stars such as the Sun are mainly composed of hydrogen in the plasma state. The majority of hydrogen on Earth resides in water molecules and organic substances. The name hydrogen derives from Greek words that indicate "water-maker." Figure 9 also illustrates the features and facts of hydrogen. [Rae, H.K., 1978].

## Hydrogen

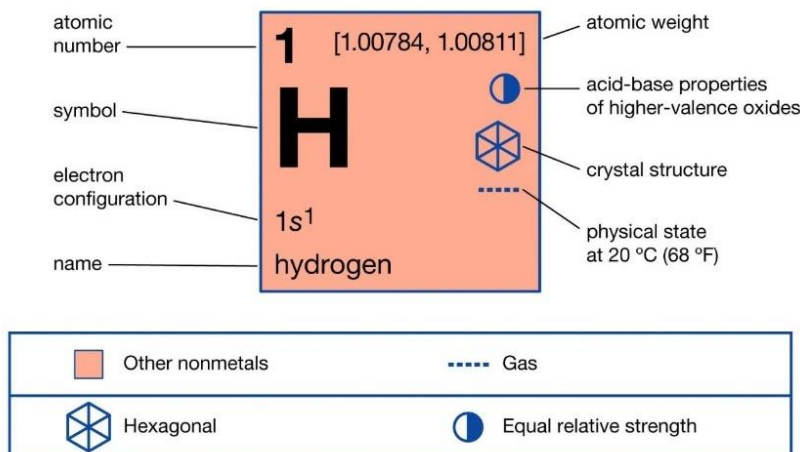


Figure 9 Hydrogen | Properties & Facts  
[Encyclopaedia Britannica. Inc.]

Ammonia production is the major industrial application of elemental hydrogen. Ammonia, represented by the chemical formula NH<sub>3</sub>, is a colourless, smelly gas comprised of nitrogen and hydrogen. It is the simplest stable compound of these elements and acts as a precursor to the creation of numerous commercially significant nitrogen compounds. [Kun and Kearney1974].

*Hydrogen has three known isotopes. The mass numbers of hydrogen's isotopes are 1, 2, and 3, the most abundant being the mass 1 isotope generally called hydrogen (symbol H, or 1H) but also known as protium. The mass 2 isotope, which has a nucleus of one proton and one neutron and has been named deuterium, or heavy hydrogen (symbol D, or 2H), constitutes 0.0156 percent of the ordinary mixture of hydrogen. Tritium (symbol T, or 3H), with one proton and two neutrons in each nucleus, is the mass 3 isotope and constitutes about 10–15 to 10–16 percent of hydrogen. The practice of giving distinct names to the hydrogen isotopes is justified by the fact that there are significant differences in their properties [Rae, H.K., 1978].*

### 2.2 Compression of hydrogen to other fuels

Choosing the future marine fuels depends on various aspects such as efficiency, safety, costs, and environmental aspects. The criteria for selecting future marine fuels are divided into four groups:

- Technical
- Economic
- Environmental
- Other criteria

some of them involve minimum levels that must be satisfied.

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

Regarding the environmental criteria, the fuel needs to fulfil the environmental regulations regarding the air emissions and its environmental life cycle performance to be acceptable.

Aspects that could consider can be the total extracted energy, the global warming potential (GWP), and the consequences of fuel leaks (BRYNOLF, 2014).

Economic criteria are the investment costs (e.g., engines), the operational costs (e.g. maintenance, crew), and the price of fuel (BRYNOLF, 2014).

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

Unlike fossil fuels, hydrogen is not readily available in nature. However, it can be created from any source of primary energy and utilised as a fuel in an internal combustion engine or a fuel cell, producing just water as a by-product. As the only carbon-free fuel with the highest energy density of any known fuel, indicated by weight (Table 3). Hydrogen's high heating value (141.9 Mj/kg) is approximately three times that of gasoline (47.6 Mj/kg). Hydrogen is generally recognised as a sustainable energy source that is less harmful to the environment than fossil fuels. An additional advantage is that, when accompanied by suitable storage technologies, hydrogen can be exploited for household consumption because it can be transported securely by ordinary routes and stored as compressed gas, cryogenic liquid, or solid hydride for feeding stationary fuel cells. [Momirlan and Veziroglu 2005].

Fuel	State	High Heating Value (Mj/kg)	Low Heating Value (Mj/kg)
Hydrogen	Gas	141.9	119.9
Methane	Gas	55.5	50
Ethane	Gas	51.9	47.8
Gasoline	Liquid	47.5	44.5
Diesel	Liquid	44.8	42.5
Methanol	Liquid	20	18.1

*Table 3 Higher and lower heating values for various fuels [Momirlan and Veziroglu 2005].*

### 2.2.3 LNG and Hydrogen complex relationship

Liquefied Natural Gas (LNG) has been advertised as a green alternative to marine oil for a number of years, and in many aspects, it is much superior in terms of sulphur, NOx, and particle emissions. However, the CO2 emissions are at most 20% less than diesel, with some saying that the amounts are comparable when liquefaction and transportation energy are considered. Consequently, LNG remains carbon intensive. In anticipation of the latest IMO announcement, corporations have been hesitant to invest extensively in LNG, which is not regarded as a future-proof alternative [Hyde, K., Ellis, A. and Power, I.T.M., 2019]. Consequently, by 2016, about fifty LNG-powered vessels were in operation annually. Before the Paris agreement, just 20 LNG-powered vessels were in operation annually from 2010 to 2015, demonstrating hesitation. Figure 10 depicts the exact global LNG production from 2010 to 2021.

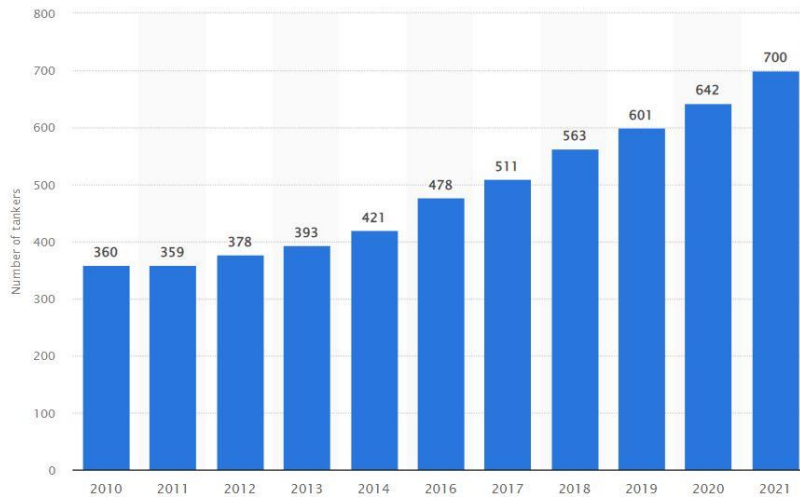


Figure 10 Number of liquefied natural gas storage vessels worldwide from 2010 to 2021  
[\[www.statista.com/statistics/468412/global-lng-tanker-fleet/\]](https://www.statista.com/statistics/468412/global-lng-tanker-fleet/)

The LNG technical readiness level is further advanced, but hydrogen and ammonia are the only fuels that can meet future emission targets. It is likely that the earliest adopters of LNG will also be the first to switch to hydrogen. Companies that have previously invested in LNG are now investing in hydrogen due to the EU's 2050 green accord objectives. Hydrogen is superior to LNG when it comes to 100% renewable energy. The current LNG infrastructure will facilitate the transition to hydrogen distribution [Ivar Krusenbergh].

Using fuels with a low flashpoint, such as hydrogen and LNG, requires the same design philosophy and safety equipment. Training courses for these fuels are also comparable. Both gases are held in tanks at high pressure. Typically, hydrogen is held at 350 or 700 bar, whereas compressed natural gas is rarely stored over 200 bar since at ambient temperature it becomes liquid at this pressure. Consequently, there is a clear advantage to storing at lower pressures. In 'normal' operation, however, the vessels pose no safety danger. This is mostly due to failure situations. Gaseous hydrogen and natural gas are not combustible on their own. They only burn when combined with oxygen (or another oxidant). Thus, hydrogen or natural gas in a sealed container is not flammable, but if it escapes into the atmosphere, it becomes extremely flammable. Hydrogen and natural gas at atmospheric pressure are both lighter than air (although hydrogen is five times lighter), hence they will both rise if a leak occurs. Both have auto-ignition temperatures considerably higher than gasoline vapor's 560 degrees Celsius. The energy necessary to commence hydrogen combustion is around 19J, which is far less than the 280J required to initiate combustion of LNG (e.g., a small spark will ignite it). However, at low hydrogen concentrations in air, the energy required to begin combustion is comparable to that of other fuels. In Table 4, an overview of the physical attributes is shown. For a future transition to hydrogen distribution, the characteristics and states of the two fuels necessitate equivalent safety precautions and equipment for their connection. [Hyde, K., A. Ellis, and I.T.M. Power, 2019].

	Hydrogen	Natural Gas
<b>Lower flammability limit (% in air)</b>	4	5
<b>Upper flammability limit (% in air)</b>	75	15

<b>Minimum ignition Energy (<math>\mu\text{J}</math>)</b>	19	280
<b>Density at atmospheric pressure (as a fraction of air)</b>	0.074	0.58
<b>Buoyant velocity in air at NTP (<math>\text{cm}^2/\text{s}</math>)</b>	1.2-9	0.8-6
<b>Diffusivity (<math>\text{cm}^2/\text{s}</math>)</b>	0.61	0.16
<b>Minimum auto-ignition temperature (C)</b>	585	540
<b>Adiabatic Flame Temperature in air (K)</b>	2318	2158
<b>Burning Velocity in Air</b>	265-325	37-45
<b>Upper Wobbe Index (<math>\text{MJ}/\text{Nm}^3</math>)</b>	48.2	53.7
<b>Calorific Value (higher heating value) (<math>\text{MJ}/\text{m}^3</math>)</b>	12.7	39.8
<b>Thermal energy radiated from flame to surroundings (%)</b>	17-25	23-33

Table 4 Summary of the safety between hydrogen and LNG.  
[Hyde, K., A. Ellis, and I.T.M. Power, 2019].

#### 2.2.4 Batteries insufficiencies in shipping

Batteries are another frequently mentioned alternative for shipping. However, their energy density is insufficient for any but the shortest journeys. The energy density and volumetric energy density of rechargeable lithium-ion batteries, which are touted by many as the future power source for ships, are quite low. Numerous people, including Tesla's press releases, have speculated that battery energy density will follow a Moore's law-like curve. Figure 11 demonstrates that despite significant increases in battery cost, energy density has remained stubbornly static [Seeking Alpha 2017].

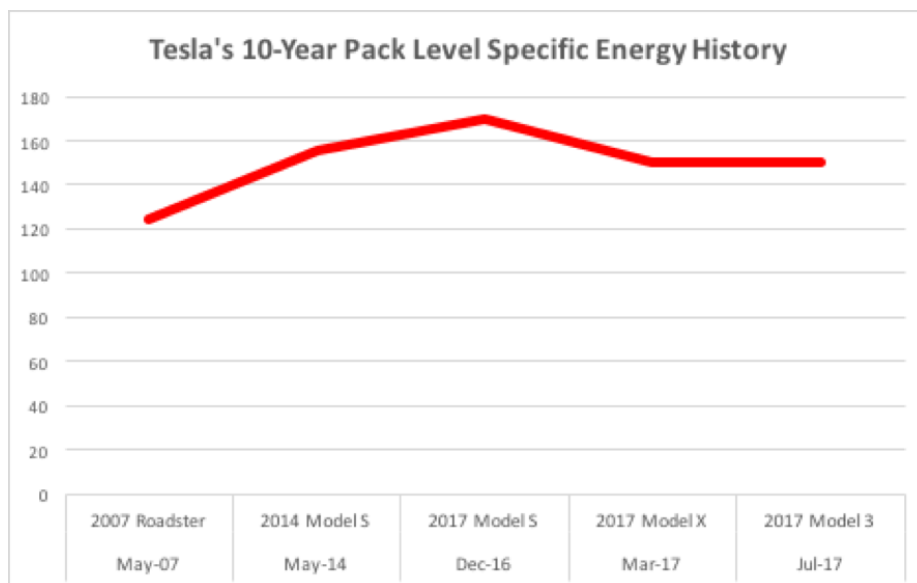


Figure 11 The specific energy density of batteries in different models of Tesla moving forward in time showing that battery improvements are difficult to achieve  
[Seeking Alpha 2017]

The batteries are not depleted too much, because there's no way to plug in for a recharge in the middle of a sea, lake, or river.

- The energy density of gasoline or diesel is hundreds of times greater than that of the finest batteries. Alternatively, 100 pounds of batteries would be required to travel the same distance as one pound of fuel or diesel.
- Power requirements for boats are significantly nonlinear. While one or two horsepower are sufficient to propel a 20-foot boat at 8 kilometres per hour, it requires 150 horsepower to propel the same vessel at 64 kilometres per hour.

However, electric is suitable if a very small boat for very short distances at a very slow speed is required. [Hyde, K., Ellis, A. and Power, I.T.M., 2019] On this basis it is believed that hydrogen is possibly the best viable solution for the shipping industry going forwards.

### 2.3 Hydrogen Net Zero Plan

Need Zero Energy's initial aim for hydrogen use is the conversion of existing fossil energy uses to low-carbon hydrogen in ways that do not require new transmission and distribution infrastructure. This covers the utilisation of hydrogen in industry, refineries, and power plants, as well as the integration of hydrogen into natural gas for distribution to consumers. The global consumption of hydrogen increases from less than 90 Mt in 2020 to more than 200 Mt in 2030, with the proportion of decarbonizing hydrogen increasing from 10% in 2020 to 70% in 2030. (Figure 12). Approximately half of the low carbon hydrogen produced globally in 2030 will come from electrolysis, with the remainder coming from coal and natural gas with CCUS (Carbon Capture, Utilization, and Storage). However, this ratio varies significantly between locations. Hydrogen is also blended with natural gas in gas networks: the global average blend in 2030 will contain 15% hydrogen by volume, resulting in a 6% reduction in CO2 emissions from gas usage.

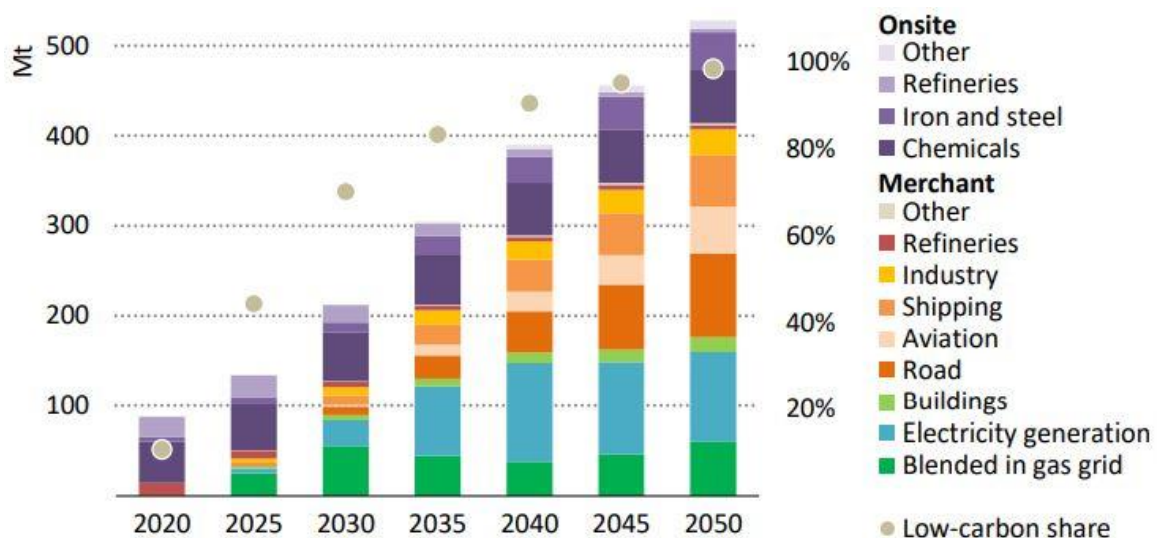


Figure 12 Global hydrogen and hydrogen-based fuel use in the NZE [IEA]

These advancements allow for the rapid expansion of electrolyser manufacturing capacity and the simultaneous creation of a new hydrogen transport infrastructure. This rapidly reduces the cost of electrolysers and hydrogen storage, particularly in salt caverns. Hydrogen storage is used to assist balance seasonal fluctuations in energy demand and potential imbalances between hydrogen demand and its supply from off-grid renewable technologies. During the

2020s, there will be a significant growth in the installation of hydrogen end-use equipment, with more than 15 million fuel cell vehicles on the road by 2030.

After 2030, the usage of low carbon hydrogen develops rapidly across all NZE industries. Hydrogen and hydrogen-based fuels represent a significant lower - carbon source of electrical system flexibility in the electricity sector, mostly through the retrofitting of existing gas-fired capacity to co-fire with hydrogen and some retrofitting of coal-fired power plants to co-fire with ammonia. Despite the fact that these fuels contribute just around 2% of total energy output in 2050, this translates to enormous volumes of hydrogen, making the electrical sector a significant driver of hydrogen demand. In 2050, hydrogen will provide approximately one-third of the fuel used by trucks in NZE if policymakers make decisions by 2030 that enable the development of the necessary infrastructure. By 2050, hydrogen-based fuels will account for about 60% of overall maritime fuel use.

Approximately 25% of the 530 Mt of hydrogen produced in 2050 will be produced in industrial facilities (including refineries), while the remainder will be commercial hydrogen (hydrogen produced by one company to sell to others). In 2050, over 30 percent of the low-carbon hydrogen utilised will be in the form of hydrogen-based fuels, such as ammonia and synthetic liquids and gases. In 2050, electrolyzers will account for sixty percent of total hydrogen production, a proportion that is growing. Electrolyzers are powered by grid energy, dedicated renewables in places with abundant renewable resources, as well as alternative low-carbon sources such as nuclear power. Rolling out electrolyzers at the pace required in the NZE is a key challenge given the lack of manufacturing capacity today, as is ensuring the availability of sufficient electricity generation capacity. Over time, huge volumes of hydrogen are exported from gas and renewables-rich regions in the Middle East, Central America, and Australia to demand hubs in Asia and Europe in the NZE.

Sector	2020	2030	2050
<b>Total production hydrogen-based fuels (Mt)</b>	<b>87</b>	<b>212</b>	<b>528</b>
Low-carbon hydrogen production	9	150	520
<i>share of fossil-based with CCUS</i>	<i>95%</i>	<i>46%</i>	<i>38%</i>
<i>share of electrolysis-based</i>	<i>5%</i>	<i>54%</i>	<i>62%</i>
Merchant production	15	127	414
Onsite production	73	85	114
<b>Total consumption hydrogen-based fuels (Mt)</b>	<b>87</b>	<b>212</b>	<b>528</b>
Electricity	0	52	102
of which hydrogen	0	43	88
of which ammonia	0	8	13
Refineries	36	25	8
Buildings and agriculture	0	17	23
Transport	0	25	207
of which hydrogen	0	11	106
of which ammonia	0	8	44
of which synthetic fuels	0	5	56
Industry	51	93	187

Note: Hydrogen-based fuels are reported in million tonnes of hydrogen required to produce them.

Table 4 Key deployment milestones for hydrogen and hydrogen-based fuels [IEA]

## 3. Hydrogen Production

### 3.1 Hydrogen colour spectrum

Numerous technologies and resources, many of which are classified as renewable, can produce hydrogen. However, current hydrogen generation is far from renewable. It relies almost exclusively on the reforming and gasification of fossil hydrocarbon sources, such as natural gas (76%) and coal (23%), resulting in annual CO<sub>2</sub> emissions of 830 Mt. Emerging technologies for alternative hydrogen production include methane pyrolysis and water electrolysis [Hermesmann and Müller 2022].

The level of cleanliness of the energy generated from hydrogen is proportional to the amount of greenhouse gases emitted during its production. In addition, the sustainability of the entire energy chain is dependent on the energy input, the type of raw material, the design of the industrial process, and CO<sub>2</sub> emissions. [Noussan and Raimondi 2021.] Using colour labels to classify carbon emissions during hydrogen production is an intriguing method. From suppliers to consumers, the colour codes of the hydrogen production process may serve as a statement of sustainability. This method provides a quick indication of the type of hydrogen (in terms of carbon emission) you or a business are handling. With sustainable products, H<sub>2</sub> suppliers are expected to demonstrate environmental responsibility and enhance their competitiveness.

As shown in Figure 13, the first proposed model for H<sub>2</sub> classification is based on three colours corresponding to CO<sub>2</sub> emissions. Fossil fuels (mostly natural gas and coal) are used as a raw material in the steam reforming process to generate grey H<sub>2</sub>. In addition, there are no restrictions on carbon emissions, and hydrogen is regarded as "dirty." Blue H<sub>2</sub> is produced in a manner similar to grey H<sub>2</sub>. However, the produced carbon is captured and stored, thereby reducing CO<sub>2</sub> emissions. Alternatively, green hydrogen is considered renewable hydrogen due to the use of water as a source of H<sub>2</sub> and renewable energy (RE) in the electrolytic process (water splitting (WS) process), which is consistent with the zero-emission carbon strategy. The diagram in Figure 1 compares these three processes. [Germescheidt and Moreira 2021].



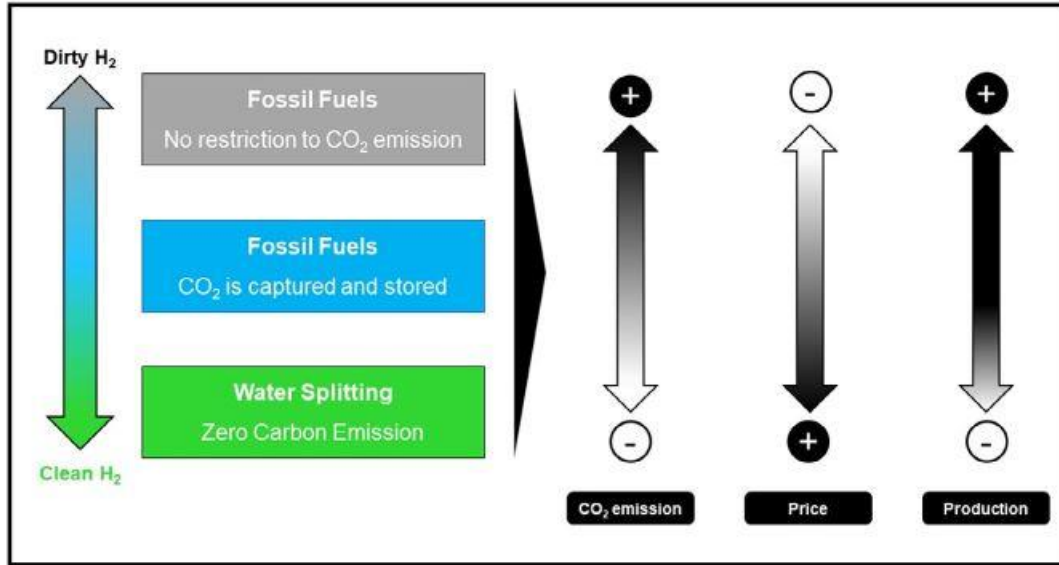


Figure 13 Scheme of three colors to classify the hydrogen production according to the carbon emission [Germescheidt, R.L., Moreira, D.E., Yoshimura, R.G., Gasbarro, N.P., Datti, E., dos Santos, P.L. and Bonacin, J.A., 2021].

Because the H<sub>2</sub> chain is plural and complex, new colour codes were added to enhance the description of the hydrogen production's level of cleanliness. Figure 6.5 contains a comprehensive colour codes table based on this concept.

The brown hydrogen (black hydrogen is a synonym) is produced from coal in the gasification process, which generates large quantities of CO<sub>2</sub> and has a high environmental impact, despite the difficulty in achieving a low cost for the produced H<sub>2</sub>. Gray and blue hydrogen were previously described. Similar to brown, blue, and grey hydrogen, turquoise hydrogen is produced from Fossil fuels, however, methane pyrolysis at high temperatures permits carbon elimination in solid form, thereby reducing CO<sub>2</sub> emissions. The central aspect of this strategy is the energy source and its carbon emissions. In other words, the process would be clean if the input energy was renewable. Thus, it may have a smaller impact on the environment (Figure 14). The electrolysis process (also known as water splitting) produces pink, yellow, and green hydrogen using water as a raw material. However, the final environmental impact is also contingent on the energy input. Pink hydrogen is derived from an electrolysis process powered by nuclear energy, while yellow hydrogen is produced using inputs of mixed origin (Fossil fuel and renewable). Green hydrogen is produced by the cleanest method, where the water electrolysis is solely powered by renewable energy (wind or solar). The cost is a barrier to the incorporation of green hydrogen into the hydrogen chain. Sustainable hydrogen is approximately four times more expensive than hydrogen produced through the fossil fuel process. White colour, for example, is only used to classify H<sub>2</sub> of natural origin, and due to its rarity on Earth, it has no commercial value. This was the initial H<sub>2</sub> white proposal. However, some authors have viewed white hydrogen as a thermochemical by-product of solar energy concentration. Additionally, Recupera defines white hydrogen as H<sub>2</sub> produced from plastic, biomass, or garbage. Undetermined is the definition of white hydrogen [Newborough and Cooley 2020].

Color Code	Process	CO <sub>2</sub> Emission	Environmental Impact	Cleanliness Level of the H <sub>2</sub>
Fossil Fuels	Coal → H <sub>2</sub> ; Gasification process, syngas, T=700°C. CO <sub>2</sub> emitted directly			
	Natural gas (CH <sub>4</sub> ) → H <sub>2</sub> ; Steam Reforming. Most common process			
	Natural gas (CH <sub>4</sub> ) → H <sub>2</sub> ; Steam reforming with capture and store of CO <sub>2</sub>			
	Natural gas (CH <sub>4</sub> ) → H <sub>2</sub> ; Methane pyrolysis with production of solid carbon			
Electrolysis	H <sub>2</sub> production from water electrolysis through nuclear energy			
	H <sub>2</sub> production from water electrolysis through mixture of sources (FF and RE)			
	H <sub>2</sub> production from water electrolysis through renewables sources			
Alternative	Natural occurrence, rare on Earth. H <sub>2</sub> is found in clathrates or in the atmosphere (1 ppm)			
	Thermochemical water splitting produced by concentrated solar energy			
	H <sub>2</sub> produced from garbage, plastic or biomass			

low    medium    large

Figure 14 Color codes of hydrogen. Complete comparison among the processes according to the CO<sub>2</sub>emission, environmental impact, and cleanliness of the hydrogen produced [Germescheidt, R.L., Moreira, D.E., Yoshimura, R.G., Gasbarro, N.P., Datti, E., dos Santos, P.L. and Bonacin, J.A., 2021]

### 3.2 The various production methods

Utilizing hydrogen gas as a fuel is hampered by its rarity in nature and the requirement for economical production techniques. Numerous methods exist for H<sub>2</sub> production, which, based on the raw materials employed, can be grouped into two broad categories: conventional and renewable technologies [Kapdan and Kargi 2006]. Figure 15 depicts in a tree diagram the main processes for hydrogen production. [Nikolaidis and Poullikkas 2017].

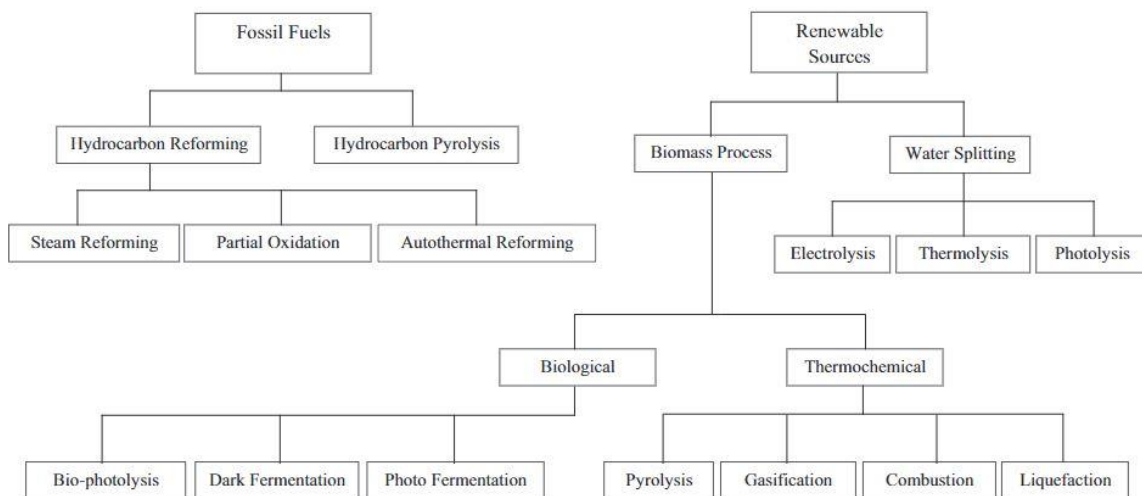


Figure 15 Hydrogen production methods [Nikolaidis and Poullikkas 2017]

### 3.2.1 Hydrogen production from fossil fuels

The first category processes fossil fuels and includes the methods of:

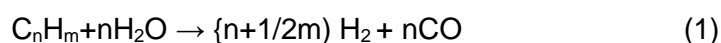
#### 3.2.1.1 *Hydrocarbon reforming:*

Is the process by which hydrocarbon fuel is converted to hydrogen via reforming systems. During the hydrocarbon reforming, additional components are utilised in addition to the hydrocarbon itself. This system, which includes carbon dioxide, is known as CO<sub>2</sub> reforming or dry reforming. In addition, steam may be included as a reactant in the hydrocarbon reforming system. This process is referred to as steam reforming. Since both dry and steam reforming reactions are endothermic, energy must be supplied. Reforming the hydrocarbon with oxygen is referred to as partial oxidation, and the reaction produces heat. Combining the steam and partial oxidation reactions results in the autothermal reforming system [Chen, H.L., Lee, H.M., Chen, S.H., Chao, Y. and Chang, M.B., 2008].

The participating chemical techniques of hydrocarbon reforming are:

- Steam reforming

In the steam reforming process, hydrocarbons are catalytically converted into hydrogen and carbon monoxide in the presence of steam in the feed. The reforming process includes gas purification, methanation, water-gas shift, and the creation of synthesis gas. The majority of feedstock consists of natural gas, methane, and a mixture of light hydrocarbons, such as propane, butane, ethane, pentane, and light and heavy naphtha. When the feed is polluted with organic sulphur compounds, a desulphurization stage should precede the reforming phase in order to prevent the deactivation of the reforming catalyst, which results in the CO<sub>2</sub> being captured and deposited in the ocean or geologic reservoirs [Damen, K., van Troost, M., Faaij, A. and Turkenburg, W., 2006]. The most important chemical process that takes place during steam reforming is:



- Partial oxidation

Feedstocks starting from methane to naphtha are often used in the catalytic process at about 950°C, while the process operation takes place at 1150–1315°C for non-catalytic systems [44]. Pure O<sub>2</sub> is used to incompletely oxidize the hydrocarbon feedstock, after the elimination of sulphur content in the feed removal. The generated synthesis is additionally purified and separated in a similar way as the output gas of the steam reforming method. The formidable price of the oxygen manufacturing and the extra expenses of desulphurization perform the process significantly expensive. In the process dealing with catalyst, the heat is delivered through the monitored combustion [Pandey 2001].

- Autothermal steam reforming

In the process of autothermal reforming technique (ATR), the endothermic steam reforming receives heat from the combined exothermic partial oxidation to promote the production of hydrogen. Fundamentally, steam, air, and oxygen are fed to the

reformer, starting the oxidation reactions as well as the reforming to happen simultaneously.

### 3.2.1.2 Hydrocarbon pyrolysis

The pyrolysis of hydrocarbon is a famous method where hydrogen solely comes from the hydrocarbon subjected to thermal decomposition via the following universal reaction:



Thermo-catalytic decomposition of light liquid hydrocarbons with boiling points below 200°C yields elemental carbon and hydrogen; however, the synthesis of hydrogen from residual fractions with boiling temperatures above 350°C needs hydrogasification and methane cracking. The direct reduction of carbon content in natural gas, also known as de-carbonization, which consists primarily of methane, is conducted in an atmosphere devoid of water and air at 980°C and atmospheric pressure. In addition, pyrolysis does not involve CO<sub>2</sub> removal or water gas shift. Carbon control and sequestration, which is an energy-intensive process, is replaced by carbon control that can be used in the chemical and metal industries. Therefore, the procedures of partial oxidation or steam conversion result in a 25–30% increase in the cost of producing hydrogen. If substantial quantities of carbon originating from the decomposition of natural gas could be sold, the price of hydrogen would decrease. Environmentally, it would be more advantageous to dissociate natural gas catalytically into carbon and hydrogen than to produce H<sub>2</sub> by steam reforming of methane coupled with CO<sub>2</sub> sequestration. For a given temperature, the continual elimination of hydrogen via membrane separation increases the carbon content reduction. Pd-Ag alloys, which function at lower temperatures and reduce carbon deposition, are typically utilised for H<sub>2</sub> separation. The principal disadvantages of the present method are attributable to the extremely low hydrogen separation, which is a result of the membrane stability being influenced by the high temperatures required for the equilibrium of the carbon content reduction and the low H<sub>2</sub> partial pressures in the reaction mixture [Zhang 2015].

### 3.2.2 Hydrogen production from renewable resources

The second category accommodates the methods which produce hydrogen from renewable resources from:

#### 3.2.2.1 Biomass Process:

Biomass can be burned by thermal conversion and used for energy. Thermal conversion involves heating the biomass feedstock to burn, dehydrate, or stabilize it. The most familiar biomass feedstocks for thermal conversion are raw materials such as municipal solid waste (MSW) and scraps from paper or lumber mills.

Before biomass can be burned, however, it must be dried. This chemical process is called torrefaction. During torrefaction, biomass is heated to about 200° to 320° Celsius (390° to 610° Fahrenheit). The biomass dries out so completely that it loses the ability to absorb moisture, or rot. It loses about 20% of its original mass but retains 90% of its energy. The lost energy and mass can be used to fuel the torrefaction process.

During torrefaction, biomass becomes a dry, blackened material. It is then compressed into briquettes. Biomass briquettes are very hydrophobic, meaning they repel water. This makes it possible to store them in moist areas. The briquettes have high energy density and are easy to burn during direct or co-firing [Ibrahim 2018.].

Utilizing biomass as a feedstock, these methods can be subdivided into two general subcategories:

- Thermochemical processes  
Thermochemical technology mainly involves pyrolysis, gasification, combustion, and liquefaction
- Biological processes  
are direct and indirect bio-photolysis, dark fermentation, photo-fermentation and sequential dark and photo-fermentation

### 3.2.2.1 Water splitting

Can produce H<sub>2</sub> through water. Thermal energy is the most prominent way to derive the water-splitting process. Almost 4% of energy is produced by thermal electrolysis to derive electrical devices. Therefore, to overcome the uphill challenge of water splitting, we are focusing on various non-renewable and renewable energy sources to split water. Thermal, solar, fossil fuels, and biomass sources used to derive water-splitting routes, such as such as electrolysis, thermolysis and photo-electrolysis, utilizing water as the only material input. Production of hydrogen using water splitting is one most humane and renewable sources of hydrogen production. Water splitting using these technologies are investigated under three systems [Maeda and Domen 2013]:

Thermal: In this thermal system, conversion of energy sources such as biomass, coal, fossil fuels, and more, are converted into H<sub>2</sub> gas, known as a thermochemical reaction.

Thermochemical water splitting utilises high temperatures and chemical reactions to produce hydrogen and oxygen from water. This is a hypothetical long-term technological route with low or no greenhouse gas emissions. Thermochemical water-splitting processes use 500°–2,000°C of heat to fuel a sequence of chemical reactions that produce hydrogen. The process chemicals are reused inside each cycle, forming a closed loop that consumes only water and generates hydrogen and oxygen. The required high temperatures can be generated as follows:

- Concentrating sunlight onto a reactor tower using a field of mirror "heliostats," as illustrated in Figure 16.
- Using waste heat from advanced nuclear reactors.

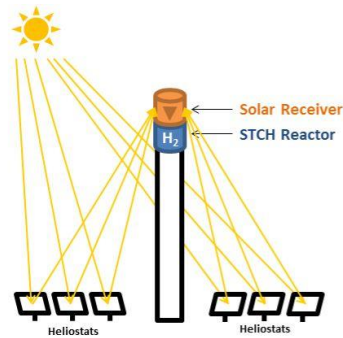


Figure 16 Central receiver / reactor tower with heliostats

[Energy efficiency & renewable energy <https://www.energy.gov/eere/fuelcells/hydrogen-production>]

- Photonic: In this system, solar energy is used to convert H<sub>2</sub>O into H<sub>2</sub> and O<sub>2</sub> molecule. This system is the most sustainable and advanced H<sub>2</sub> production system; photoelectrochemical and photobiological are examples of this process

In photoelectrochemical (PEC) water splitting, hydrogen is created from water using sunlight and photoelectrochemical materials, which directly break water molecules into hydrogen and oxygen using light energy. This is a hypothetical long-term technology route with low or no greenhouse gas emissions.

The PEC water splitting process uses semiconductor materials to convert solar energy directly to chemical energy in the form of hydrogen. The semiconductor materials used in the PEC process are similar to those used in photovoltaic solar electricity generation, but for PEC applications the semiconductor is immersed in a water-based electrolyte, where sunlight energizes the water-splitting process. PEC reactors can be constructed in panel form (similar to photovoltaic panels) as electrode systems or as slurry-based particle systems, each approach with its own advantages and challenges. To date, panel systems have been the most widely studied, owing to the similarities with established photovoltaic panel technologies. PEC water splitting is a promising solar-to-hydrogen pathway, offering the potential for high conversion efficiency at low operating temperatures using cost-effective thin-film and/or particle semiconductor materials.

Photobiological hydrogen generation utilises microorganisms and sunshine to convert water and occasionally organic materials into hydrogen. This is a longer-term technology path in the early phases of study that has the potential for sustainable hydrogen production with minimal environmental impact in the future.

In photolytic biological systems, microorganisms such as green microalgae and cyanobacteria break water into oxygen and hydrogen ions using sunlight. Hydrogen ions can be mixed directly or indirectly and released as hydrogen gas. Low hydrogen production rates and the fact that splitting water also produces oxygen, which quickly limits the hydrogen generation reaction and poses a safety risk when coupled with hydrogen at certain concentrations are obstacles for this approach. Researchers are striving to develop techniques

that will allow bacteria to create hydrogen for longer periods of time and at a faster rate.

Some photosynthetic microorganisms use sunlight to decompose organic materials and release hydrogen. This is referred to as photochemical hydrogen generation. This approach for hydrogen production is not commercially viable at this moment due to its poor hydrogen production rate and low solar-to-hydrogen efficiency.

Researchers are investigating strategies to make bacteria more efficient at collecting and utilising energy to improve the amount of energy available for hydrogen generation, as well as altering their regular metabolic pathways to increase the pace of hydrogen synthesis.

In the long term, photobiological production technologies may provide economical hydrogen production from sunlight with low- to net-zero carbon emissions. The algae and bacteria could be grown in water that cannot be used for drinking or for agriculture and could potentially even use wastewater.

- **Electrolytic:** Break down of water molecule  $H_2O$  into gaseous  $H_2$  and oxygen. In this process, zero emission of greenhouse gases depend on the source of energy that is used to proceed with this reaction.

Electrolysis is a leading method for achieving the Hydrogen Energy Earth shot target of reducing the price of clean hydrogen by 80% to \$1 per kilogramme in a decade. Depending on the source of the electricity utilised, electrolysis of hydrogen can cause zero greenhouse gas emissions. When analysing the benefits and economic viability of hydrogen production via electrolysis, the source of the necessary electricity, including its cost and efficiency, as well as emissions from electricity generation, must be taken into account. In many sections of the country, the current power grid is not optimal for supplying the electricity necessary for electrolysis due to the greenhouse gases emitted and the amount of fuel required as a result of the inefficiency of the electricity generation process. Electrolysis is being pursued to produce hydrogen for renewable (wind, solar, hydro, and geothermal) and nuclear energy choices. These hydrogen generation methods result in nearly no greenhouse gas and criterion pollutant emissions; nevertheless, the production cost must be greatly reduced in order to be competitive with more mature carbon-based pathways, such as natural gas reforming. Some photosynthetic microorganisms use sunlight to decompose organic materials and release hydrogen. This is referred to as photochemical hydrogen generation. This approach for hydrogen production is not commercially viable at this moment due to its poor hydrogen production rate and low solar-to-hydrogen efficiency.

Researchers are investigating strategies to make bacteria more efficient at collecting and utilising energy to improve the amount of energy available for hydrogen generation, as well as altering their regular metabolic pathways to increase the pace of hydrogen synthesis. This, study will focus and use water electrolysis because the hydrogen refuelling station is grid connected

### 3.3 Water electrolysis for hydrogen production

Water electrolysis driven by renewable energy sources is projected to facilitate the expansion of hydrogen production, and water electrolysis methods produce no  $CO_2$  emissions.

[Borgschulte 2016]. Water electrolysis is endothermic and one of the most purified and fundamental methods for hydrogen production at an industrial scale. Production of H<sub>2</sub> using electrolysis techniques, including alkaline method, polymer membrane, and several electrolyzers, are the most emerging technologies. Productivity and efficiency of this process is measured by the energy required to proceed this reaction; consequently, some useful catalysts, electrolytes, and electrode materials are introduced in this reaction to enhance the efficiency and rate of chemical reaction. In this process, various electricity sources are required to pass through electrodes and break down H<sub>2</sub>O into oxygen and H<sub>2</sub>. Reduction process of cations, H<sup>+</sup> ions, occurs at cathode, which then combines to form gaseous H<sub>2</sub>. In this equation, the fundamental reaction is presented [Maeda and Domen 2013]:



In this technique the efficiency of producing hydrogen through electrolysis of water is insufficient to be economically competitive due to its high energy consumption and poor hydrogen evolution rate. To boost efficiency and decrease energy consumption, numerous researchers have focused on the creation of alternative, low-cost electrocatalysts, efficiency, and energy reduction. In addition, water electrolysis's significant benefits, including as high cell efficiency and a greater hydrogen production rate with high purity, are advantageous for its subsequent conversion to electrical energy using low-temperature fuel cells. However, electrolysis of water using renewable energy sources without emission of CO<sub>2</sub> is considered a promising way to scale up the hydrogen production rate. The four forms of water electrolysis are distinguished by their electrolyte, working conditions, and ionic agents (OH<sup>-</sup>, H<sup>+</sup>, O<sup>2-</sup>) [Kumar and Himabindu 2019].

The four kinds of electrolysis methods are

- (i) Alkaline water electrolysis (AWE)
- (ii) Solid oxide electrolysis (SOE)
- (iii) Microbial electrolysis cells (MEC)
- (iv) Polymer electrolyte membrane water electrolysis (PEM)

### 3.3.1 Alkaline water electrolysis (AWE)

Alkaline water electrolysis appeared at the industrial scale at the beginning of the 20<sup>th</sup> century. This method is mainly used for application of hydrogen production for ammonia synthesis. The two major goals it has is improving the efficiency and reducing capital expenses. The advantages of the method are the low cost, the high reliability and durability and the possibility to operate at elevated pressure. The drawbacks are the electrolyzers are not compact, they operate at moderate current density so sources alkaline electrolyzers cannot start up quickly and have a slow loading response. Long start- up preparation makes it difficult to adapt alkaline electrolyzers to the variable nature of renewable energy sources. Therefore, alkaline electrolyzers are normally used with a steady power input. [UPV]

Alkaline water electrolysis process initially at the cathode side two molecules of alkaline solution (KOH/NaOH) were reduced to one molecule of hydrogen (H<sub>2</sub>) and two hydroxyl ions (OH<sup>-</sup>) are produced. The produced H<sub>2</sub> eliminate from the cathode surface to recombine in a gaseous form and the hydroxyl ions (OH<sup>-</sup>) transfer under an electrochemical reaction occur at the electrode surface between anode and cathode through the porous diaphragm to the anode, here in discharged to ½ molecule of oxygen (O<sub>2</sub>) and one molecule of water (H<sub>2</sub>O). The O<sub>2</sub> recombined at the surface of electrode and escapes as hydrogen. Figure 17 illustrates the process of alkaline electrolysis. The amount of gas produced is directly proportional to the



current duo Faradays law. Two types of electrolytes are used for the cell structure, sodium hydroxide (NaOH) and potassium hydroxide (KOH) aqueous solution as the electrolyte, the concentration of the electrolyte is approximately 20%–30%. Electrolytes are substances that allows electrical current to flow between the anode and the cathode. The volume is determined by the distance (gap) between the electrodes. Also, the Anode (OER) is nickel plates + porous layer of nickel or a nickel-iron alloy and the Cathode (HER) is nickel or nickel-sulphur alloy. Nickel is used because of his good resistant to corrosion and electrochemical activate but most importantly the reasonable cost. As for the separator(diaphragm) is made from porous and electrically insulating material (Zirfen Perl) to prevent gas crossover and a hight ionic conductor for transportation of OH<sup>-</sup> ions [UPV].

- Alkaline water electrolysis operates at low temperature (30–80 °C)
- The maximum operating current density of an alkaline electrolyser is less than 400 mA/cm<sup>2</sup>
- The power consumption for H<sub>2</sub> production is ap- proximately 4.5–5.5 kWh/Nm<sup>3</sup> with an efficiency of approximately 60%.

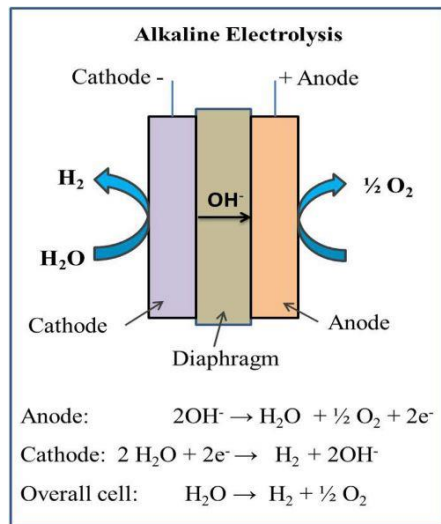


Figure 17 Schematic illustration of alkaline water electrolysis [Kumar and Himabindu 2019]

### 3.3.2 Solid oxide electrolysis (SOE)

Typically, solid oxide electrolyzers (SOE) work at temperatures exceeding 500°C, utilising steam water. In the past, O<sub>2</sub>-conductors made primarily of nickel/yttria stabilised zirconia were used in the Solid oxide electrolysis method, however in recent years, different ceramic proton conductors have been introduced. Since ceramic proton conductors in steam electrolysis at intermediate temperatures (500-700°C) exhibit greater efficiency and ionic conductivity than oxygen ion conductors, these materials have attracted a great deal of interest. Moreover, the chemical compatibility of these materials with nickel, the most used hydrogen electrode in SOEs, is remarkable. To commercialise SOE system and deploy it on a wide scale in the hydrogen production process, the challenges caused by the high temperature nature of SOE systems, such as degradation and instability, must be resolved [Sapountzi, Gracia, Fredriksson and Niemantsverdriet 2017].

The stored chemical energy can be used for generating electricity when power from renewable sources is not available by simply operating SOECs in the reverse fuel cell mode. Figure 18 shows a conceptual diagram of sustainable energy system applications based on SOEC/SOFC technology. Wind energy and solar energy, when produced in excess, may provide electricity for steam electrolysis to SOEC devices, coupled with heat energy from waste heat, for producing hydrogen that can be used for many industrial applications as well as an energy storage means. When electricity is needed, SOECs can work reversely in the fuel cell mode and the stored hydrogen can be used as a fuel for SOFCs, generating electricity from several W to MW, for different applications, ranging from portable devices to power plants. In this whole energy conversion and consumption process, only H<sub>2</sub>O will be consumed (in SOEC) and the only chemical product is H<sub>2</sub>O (in SOFC), with no consumption of fossil fuels and no emission of greenhouse gases. [Boulfrad and Traversa 2014].

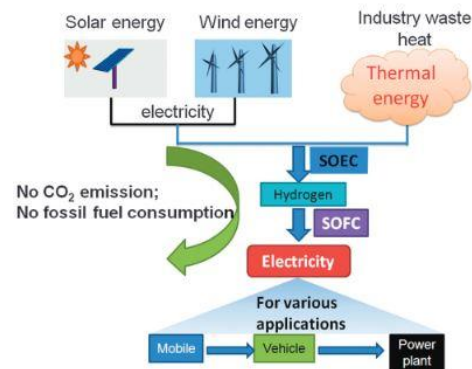


Figure 21 Concept diagram of applications of a sustainable energy system based on SOEC/SOFC technology.

[Bi, L., Boulfrad, S. and Traversa, E., 2014]

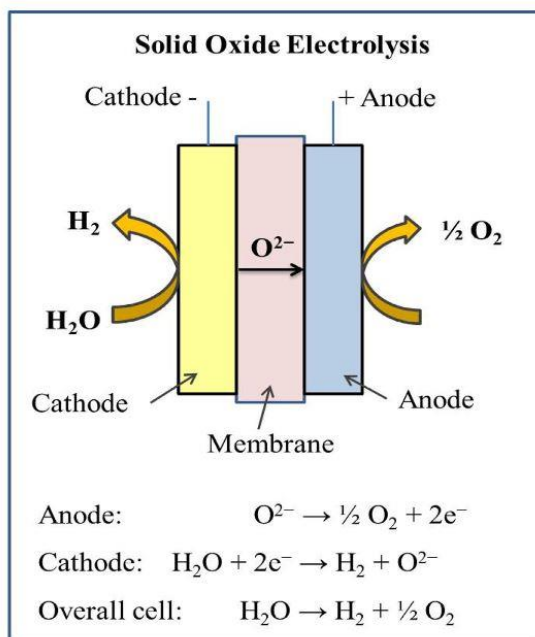


Figure 18 Schematic illustration of Solid Oxide electrolysis

[Kumar and Himabindu 2019]]

### 3.3.3 Microbial electrolysis cells (MEC)

Hydrogen production by Microbial electrolysis cell (MEC) technology can be achieved by organic matter including renewable biomass and wastewaters and this MEC technology is closely related to microbial fuel cells (MFCs), but operational principle is reverse of MFCs

In microbial electrolysis cells (MECs), electrical energy converted into chemical energy. MECs produced hydrogen from organic materials in the influence of electric current. In microbial electrolysis process, initially in anode side the substrate is oxidized by microbes and then produces CO<sub>2</sub>, protons, and electrons. The electrons are moving through the external circuit to cathode side and the protons are travelled to cathode via proton conducting membrane



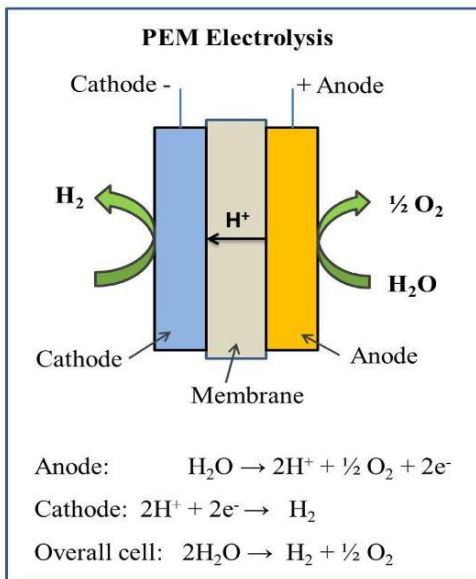


Figure 20 Schematic illustration of PEM water electrolysis [Kumar and Himabindu 2019]

The membrane electrode assemblies are consisting of membrane, ionomer solution and anode, cathode electrocatalysts which is responsible 24% of overall cell cost. Membrane is backbone of the PEMWE cell, the most commonly used membranes are Perfluoro sulfonic acid polymer membranes such as Nafion, Fumapem, Flemion, and Aciplex. These membranes have unique properties such as high strength, high efficiency and high oxidative stability, dimensionally stable with change of temperatures, good durability and high proton conductivity. However, currently Nafion membranes are mostly used in PEM water electrolyzers because Nafion membranes have tough advantages such as operating at higher current densities ( $2 \text{ A/cm}^2$ ), high durability, high proton conductivity and good mechanical stability [Carmo, Fritz, Mergel and Stolten 2013].

### 3.3.5 Comparison and Choice

Alkaline electrolysis is the most proven and commercialised technology and technique, with the lowest cost and overall good energy efficiency of 70-80%. However, alkaline technology has low current densities, purity of gases, operational pressure, and dynamic operation, making it suited for small and slow-scale industries. On the contrary, Solid Oxide and Microbial electrolysis are still in the laboratory development stage. With its high current densities, compact system design, quick responsiveness, and high hydrogen generation rate, Pem electrolysis appears to be the most suited option in this scenario. Pem's high gas purity, high energy efficiency, and high operations make it suited for the creation of complex and expansive systems. The problem with PEM technology is the high cost of its components, its low durability, and the fact that it is new and incompletely developed. However, these disadvantages are subject to alter over time, and some issues are amenable to more straightforward fixes. PEM electrolyser systems can generate H<sub>2</sub> approximately 4.5 times more effectively than other systems, so a PEM type electrolyser is chosen for the operation of the marine refuelling station. Table 5 summarises the overall benefits and drawbacks of the various water electrolysis productions.

Electrolysis process	Advantages	Disadvantages
<b>Alkaline Electrolysis</b>	Well established technology Non-noble electro catalysts Low-cost technology The energy efficiency is (70-80%) Commercialized	Low current densities Formation of carbonates on the electrode decreases the performance of the electrolyser Low purity of gases Low operational pressure (3-30 bar) Low dynamic operation
<b>Solid Oxide Electrolysis</b>	Higher efficiency (90-100%) Non-noble electro catalysts High working Pressure	Laboratory stage Large system design Low durability
<b>Microbial Electrolysis</b>	Used different organic waste waters	Under development Low hydrogen production rate Low purity of hydrogen
<b>PEM Electrolysis</b>	High current densities Compact system design Quick response Great hydrogen production rate High purity of gases (99.99%) High energy efficiency (80-90%) High dynamic operation	New and partially established High cost of components Acidic environment Low durability Commercialization is in near term

*Table 5 Advantages and Disadvantages of different water electrolysis technologies  
[Kumar and Himabindu 2019]*

## 4. Solar Hydrogen technology

### 4.1 Solar Energy advantages

Renewable energy sources have a great potential, as they could theoretically supply the world's energy demand many times over. Renewable energy sources such as biomass, wind, sun, hydropower, and geothermal can provide sustainable energy services based on the usage of indigenous, habitually accessible resources. As the cost of solar and wind power systems has decreased significantly over the past three decades and continues to diminish, while the price of oil and natural gas continues to vary, a transition to renewable energy sources becomes increasingly likely. In actuality, the prices of fossil fuels and renewable energy, as well as their associated social and environmental impacts, are declining. In addition, the economic and policy processes necessary to support the extensive diffusion and sustained markets for renewable energy sources have grown swiftly. Not conventional oil and coal sources, but the new regime of renewable and, to a lesser extent, natural gas-based systems will drive future growth in the energy sector. The financial markets are becoming aware of the future growth potential of renewable and other new energy technologies, which is likely a precursor to the economic reality of genuinely competitive renewable energy systems.

Moreover, renewable energy systems are typically based on a small-scale, decentralised paradigm that is intrinsically compatible with numerous electricity distribution, cogeneration (combined heat and power), environmental, and capital cost concerns. As an alternative to custom, on-site construction of centralised power plants, renewable systems based on photovoltaic arrays, wind turbines, biomass, or small hydropower can be mass-produced "energy appliances" that can be manufactured cheaply and customised to meet specific energy loads and service conditions. These systems can have significantly decreased and widely scattered environmental consequences, as opposed to bigger, more concentrated impacts that, in some instances, are significant contributors to ambient air pollution, acid rain, and global climate change. [Herzog 2001]

Therefore, it is vital to go for eco-friendly energy sources for the betterment of the future world. Considering renewable energy sources are critically important in this sense as they are eco-friendly and available all over the planet. However, solar energy could be the best option for the future world because of several reasons:

1. Solar energy is the most abundant energy source of renewable energy. The sun emits it at the rate of  $3.8 \times 10^{23}$  kW, out of which approximately  $1.8 \times 10^{14}$  kW is intercepted by the earth. (Panwar, N.L., Kaushik, S.C. and Kothari, S., 2011). Solar energy reaches the earth in various forms like heat and light. As this energy travels, majority of its portion is lost by scattering, reflection, and absorption by clouds. Studies revealed that global energy demand can be fulfilled by using solar energy satisfactorily as it is abundant in nature and freely available source of energy with no cost (Lewis, N.S., 2007).
2. It is a promising source of energy in the world because it is not exhaustible, giving solid and increasing output efficiencies than other sources of energy. Solar radiation distribution and its intensity are two key factors which determine the efficiency of solar PV industry. Such two parameters are highly variable over the countries. It has clearly

been indicated in Figure 22. It is important to note that much of solar radiation is not used and basically wasted [Löf, G.O., Duffie, J.A. and Smith, C.O., 1966].

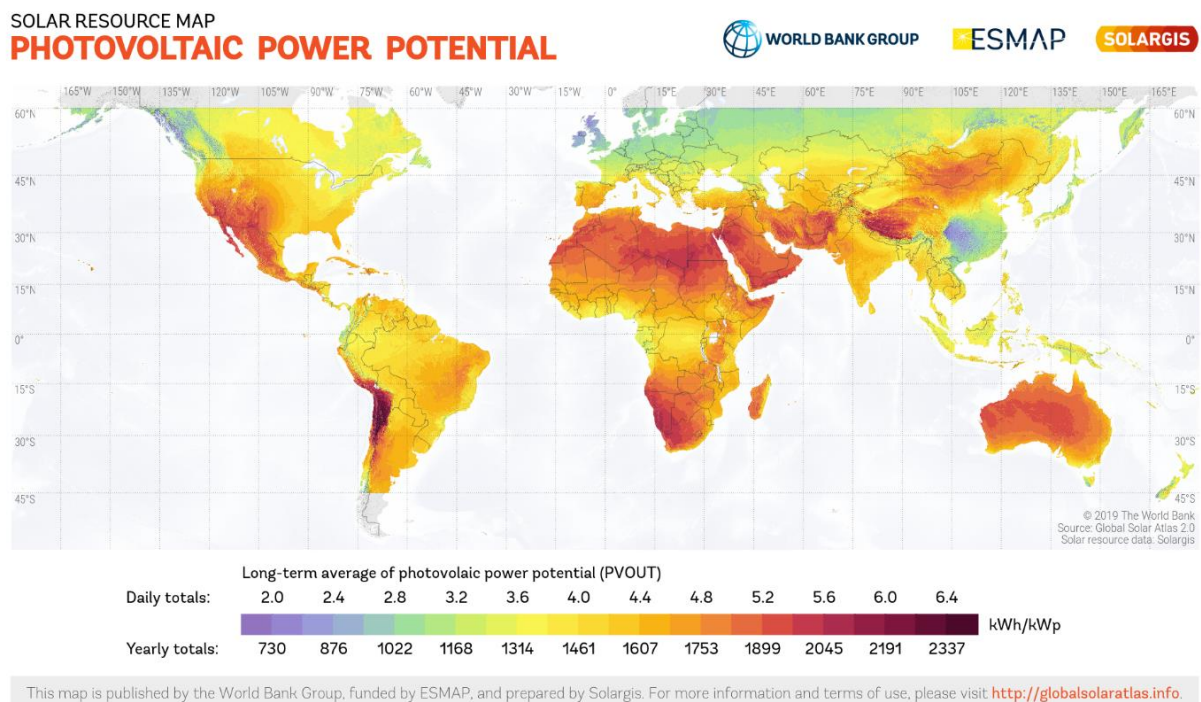


Figure 22 Solar Radiation of the World  
[\[https://solargis.com/\]](https://solargis.com/)

3. The utilization and tracking of solar energy do not have any harmful impact on ecosystem in which natural balance is kept consistent for the betterment of living organisms. Exploitation of fossil fuel leads to ecosystems damage which in-turn damages natural balances (Schlamadinger, B., Apps, M., Bohlin, F., Gustavsson, L., Jungmeier, G., Marland, G., Pingoud, K. and Savolainen, I., 1997).
4. A solar system can effectively be used for village system, industrial operations, and homes since it is easily affordable and applicable. In addition, world is now in a hurry to search for solar energy because of rising independence of global population on fossil fuel for energy recovery to perform various activities.

The use of this technology in a proper way would be a best option for future world to avoid unwanted consequences arising from energy crisis. (Kannan and Vakeesan 2016)

#### 4.2 Solar energy in Greece

The climate in South-eastern European countries and especially in Greece is relatively like that of the Middle East and North Africa, where the annual sun irradiation is theoretically high according to SolarGIS data. Figure 23 shows the high photovoltaic power potential that Greece has the period 1994 until 2018. The long-term average of PVOUT almost reach 1800Kwp, that makes Greece an excellent solution for solar energy. Today, the photovoltaic systems technology sector is exponentially expanding in the international energy market. [Alkholdi 2019]



Figure 23 Greece Photovoltaic Electricity Potential  
 [https://solargis.com/]

Greece adopted a National Plan for Energy and Climate (NPEC) in December 2019 to combat climate change and protect the natural environment mainly through Renewable Energy Sources. According to the National Plan, decarbonisation i.e., *the ending of Greece's reliance* on lignite, is scheduled to be achieved by 2028, as a top priority, while Renewable Energy Sources (RES) are projected to reach the 65% of electricity production in 2030, becoming the main national energy source in Greece. [Ministry of the Environment and Energy - *Εθνικό σχέδιο για την Ενέργεια και το κλίμα*]

Aiming to address the climate change by reducing the greenhouse gas emissions increasing *at the same time the country's energy self-sufficiency* the Greek government is preparing a bill for RES and electrical energy storage projects. The main areas of the draft bill are the simplification of the licensing process for renewables and storage licensing, while the main objectives of the draft law are to:

- *reduce the average licensing time for new RES projects from five years to 14 months*
- *develop electricity storage projects with an installed capacity of at least 3.5 GW by 2030*
- *increase the capacity of the electricity network to enable the integration of more RES units*

Also, a new solar park the biggest system with two-sided, or bifacial, panels in Europe was inaugurated. The 204-megawatt solar park was built in the northern Greek town of Kozani by Greece's biggest oil refiner Hellenic Petroleum, one of the largest oil companies in the Balkans that is undergoing a transformation into clean energy. The park will supply power to 75,000 *households and connect to the country's power grid reflecting Greece's national goals* for cheap and clean energy from the sun, the wind, and the water. [Hellenic Electronic Center *Portal Europe's Largest Photovoltaic Park in Greece*]



### 4.3 Solar energy for hydrogen production

Solar hydrogen is a clean alternative fuel, is capable of substituting fossil fuels, and ceases the addiction to oil and gaseous fuels, abating CO<sup>2</sup> emissions to save the world from global warming. [Pagliaro and Konstandopoulos, 2010].

Solar hydrogen is a feasible candidate to tackling this issue by linking the solar system to the electrolysis process. Solar hydrogen can be utilized in a broad range such as industrial and household utilization, transportation sector, and power generation in the form of fuel cell or direct combustion with water as the emission. The process efficiency of a solar-to-hydrogen system is the most important indicator of the plant's performance. Investigations show that solar hydrogen production efficiency could be increased up to 12% in a PV-based plant [Fujii 2013].

Hydrogen fuel can be generated from solar energy through different routes such as solar-to-thermal energy for thermochemical cycles and thermolysis, solar-to-electrical power using PV for electrolysis, and solar-to-photon energy via photobiological process or photocatalysis [Yang 2019].

Using PV system for electricity generation coupled with low-temperature electrolyser is one of the most affordable solar-to-hydrogen processes being developed on both electrolysis and solar sections. Hydrogen production using PV system coupled with water electrolysis was started in the beginning of 70s. [Bilgen 2001] Considering the eco-logical and economic issues, the most affordable solar hydrogen production method could be using a PV current source because of directly converting solar power into electricity. Lodhi developed the concept of solar-to-hydrogen using solar PV cells and the feasibility of using hydrogen as clean fuel to substitute liquid and gaseous fossil fuels [Lodhi 1995].

Although PV-based hydrogen production is not a cost-effective technology, this method is an environmentally friendly technology, which does not emit GHGs and noise pollution during operation, and its maintenance is not complicated as it does not involve any moving part. Kothari pointed out that by deployment of PV cells and electrolysis, solar hydrogen production process efficiency could be enhanced up to 25% to 30%. [Kothari 2008]. Ulleberg studied the performance of solar-to-hydrogen systems at sub-zero temperature areas under low solar radiation circumstances and concluded that the size of solar hydrogen production systems in this condition required to be quite large to fulfil the demands. The efficiency of PV system mitigates in high temperatures. Therefore, the PV heat should be transmitted to electrolyser, where higher temperature ameliorates the system performance [Ulleberg and Mørner 1997].

The HRS electricity demand is supplied by the electrical grid and the PV plant. The electric energy production by a PV plant is related to the site installation. In this study, the site is in Piraeus (Greece). The location latitude and longitude are 37.946, 23.619 respectively and 33 degrees slope angle to maximize the efficiency. The Yearly in-plane irradiation is 2004.05 kWh/m<sup>2</sup> with a total loss around 18%. The losses are due angle incidents, spectral effects, and temperature changes. The solar irradiation data and climate conditions are summarized in Table 6 using the Photovoltaic Geographical Information System (PVGIS ver. 5.2) for grid connect PV simulations, from the European commission. [jrc.ec.europa.eu]

Climatic and Solar irradiation parameters of the installation site	
Installed peak PV power [kWp]*	
Provided inputs:	
Location [Lat/Lon]:	37.946,23.619
Horizon:	Calculated
Database used:	PVGIS-SARAH2
PV technology:	Crystalline silicon
System loss [%]:	14
Fixed mounting options:	Free-standing
Slope angle [°]:	33
Azimuth angle [°]:	0
Yearly in-plane irradiation [kWh/m2]:	2004.05
Changes in output due to:	
Angle of incidence [%]:	-2.67
Spectral effects [%]:	0.47
Temperature and low irradiance [%]:	-1.86
Total loss [%]:	-17.47

Table 6

[Photovoltaic Geographical Information System (PVGIS ver. 5.2)]

## 5. Analysis of the PV-hydrogen marine refuelling station

### 5.1 Details on how the hydrogen refuelling station operates

A grid-connected photovoltaic solar system supplies the electricity required for PEM electrolysis processes. The essential element of a solar photovoltaic system is the photovoltaic panel, which transforms solar energy into Direct Current (DC). Specific converters adjust the voltage and current of solar panels for maximum output. The electricity is then converted to Alternating Current (AC) by an inverter and utilised by AC loads or pumped into a power system if it is not immediately consumed [Micena and Llerena-Pizarro 2020]. The electrolyzer employs the produced energy to separate the electrolyte into hydrogen and oxygen. The photovoltaic panels capture solar radiation and transform it into electricity. The conversion of solar energy to hydrogen gas can be summed up in two steps: the conversion of solar or grid energy to electrical energy and the generation of hydrogen by electrolysis. Later, the hydrogen is turned into electrical energy to power fuel cells, which produce electricity. Hydrogen storage is a difficult process due to demanding safety standards and constraints. Figure 25 depicts the procedure for storing hydrogen gas. The heat exchanger regulates the compression work during compression and inter-cooling, which impacts the storage process's efficiency. Since Hydrogen can be stored in a gaseous or liquid state, containers that can withstand high pressure are required for gaseous hydrogen storage (350-700 Bar) [Nieminen, Dincer, and Naterer, 2010]. These are the primary components of the PV PV-hydrogen marine refuelling station:

- Electrolysers
- Converters
- Compressors
- Storage tanks
- Photo-voltaic panels

Figure 24 depicts the layout of the hydrogen refuelling station.

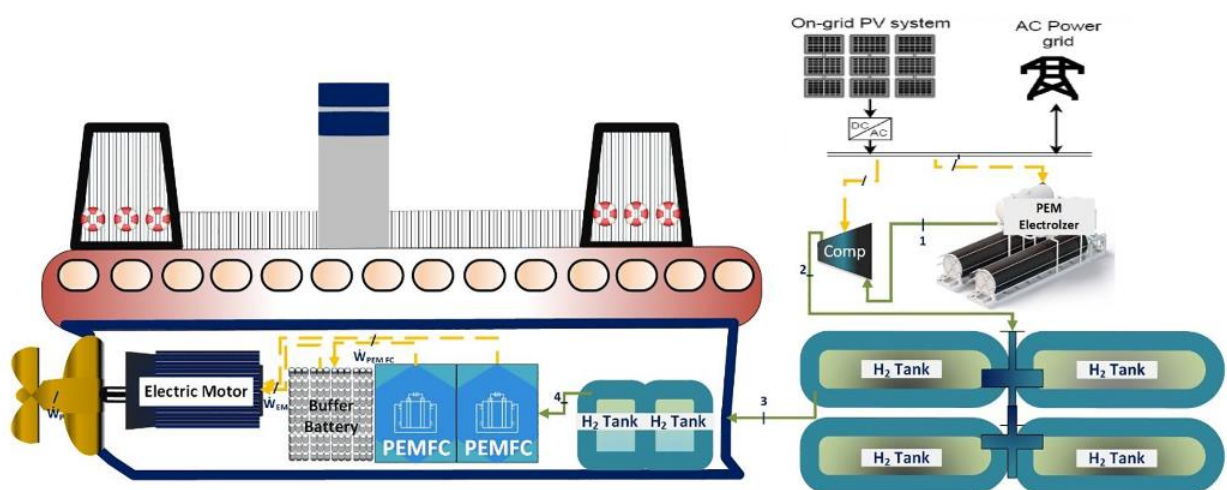


Figure 24 Simplified diagram of hydrogen production station  
[Temiz, M. and Dincer, I., 2021]

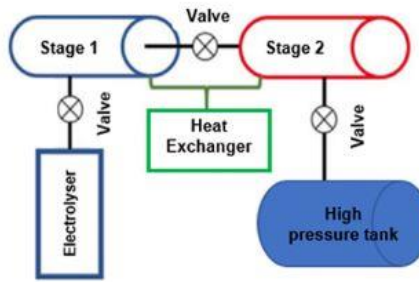


Figure 25 Production and storage of hydrogen  
[Micena and Llerena-Pizarro 2020]

## 5.2 Sizing of the different scenarios

To size the PV plant in the considered plant configurations, the annual electric energy demand for the selected hydrogen production capacities has been calculated, considering the electric energy required by the Annual Electric energy Consumption from the electrolysis unit, the hydrogen compression unit, and the convertor. Three hydrogen production capacities have been selected in accordance with small, regular, and big production scenarios that forecast different levels of hydrogen production. For the small scenario, the hydrogen production capacity is 136.58 kg/day, while in the regular and big plant size scenarios it is equal to 215 kg/day and 430 kg/day, respectively (Table 11). With referring to the electricity mix, different management strategies are selected in terms of annual sharing of electricity supply by the grid and the PV plant, starting from the full grid (FG) strategy, in which the electricity for the hydrogen production comes exclusively from the grid to the low grid (LG) strategy where the PV plant provides the 75% of the annual electricity demand. The full renewable operation (i.e., 100% PV) is not considered because the refueling station is grid-connected, but a minimum scenario of 95% PV is estimated just to compare the results. Intermediate energy management strategies are identified by increasing the percentage of the renewable Table 7 summarizes the plant configurations studied.

The selected hydrogen production capacities:

Three plant capacities	
Small	136.58 Kg/day
Medium	215 Kg/day
High	430 Kg/day

Table 7

For each of the three plant capabilities, five distinct electricity mix situations are analyzed, resulting in a total of 15 scenarios. Table 8 summarizes the plant configurations studied.

Electric Energy Supply Management Strategies					
Plant size	Full Grid 100%	High Grid 75%	Mid Grid 50%	Low Grid 25%	Minimum Grid 5%
Small (136.58 kg/day)	Small_FG	Small_HG	Small_MG	Small_LG	Small_MinG
Regular (215 kg/day)	Regular_FG	Regular_HG	Regular_MG	Regular_LG	Regular_MinG
Big (430 kg/day)	Big_FG	Big_HG	Big_MG	Big_LG	Big_MinG


Table 8 The analyzed plant configurations

## 5.3 Primary components

### 5.3.1 Electrolysers

The electrolysis unit is based on the PEM electrolysis technology. The electrolysis used in this study are medium and large-scale electrolysers from H2B2. Three groups are established for the chosen sizes (Small, Regular, Big).


The Small Size has an EL60N electrolyser with a hydrogen production capacity of 63.3 Nm<sup>3</sup>/h (136.58 kg/day) at an operating pressure of 15-40 bar with an AC power consumption of 5.2 kWh/Nm<sup>3</sup>. The hydrogen flow ranges from 10% to 100% and the purity is 99.99%. For the electrical requirements a power of 329.2 Kw (BOP + Stacks) is needed. The corresponding water consumption is 1520 L/day with an operation pressure of 2-3 barg and a temperature of 5 °C to 40 °C. The dimension of the electrolyser is 6.0mx2.4mx2.9m and the weight is 13,000 kg. Finally, it has a start-up time under 1 seconds and a cool start up time under 5 minutes. Table 9 summarizes all the characteristics of EL60N [H2B2].

<b>EL60N</b>	
Hydrogen Gas production:	
Electolysis Type:	PEM (Proton exchange membrane, caustic free)
Number of Cell Stacks:	2
<b>Hydrogen Gas production</b>	
Max. nominal hydrogen flow:	63.3 (Nm <sup>3</sup> /h)      136.58 (kg/day)
Operating Pressure:	15-40 Barg      (217-580 psig)
Hydrogen flow range:	10 -100%
Hydrogen purity:	99.99%
<b>Electrical requirements</b>	
Voltage:	3 x 400 VAC ± 10% (3Ph+N) / 3 x 480 VAC ± 10% (3Ph+N)
Frequency:	50 Hz ± 5% / 60 Hz ± 3%
Power(BOP + Stacks):	329.2      Kw
Stack consumption:	4.7      kWh/Nm <sup>3</sup> H <sub>2</sub>
AC power consumption (BoP + stack):	5.2      kWh/Nm <sup>3</sup> H <sub>2</sub>
<b>Feed Water</b>	
Consumption:	1      L/Nm <sup>3</sup> H <sub>2</sub>
	11.126      L/kgH <sub>2</sub>
	1520      L/day
Conductivity:	10 MΩcm (< 0.1 uS/cm) TOC < 30 ppb
Pressure:	2-3 barg      29-43 psig
Temperature:	5 °C to 40 °C
<b>Control System</b>	
PLC:	Fully automated and unattended with 15" color touch screen
Communication:	Modbus TCP/IP or Profinet (RJ45 port)
<b>Environmental Conditions</b>	
Ambient Temperature Range:	5 °C to 45 °C
Humidity:	0 °C to 95 °C (non-condensing)

Air Ventilation:	Available from a non-hazardous area
Installation Area:	Indoor/outdoor
<b>Dimensions and weight</b>	
Dimensions (LXWXH):	20 ft container (6.0mx2.4mx2.9m)
Approx. Weight:	13,000 Kg
<b>Standars &amp; Regulations</b>	
Compliance:	CE, ISO 22734-1 / NFPA 2-2016 & NFPA 70
<b>Other Characteristics</b>	
Duty Cycle :	100% (24/7)
Start-up Time (from Stand-by):	<1 sec
Cold Start Time:	< 5 min

Table 9 EL60N Characteristics [H2B2]


The Regular Size is equipped with an EL100N electrolyser with a hydrogen production capacity of 100 Nm<sup>3</sup>/h (215 kg/day) at an operating pressure of 15-40 bar and a power consumption of 5.2 kWh/Nm<sup>3</sup> from an AC source. The range of hydrogen flow is 10% to 100%, and its purity is 99.99%. The electrical requirements necessitate a power of 515 kW (BOP + Stacks). With an operating pressure of 1-2 barg and a temperature range of 5 °C to 40 °C, the daily water consumption is 2,392 litres. The electrolyser measures 12.0m by 2.4m by 2.9m and weighs 18,000 kg. It boasts a start-up time of less than 1 second and a cool start-up time of less than 5 minutes. Table 10 outlines all EL100N features. [H2B2].

Hydrogen Gas production:	<b>EL100N</b> 	
Electolysis Type:	PEM (Proton exchange membrane, caustic free)	
Number of Cell Stacks:	1	
<b>Hydrogen Gas production</b>		
Max. nominal hydrogen flow:	100 (Nm <sup>3</sup> /h)	215 (kg/day)
Operating Pressure:	15-40 Barg	(217-580 psig)
Hydrogen flow range:	10 -100%	
Hydrogen purity:	99.99%	
<b>Electrical requirements</b>		
Voltage:	3 x 400 VAC ± 10% (3Ph+N) / 3 x 480 VAC ± 10% (3Ph+N)	
Frequency:	50 Hz ± 5% / 60 Hz ± 3%	
Power(BOP + Stacks):	515	Kw
Stack consumption:	4.7	kWh/Nm <sup>3</sup> H <sub>2</sub>
AC power consumption (BoP + stack):	5.1	kWh/Nm <sup>3</sup> H <sub>2</sub>
<b>Feed Water</b>		
Consumption:	1	L/Nm <sup>3</sup> H <sub>2</sub>
	11.126	L/kgH <sub>2</sub>
	2392	L/day
Conductivity:	10 MΩcm (< 0.1 uS/cm) TOC < 30 ppb	
Pressure:	2-3 barg	29-43 psig
Temperature:	5 °C to 40 °C	
<b>Control System</b>		

PLC:	Fully automated and unattended with 15" color touch screen
Communication	Modbus TCP/IP or Profinet (RJ45 port)
<b>Environmental Conditions</b>	
Ambient Temperature Range:	5 °C to 45 °C
Humidity:	0 °C to 95 °C (non-condensing)
Air Ventilation:	Available from a non-hazardous area
Installation Area:	Indoor/outdoor
<b>Dimensions and weight</b>	
Dimensions (LXWXH):	40 ft container (12.0mx2.4mx2.9m)
Approx. Weight:	18,000 Kg
<b>Standars &amp; Regulations</b>	
Compliance:	CE, ISO 22734-1 / NFPA 2-2016 & NFPA 70
<b>Other Characteristics</b>	
Duty Cycle :	100% (24/7)
Start-up Time (from Stand-by):	<1 sec
Cold Start Time:	< 5 min

Table 10 EL100N Characteristics [H2B2]

The Big Size possesses an EL200N electrolyzer with a hydrogen production capability of 200 Nm<sup>3</sup>/h (430 kg/day) at an operating pressure of 15-40 bar and an AC power consumption of 5.2 kWh/Nm<sup>3</sup>. The range of hydrogen flow is 10% to 100%, and its purity is 99.99%. The electrical requirements necessitate a power of 1030 kW (BOP + Stacks). With an operating pressure of 1-2 barg and a temperature range of 5 °C to 40 °C, the daily water consumption is 4,784 litres. The electrolyser measures 12.0m by 2.4m by 2.9m and weighs 18,000 kg. It boasts a start-up time of less than 1 second and a cool start-up time of less than 5 minutes. Table 11 highlights all EL200N [H2B2] features.

Hydrogen Gas production:	<b>EL200N</b> 	
Electolysis Type:	PEM (Proton exchange membrane, caustic free)	
Number of Cell Stacks:	1	
<b>Hydrogen Gas production</b>		
Max. nominal hydrogen flow:	200 (Nm <sup>3</sup> /h)	430 (kg/day)
Operating Pressure:	15-40 Barg	(217-580 psig)
Hydrogen flow range:	10 -100%	
Hydrogen purity:	99.99%	
<b>Electrical requirements</b>		
Voltage:	3 x 400 VAC ± 10% (3Ph+N) / 3 x 480 VAC ± 10% (3Ph+N)	
Frequency:	50 Hz ± 5% / 60 Hz ± 3%	
Power(BOP + Stacks):	1030	Kw
Stack consumption:	4.7	kWh/Nm <sup>3</sup> H <sub>2</sub>
AC power consumption (BoP + stack):	5.1	kWh/Nm <sup>3</sup> H <sub>2</sub>
<b>Feed Water</b>		
Consumption:	1	L/Nm <sup>3</sup> H <sub>2</sub>
	11.126	L/kgH <sub>2</sub>

	4784	L/day
Conductivity:	10 MΩcm (< 0.1 uS/cm) TOC < 30 ppb	
Pressure:	2-3 barg	29-43 psig
Temperature:	5 °C to 40 °C	
<b>Control System</b>		
PLC	Fully automated and unattended with 15" color touch screen	
Communication	Modbus TCP/IP or Profinet (RJ45 port)	
<b>Environmental Conditions</b>		
Ambient Temperature Range	5 °C to 45 °C	
Humidity	0 °C to 95 °C (non-condensing)	
Air Ventilation	Available from a non-hazardous area	
Installation Area	Indoor/outdoor	
<b>Dimensions and weight</b>		
Dimensions (LXWXH)	40 ft container (12.0mx2.4mx2.9m)	
Approx. Weight	18,000 Kg	
<b>Standars &amp; Regulations</b>		
Compliance	CE, ISO 22734-1 / NFPA 2-2016 & NFPA 70	
<b>Other Characteristics</b>		
Duty Cycle	100% (24/7)	
Start-up Time (from Stand-by)	<1 sec	
Cold Start Time	< 5 min	

Table 11 EL200N Characteristics [H2B2]

All the electrolyzers also include a hydrogen cooling system, an emergency shut down system, an overpressure relief system, a redundancy on critical safety parameters, an uninterruptible power supply (UPS), their own heat management so no cooling water is needed and virtual private network (VPN) connection [H2B2].

### 5.3.2 Compressors

Even if advanced solutions for the hydrogen compression unit are currently available (i.e., the ionic compressor by Linde), the compressor mostly installed in the hydrogen refuelling stations is the reciprocating compressor that uses a piston to compress the hydrogen. The compressor unit has to increase the hydrogen pressure from 10 bar (electrolysis operating pressure) to 820 bar. The high-pressure storage consists of more tanks at different pressures. The storage tanks are filled one after the other by using the compressor unit: firstly, the low-pressure tanks, then the medium-pressure storage tanks and finally high-pressure tanks according to a cascade system [Farzaneh-Gord, Deymi-Dashtebayaz, Rahbari and Niazm and 2012].



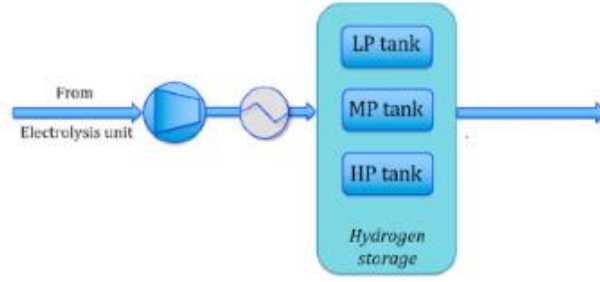


Figure 26 Hydrogen compression and storage unit  
[Farzaneh-Gord, Deymi-Dashtebayaz, Rahbari and Niazm and 2012]

The specific work (kJ/kg) of the compressor unit is calculated by applying the well-known equation for ideal conditions:

$$L_{is,c} = \frac{k}{k-1} \cdot R_{H_2} \cdot T_{in} \cdot \left[ \frac{p_{out}^{\frac{k-1}{k}}}{p_{in}^{\frac{k-1}{k}}} - 1 \right] \quad (3)$$

Where  $k$  (1.4) is the ratio of the specific heats ( $c_p$  and  $c_v$ ),  $R_{H_2}$  is the hydrogen gas constant (4.12 kJ/kg K),  $T_{in}$ (K) is the hydrogen inlet temperature (25 C) and  $p_{in}$  and  $p_{out}$  are the inlet (10 bar) and outlet (820 bar) pressures, respectively. The calculated specific work is 10.84 kJ/g. Starting from this value, the required electric power (for each hydrogen production capacities) is calculated by assuming the isentropic efficiency ( $\eta_{is,c}$ ), the mechanical efficiency ( $\eta_m$ ) and the electric generator efficiency ( $\eta_e$ ) equal to 80%, 98% and 96%, respectively. By applying this equation, the sizes of the compressors are 23.2 kW, 35 kW and 72.7 kW for the three considered hydrogen production capacities.

$$P_{compressor} = \frac{\dot{m}_{H_2} \cdot L_{is,c}}{\eta_{is,c} \cdot \eta_m \cdot \eta_e} \quad (4)$$

### 5.3.3 Bi-directional converter

The bi-directional converter is used for the regulation of the flow of current into either direction (between AC and DC bus lines). The main function of the converter is to provide power from DC sources to the load. The size of the converter is based on the maximum energy level in the system. The capacity of the converter is similar to the capacity of its corresponding electrolyser. In particular, the sizes of the converter are 350kw, 550kw and 1080 kw for the Small, Regular and Big sizing respectively. [Sethi 2020].

### 5.3.4 Hydrogen Tanks

Bunkering methods depends completely on the method of fuel storage.

Gaseous hydrogen: Stored as a gas at the port and transferred to the vessel. As discussed, the flow rate of the hydrogen needs to be carefully controlled to prevent excessive adiabatic heating. There are two key options for transferring gaseous hydrogen to the ships:

- Pressure balancing: Store hydrogen in the port at a higher pressure than the vessel requires (for example, a ship requiring 350 bar would commonly have 500 bar stored in the port). Then open a valve and allow the hydrogen to flow into the vessel under its own pressure. This method does not require compressors to move the gas across at high throughput, but needs considerable storage capacity at the port, as much of the storage is inaccessible (once the pressure in the port storage drops below 350 bar, it *is unable to fill a ship to 350 bar*). This can be mitigated to some extent using 'cascade filling' whereby several smaller hydrogen stores are employed, and each is utilised in turn to fill the ship to the required level
- Compressing the gas into the ship: A high throughput compressor is used to move hydrogen from a low pressure (typically 20 bar) store in the port, to the ship. This allows careful control of the hydrogen flow but requires expensive equipment.

Liquid hydrogen: Stored as liquid hydrogen at the port and transferred to the vessel using cryogenic pumps. This technology is now reasonably well understood from experience of bunkering LNG. However, while LNG is generally transported to a port for subsequent bunkering, it is likely that a hydrogen liquefaction plant would be located nearby.

- Metal hydride: Stored as a high-pressure gas at the port and transferred to the vessel either using pressure balancing or transferred via a compressor. Heat extraction is required from the store to allow the hydrogen to enter the metal matrix.

- LOHC: Stored on the dock as hydrogenated organic compound. Transferred to the vessel via pumps. Dehydrogenated oil removed from the vessel and stored at the port. [Hyde, K., [Ellis, A. and Power, I.T.M., 2019]

In the study hydrogen is going to be used in gaseous form. The gaseous form has the advantage of simplicity in transportation of gaseous fuel, excellent dormancy characteristics, and low infrastructure impact along with added benefits of large-scale, low-cost storage. *Storing a kg of hydrogen at 100 kPa and 25 °C requires a tank of volume around 12 m<sup>3</sup>*. Compressing hydrogen to pressures of up to 350 bar decreases the required storage volume by 99.6%. Further pressure increase lowers the storage volume but leads to increasing compression work and safety concerns. To save compression energy, a buffer tank can be installed after the electrolyser and compression can start when the tank is at full charge. Compressed hydrogen can be stored in closed tanks with volumetric densities of around 20-50 kg/m<sup>3</sup>. The size of long-term hydrogen storage tank is decided based on the availability and seasonal variation of renewable power sources and the desired system autonomy [Sethi, R 2020]. In this case, the hydrogen tanks must have around 30%-40% more capacity from their corresponding daily production, because there is no battery or an immediate constant use.

The Small size station consumes 2883.792 MWh/year of electricity from the PEM electrolyser. 49851.7 kg of hydrogen is produced annually. Mean production is found as 5.7 kg/ hour. For each kg of hydrogen, 57.8 kWh electricity is consumed. A 200 kg hydrogen tank is used about 30% capacity more from the daily production for safety reasons.

The Regular size station consumes 4511.4 MWh/year of electricity from the PEM electrolyser. 78475 kg of hydrogen is produced annually. Mean production is found as 8.9 kg/ hour. For each kg of hydrogen, 57.5 kWh electricity is consumed. A 300 kg hydrogen tank is used about 30% capacity more from the daily production for safety reasons.

The Big size station consumes 9022.8 MWh/year of electricity from the PEM electrolyser. 156950 kg of hydrogen is produced annually. Mean production is found as 17.9 kg/ hour. For each kg of hydrogen, 57.5 kWh electricity is consumed. A 500 kg hydrogen tank is used about 30% capacity more from the daily production for safety reasons.



Figure 27 Example of a hydrogen buffer tank  
[<https://h2ports.eu/>]

### 5.3.5 Photo-voltaic panels

Table 12 summarizes the annual electric energy demands of each component and the total electric energy demand according to the annual refueling station operating time. The total annual electric energy demands are satisfied by the grid and the PV plant, according to the different energy mix established by the electric energy supply management strategies.

Annual Electric energy Consumption (MWh/year)				
Plant Capacity	EL60N-Small	EL100N-Regular	EL200N- Big	
Electrolysis Unit	2883.79	4511.40	9022.80	MWh/year
Compressor	203.23	306.60	636.85	MWh/year
Convertor	214.62	337.26	662.26	MWh/year
TOTAL	3301.64	5155.26	10321.91	MWh/year

Table 12

With the use of PVGIS ver. 5.2 simulator the necessary installed peak PV power in [kWp] is calculated for all three capacities (Small, Regular, Big). It is important so we can achieve the exact electricity mix. Table 13,14,15 illustrates the energy combinations, the Year-to-year variability and PV Plant Size of the different capacities. For the Small capacity plant side, the energy demand for a year is 3301.64 MWh/year. For the Regular and Big is 5155.26 MWh/year and 10321.91 MWh/year respectively.

Small Capacity- EL60N							
Electricity Mix	HRS energy demand (MWh/year)	Gird (MWh/year)	PV (MWh/year)	Year-to-year variability [MWh/year]	PV Plant Size (KWP)	Grid%	PV%
Full Gird 100%	3301.64	3301.64	-	-	-	100	0
High Grid 75%	3301.64	2474.62	827.02	14.43	500	75	25
Mid Grid 50%	3301.64	1664.14	1637.50	28.57	990	50	50
Low Grid 25%	3301.64	820.58	2481.06	43.29	1500	25	75
Minimum Grid 5%	3301.64	158.97	3142.68	54.84	1900	5	95

Table 13

Regular Capacity- EL100N							
Electricity Mix	HRS energy demand (MWh/year)	Gird (MWh/year)	PV (MWh/year)	Year-to-year variability [MWh/year]	PV Plant Size (KWP)	Grid%	PV%
Full Gird 100%	5155.26	5155.26	-	-	-	100	0
High Grid 75%	5155.26	3881.65	1273.61	22.22	770	75	25
Mid Grid 50%	5155.26	2591.50	2563.76	44.74	1550	50	50
Low Grid 25%	5155.26	1268.26	3887.00	67.83	2350	25	75
Minimum Grid 5%	5155.26	275.84	4879.42	85.15	2950	5	95

Table 14

Big Capacity- EL200N							
Electricity Mix	HRS energy demand (MWh/year)	Gird (MWh/year)	PV (MWh/year)	Year-to-year variability [MWh/year]	PV Plant Size (KWP)	Grid%	PV%
Full Gird 100%	10321.91	10321.91	-	-	-	100	0
High Grid 75%	10321.91	7758.14	2563.76	44.74	1550	75	25
Mid Grid 50%	10321.91	5111.68	5210.23	90.92	3150	50	50
Low Grid 25%	10321.91	2547.92	7773.99	135.66	4700	25	75
Minimum Grid 5%	10321.91	563.07	9758.84	170.29	5900	5	95

Table 15

The annual energy production from fix-angle PV system of the different simulations is reported in the Figures below. It is important to note the wide variability during the year: in July the power production reached the maximum values in alternative current and in December the power production reached the minimum values.

## Small Capacity- EL60N

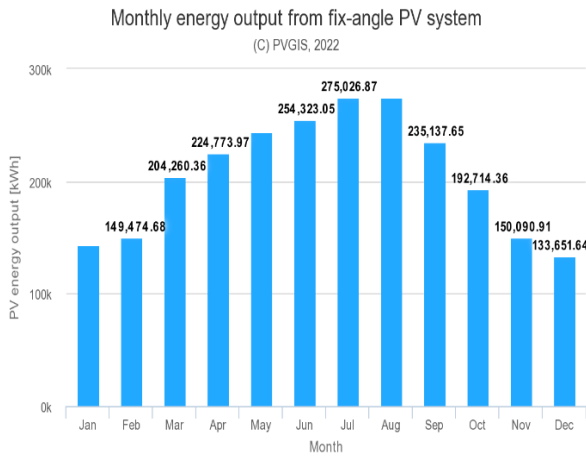


Figure 28 Pv Peak 1500 Kwp

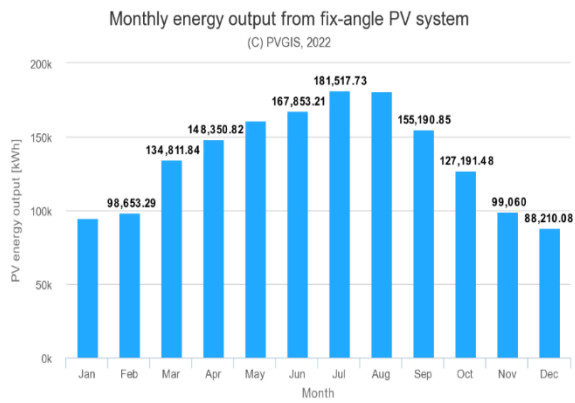


Figure 29 Pv Peak 990Kwp

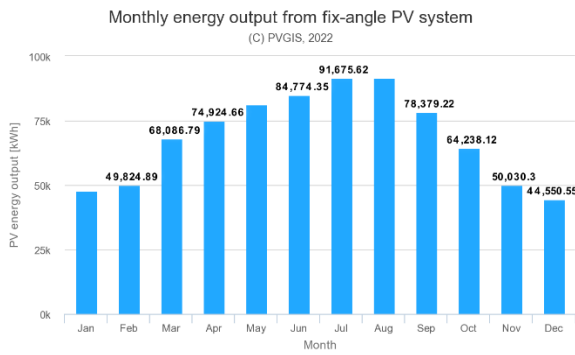


Figure 30 PV Peak 500 Kwp

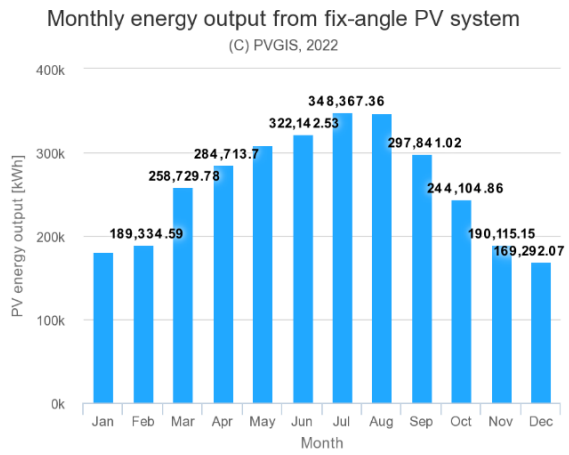


Figure 31 PV Peak 1900 kWP

## Regular Capacity- EL100N

Monthly energy output from fix-angle PV system

(C) PVGIS, 2022

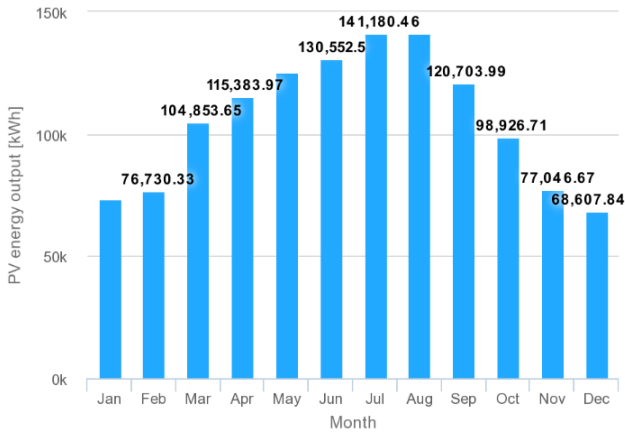


Figure 32 Pv Peak 770 Kwp

Monthly energy output from fix-angle PV system

(C) PVGIS, 2022

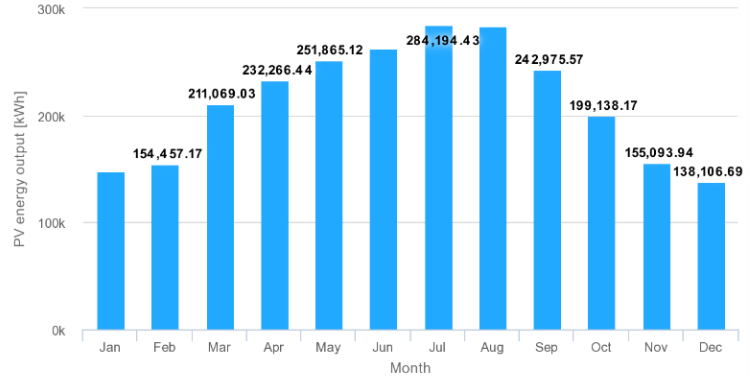


Figure 33 Pv Peak 1550 Kwp

Monthly energy output from fix-angle PV system

(C) PVGIS, 2022

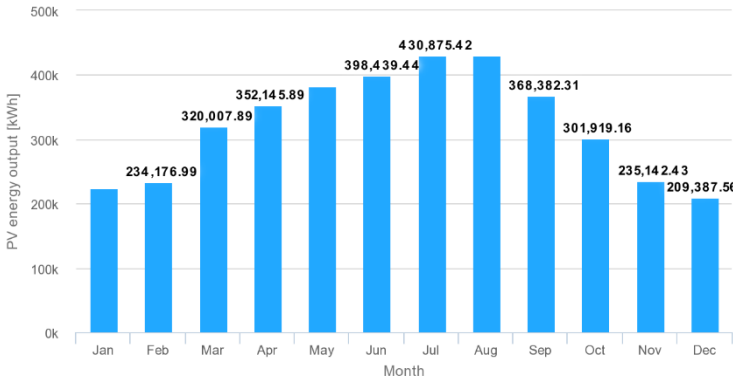


Figure 34 Pv Peak 2350 Kwp

Monthly energy output from fix-angle PV system

(C) PVGIS, 2022

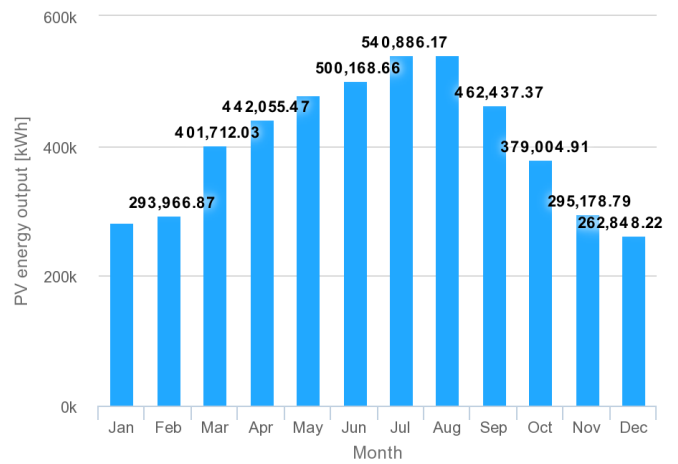


Figure 35 Pv Peak 2950 Kwp

# Big Capacity- EL200N

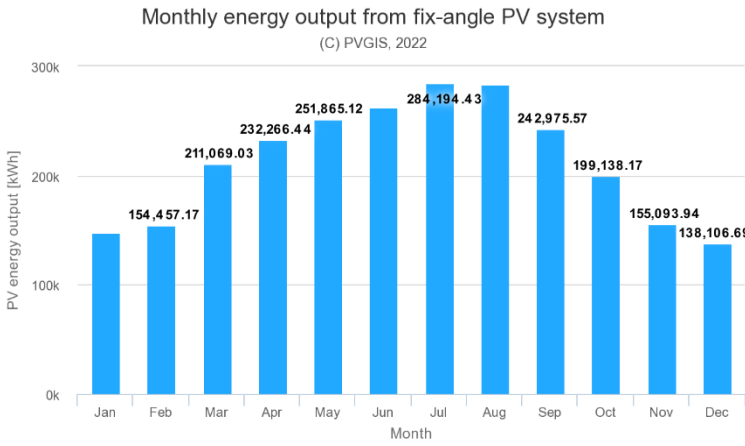


Figure 36 P<sub>v</sub> Peak 1550 Kwp

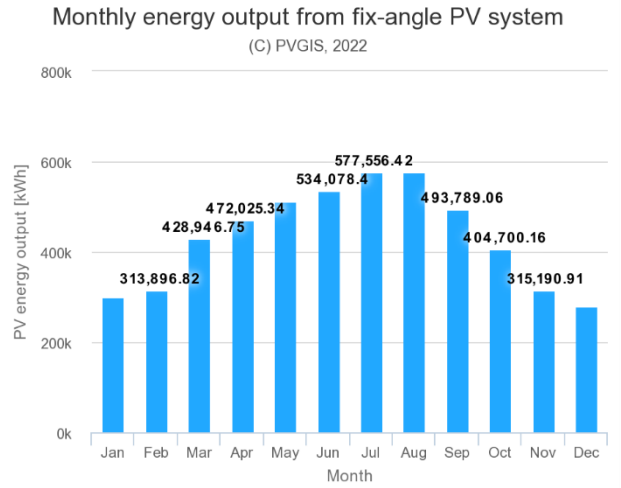


Figure 37 P<sub>v</sub> Peak 3150 Kwp

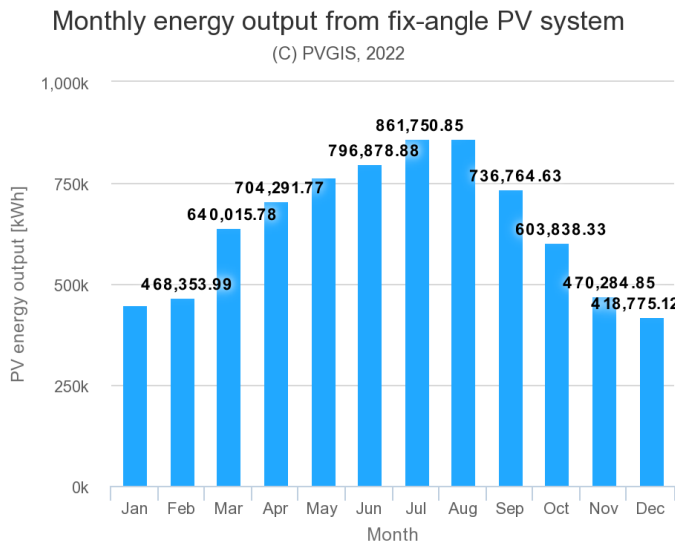


Figure 38 P<sub>v</sub> Peak 4700 Kwp

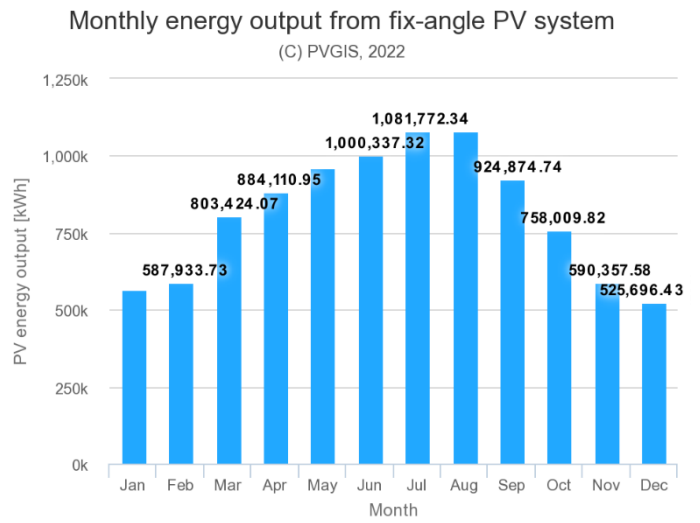


Figure 39 P<sub>v</sub> Peak 5900 Kwp

Given the intermittent behavior of the photovoltaic plant, if the PV power production is not enough to satisfy the hourly electric demand, the grid compensates the “*electricity deficit*”. On the other hand, when the electric energy requirement is fully covered and the PV produces an “*electricity excess*”, it is diverted to the grid. Over a year, this “*electricity excess*” is equal to the “*electricity deficit*”. Thus, if from an energetic point of view, the deficit and the excess are balanced, from an economic point of view there is a difference in costs and revenues. Table 16 illustrates the electric energy demand and, therefore, the electric energy that must be supplied by the PV plant and by the grid, according to the energy management strategies.

Different Pv sizes					
Electricity Mix	HRS Configuration	HRS energy demand (MWh/year)	Gird (MWh/year)	PV (MWh/year)	Pv plant Size (kWp)
Full Grid (100%)	EL60N - Small	3301.64	3301.64	-	-
	EL100N - Regular	5155.26	5155.26	-	-
	EL200 – Big	10321.91	10321.91	-	-
High Grid (75%)	EL60N - Small	3301.64	2474.62	827.02	500.00
	EL100N - Regular	5155.26	3881.65	1273.61	770.00
	EL200 – Big	10321.91	7758.14	2563.76	1550.00
Mid Grid (50%)	EL60N - Small	3301.64	1664.14	1637.50	990.00
	EL100N - Regular	5155.26	2591.50	2563.76	1550.00
	EL200 – Big	10321.91	5111.68	5210.23	3150.00
Low Grid (25%)	EL60N - Small	3301.64	820.58	2481.06	1500.00
	EL100N - Regular	5155.26	1268.26	3887.00	2350.00
	EL200 – Big	10321.91	2547.92	7773.99	4700.00
Minimum Grid (5%)	EL60N - Small	3301.64	158.97	3142.68	1900.00
	EL100N - Regular	5155.26	275.84	4879.42	2950.00
	EL200 – Big	10321.91	563.07	9758.84	5900.00

Table 16 Different Pv sizes



## 6. Techno-economic assessment of on-site hydrogen Refuelling station

Hydrogen production via water electrolysis is expensive due to the high investment and running costs which make an economic assessment of such systems important. Life cycle cost (LCC) analysis has been the method to study the cost due to its capability of capturing all upstream costs associated with the overall lifetime of the selected system [Zakeri 2015]. Hydrogen systems are often considered as a replacement or addition to conventional energy sources at remote locations where diesel generators are used extensively with relevant emissions and diesel cost. Therefore, as a means to compare different systems, the levelized cost of hydrogen (LCOH) method has been implemented in order to evaluate the LCC in terms of cost per energy unit (kWh) or in terms of hydrogen mass (kg) [Lee 2009]. Three indicators will be used the LCOH, NPC and the NPV with the IRR for the one example with the ferry.

### 6.1 Life Cycle Costing (LCC)

LCC is an important method to evaluate the total cost of a product or a system over its given lifetime. By applying LCC into the early life cycle stage, changes are easier in terms of minimizing the LCC. There is no global approach that fits all situations and as the literature reveals the LCC discourse has been a long journey. Many methods have been proposed and are rather general in approach. Although the methods are different, many of the main steps are similar to some of the first methods such as the steps in the method by Harvey [Harvey 1976]:

- Define the cost elements
- Define the cost structure
- Establish cost estimating relationships
- Establish the method of LCC formulation

Although LCC has been accepted as a methodology it is still being criticized. The main disadvantages of the LCC method come from the fact that it includes a future estimation and can lead to uncertain results. Despite the flaws of the LCC method it still provides a somewhat holistic universal method to evaluate and compare different investment opportunities.

#### Levelized Cost of Hydrogen (LCOH)

Essentially the LCOH method is based on the levelized cost of energy (LCOE) method which is widely used in the renewable energy sector where the LCC of renewables is presented in terms of cost per energy output unit. The definition of the LCOE by IRENA [Viktorsson 2017] is depicted in Equation (5):

$$\text{LCOE} = \frac{\sum_{n=1}^N (I_n + M_n + F_n) \times (1+i)^{-n}}{\sum_{n=1}^N E_n \times (1+i)^{-n}} \quad (5)$$

Where  $I_n$  is the initial investment cost for year  $n$ ,  $M_n$  is the maintenance cost in year  $n$ ,  $F_n$  is the fuel cost in year  $n$ ,  $E_n$  is the energy generation in year  $n$ ,  $i$  is the discount rate and  $N$  is the lifetime. The LCOE method is a valuable tool when comparing different case studies and is not limited to renewable energy sources but has been used widely to assess the cost of hydrogen. Hydrogen output is usually measured in terms of energy and therefore, similarly to

electrical calculations, the cost can be presented in terms of cost per unit energy or mass of hydrogen. The equation for hydrogen is as follows [Zakeri 2015].

$$LCOH = \frac{\sum_{n=1}^N \frac{(i) \times (1+i)^n}{(1+i)^{n-1}} \times (C_{inv} + \frac{C_{rep}}{(1+i)^n}) + C_{O\&M}}{M_{H_2}} \quad (6)$$

$C_{inv}$ : initial investment cost for year n

$C_{O\&M}$ : maintenance cost in year n

$C_{rep}$ : replacement in year n

$M_{H_2}$ : hydrogen production in year n

i: discount rate

N: lifetime

CRF: capital recovery factor ( $\frac{i \times (1+i)^{-n}}{(1+i)^{-n} - 1}$ )

### 6.1.1 LCC Assessment

The cost of hydrogen production considers not only the initial investment due to plant construction, but also all the management costs over the entire lifetime. These costs can significantly vary, depending on the size of the plant and the primary energy source employed for its production. To compare the economic performance of the proposed plant configurations characterized by different plant sizes and different percentages of energy sharing and production [Woodward 1997].

Equation (7) depicts how the investment cost was calculated:

$$C_{inv} = C_{we} + C_c + C_{con} + C_s + C_d + C_{misc} \quad (7)$$

Where  $C_{inv}$  is the investment cost,  $C_{we}$  is the WE cost,  $C_c$  is the compressor cost,  $C_{con}$  is the convertor cost,  $C_s$  is the storage unit cost,  $C_d$  is the dispenser cost and  $C_{misc}$  is miscellaneous costs or all other costs that were connected to the station.

The investment costs were annualized by the capital recovery factor (CRF) depicted in Equation (8):

$$CRF = \frac{i \times (1+i)^{-n}}{(1+i)^{-n} - 1} \quad (8)$$

where i is the nominal discount rate and n is the economic lifetime of the station. The annualized, a, investment costs are therefore:

$$C_{inv,a} = CRF \times C_{inv} \quad (9)$$

The operational and maintenance (O&M) costs were divided between fixed and variable expenses. The annual fixed O&M is denoted by:

$$C_{form,a} = C_{mc} + C_{rep,a} \quad (10)$$

where  $C_{mc}$  is the maintenance cost, and  $C_{rep,a}$  is the annualized replacement cost

Annual replacement costs were calculated by applying the single amount present value formula and the CRF to the replacement costs. Equation (11) depicts how the annual

replacement costs were calculated, where  $t$  is the year of replacement,  $i$  is the nominal discount rate and  $C_{rep}$  is the current value of the component to be replaced:

$$C_{rep,a} = CRF \times \frac{C_{rep}}{(1+i)^t} \quad (11)$$

Similarly, the variable O&M is presented by:

$$C_{vom,a} = C_e \times C_w \quad (12)$$

where  $C_e$  is the annual electricity cost and  $C_w$  is the annual water cost. The annualized LCC can therefore be expressed by Equation (13):

$$C_{LCC,a} = C_{form,a} + C_{inv,a} + C_{vom,a} \quad (13)$$

After the annualized LCC have been calculated the LCOH can be assessed by dividing the annualized LCC noted as  $C_{LCC,a}$  by the amount of produced hydrogen ( $\text{kgH}_2$ ) noted as  $E_{H_2,a}$ , on an annual basis:

$$LCOH = \frac{C_{LCC,a}}{E_{H_2,a}} \quad (14)$$

The calculation of the LCOH allows to evaluate the overall economic performance of the hypothesized plant configurations and therefore the one which corresponds to the lowest hydrogen production cost. Moreover, it is possible to evaluate how the incidence of the different cost categories varies, depending on the size and power sharing between PV and grid variations.

### 6.1.2 Costs assessment

Based on the LCOH computation, the Capital Expenditure (CAPEX), Operational Expenditure (OPEX), and Replacement Expenditure (REFLEX) have been determined for the economic analysis. For calculating the cost (calculated as operating costs) associated with water usage, *2 €/m<sup>3</sup> water prices in Greece were used. Electricity usage is the plant's largest operating expense. In Greece, the price of electricity fluctuates about 0.08 €/kWh.*

According to the technical literature, Table 17 provides a summary of the primary economic data used for the analysis. Capital expenditures consist of site preparation, engineering and design, approvals, and project contingencies. All these data have allowed to estimate the economic parameters for the LCOH calculation, the net present cost and the net present value for the one example. From table 18 through table 22, the following is a comprehensive summary of all costs and electric revenues for the proposed plant configurations, beginning with Full Grid and ending with Minimum Grid. Summarize the Capex, Opex, and Reflex of each configuration's components.

Parameter	Value	Unit
Plant Life time	25	years
Nominal interest rate	3%	
Pv plant cost	852.43	€/kW
Compressor cost	$43872 * p^{0.5861}$	€
Electrolyzer cost	1100	€/kW
Storage system cost	1000	€/kgH <sub>2</sub>
Converter	210	€/kW

Dispenser cost	150,000	€
Water aux. cost	8.47	€/kW
O&M cost (PV plant)	1.58%	
O&M cost (electrolyzer)	2%	
O&M cost (Compressor)	8%	
O&M cost (converter)	1%	
O&M cost (dispenser)	4%	
O&M cost (water aux.)	2%	
Time for components replacement	15	years
O&M cost (storage)	1%	

Table 17 Economic assumptions and costs data

Cost for Full Grid energy management strategy			
Electricity Mix: Full Grid	Small	Regular	Big
CAPEX (€)			
Storage system	200000	300000	500000
Electolyzer	362120	566500	1133000
Compressor	277013	352505	541044
Converter	73500	115500	226800
Dispenser	150000	150000	300000
Water System	2788	4362.05	8724.1
TOTAL	€1,065,421.19	€1,488,867.40	€2,709,568.31
OPEX (€/year)			
Electolyzer	14485	22660	45320
Compressor	16621	21150	32463
Converter	735	1155	2268
Dispenser	6000	6000	12000
Water System	56	87	174
Storage tank	2000	3000	5000
Annual Water purchase	1109	1746	3492
Annual Electricity purchase	264132	412421	825753
TOTAL	€305,137.16	€468,219.59	€926,470.23
REPLEX (€)			
Storage tank	-	-	-
Electolyzer	144848	226600	453200
Compressor	277013	352505	541044
Converter	73500	115500	226800
Dispenser	150000	150000	300000
Water System	2788	4362	8724
TOTAL	€648,149.19	€848,967.40	€1,529,768.31

Table 18

Cost for High Gird energy management strategy			
Electricity Mix: High Grid	Small	Regular	Big
CAPEX (€)			
PV modules	426215	656371	1321267
Storage system	200000	300000	500000
Electolyzer	362120	566500	1133000
Compressor	277013	352505	541044
Converter	73500	115500	226800
Dispenser	150000	150000	300000
Water System	2788	4362	8724
TOTAL	€1,491,636.19	€2,145,238.50	€4,030,834.81
OPEX (€/year)			
PV modules	6734	10371	20876
Electolyzer	14485	22660	45320
Compressor cost	16621	21150	32463
Converter	735	1155	2268
Dispenser	6000	6000	12000
Water System	56	87	174
Storage tank	2000	3000	5000
Annual Water purchase	1109	1746	3492
Annual Electricity purchase	197970	310532	620652
TOTAL	€245,709.73	€376,701.34	€742,245.19
REPLEX (€)			
Storage tank	-	-	-
Pv modules	-	-	-
Electolyzer	144848	226600	453200
Compressor	277013	352505	541044
Converter	73500	115500	226800
Dispenser	150000	150000	300000
Water System	2788	4362	8724
TOTAL	€648,149.19	€848,967.40	€1,529,768.31

Table 19

Cost for Mid Gird energy management strategy			
Electricity Mix: Mid Grid	Small	Regular	Big
CAPEX (€)			
PV modules	843906	1321267	2685155
Storage system	200000	300000	500000
Electolyzer	362120	566500	1133000
Compressor	277013	352505	541044
Converter	73500	115500	226800
Dispenser	150000	150000	300000

Water System	2788	4362	8724
TOTAL	€1,909,326.89	€2,810,133.90	€5,394,722.81
<b>OPEX (€/year)</b>			
PV modules	13334	20876	42425
Electolyzer	14485	22660	45320
Compressor	16621	21150	32463
Converter	735	1155	2268
Dispenser	6000	6000	12000
Water System	56	87	174
Storage tank	2000	3000	5000
Annual Water purchase	1109	1746	3492
Annual Electricity purchase	133131	207320	408934
TOTAL	€187,470.84	€283,994.55	€552,077.41
<b>REPLEX (€)</b>			
Storage tank	-	-	-
Pv modules	-	-	-
Electolyzer	144848	226600	453200
Compressor	277013	352505	541044
Converter	73500	115500	226800
Dispenser	150000	150000	300000
Water System	2788	4362	8724
TOTAL	€648,149.19	€848,967.40	€1,529,768.31

Table 20

Cost for Low Grid energy management strategy			
Electricity Mix: Low Grid	Small	Regular	Big
<b>CAPEX (€)</b>			
PV modules	1278645	2003211	4006421
Storage system	200000	300000	500000
Electolyzer	362120	566500	1133000
Compressor	277013	352505	541044
Converter	73500	115500	226800
Dispenser	150000	150000	300000
Water System	2788	4362	8724
TOTAL	€2,344,066.19	€3,492,077.90	€6,715,989.31
<b>OPEX (€/year)</b>			
PV modules	20203	31651	63301
Electolyzer	14485	22660	45320
Compressor	16621	21150	32463
Converter	735	1155	2268
Dispenser	6000	6000	12000
Water System	56	87	174

Storage tank	2000	3000	5000
Annual Water purchase	1109	1746	3492
Annual Electricity purchase	65647	101461	203833
TOTAL	€126,854.86	€188,910.66	€367,852.37
<b>REPLEX (€)</b>			
Storage tank	-	-	-
Pv modules	-	-	-
Electolyzer	144848	226600	453200
Compressor	277013	352505	541044
Converter	73500	115500	226800
Dispenser	150000	150000	300000
Water System	2788	4362	8724
TOTAL	€648,149.19	€848,967.40	€1,529,768.31

Table 21

Cost for Minimum Grid energy management strategy			
Electricity Mix: Minimum Grid	Small	Regular	Big
<b>CAPEX (€)</b>			
PV modules	1619617	2514669	5029337
Storage system	200000	300000	500000
Electolyzer	362120	566500	1133000
Compressor	277013	352505	541044
Converter	73500	115500	226800
Dispenser	150000	150000	300000
Water System	2788	4362	8724
TOTAL	€2,685,038.19	€4,003,535.90	€7,738,905.31
<b>OPEX (€/year)</b>			
PV modules	25590	39732	79464
Electolyzer	14485	22660	45320
Compressor	16621	21150	32463
Converter	735	1155	2268
Dispenser	6000	6000	12000
Water System	56	87	174
Storage tank	2000	3000	5000
Annual Water purchase	1109	1746	3492
Annual Electricity purchase	2004	6032	6025
TOTAL	€68,599.49	€101,562.44	€186,206.35
<b>REPLEX (€)</b>			
Storage tank	-	-	-
Pv modules	-	-	-
Electolyzer	144848	226600	453200
Compressor	277013	352505	541044

Converter	73500	115500	226800
Dispenser	150000	150000	300000
Water System	2788	4362	8724
<b>TOTAL</b>	<b>€648,149.19</b>	<b>€848,967.40</b>	<b>€1,529,768.31</b>

Table 22

### 6.1.3 Net Present Cost instigator

NPC is the difference between the present cost of the all the costs of installing and operating the components of the system and the present value of total revenue generated over the lifetime of the project and is calculated using the following equation [15]:

$$NPC = C_0 + \sum \frac{C \cdot t}{(1 + r)^t} \quad (15)$$

where:

- Co: Initial Investment
- C: Cash flow
- r: Discount rate
- t: time

The initial investment and cash flow are distinct for each scenario, but the discount rate and timeframe are the same: 3% and 25 years, respectively. For example, the Regular MG size has an Initial Investment (Co) of €2,810,133.90, which is the Capex for that mix. The Cash Flow (C) is dependent on the operation & maintenance and the replacement. The measures taken up until the twenty-fifth year are depicted in Table 23, which evaluates the net present cost of €8,300,292.82 in 25 years.

Regular_MG - PV Plant 50%/ Grid 50%									
Year	Discount	Nominal Cash Flows				Discounted Cash Flows			
	Factor	Capital	Replacement	O&M	Total	Capital	Replacement	O&M	Total
0	1	-2810134			-2,810,134	-2,810,134			-2,810,134
1	0.970873786			-283,995	-283,995			-275,723	-275,723
2	0.942595909			-283,995	-283,995			-267,692	-267,692
3	0.915141659			-283,995	-283,995			-259,895	-259,895
4	0.888487048			-283,995	-283,995			-252,325	-252,325
5	0.862608784			-283,995	-283,995			-244,976	-244,976
6	0.837484257			-283,995	-283,995			-237,841	-237,841
7	0.813091511			-283,995	-283,995			-230,914	-230,914
8	0.789409234			-283,995	-283,995			-224,188	-224,188
9	0.766416732			-283,995	-283,995			-217,658	-217,658
10	0.744093915			-283,995	-283,995			-211,319	-211,319
11	0.722421277			-283,995	-283,995			-205,164	-205,164
12	0.70137988			-283,995	-283,995			-199,188	-199,188
13	0.68095134			-283,995	-283,995			-193,386	-193,386



14	0.661117806			-283,995	-283,995			-187,754	<b>-187,754</b>
15	0.641861947		-848967.4	-283,995	-1,132,962		-544919.869	-182,285	<b>-727,205</b>
16	0.623166939			-283,995	-283,995			-176,976	<b>-176,976</b>
17	0.605016446			-283,995	-283,995			-171,821	<b>-171,821</b>
18	0.587394608			-283,995	-283,995			-166,817	<b>-166,817</b>
19	0.570286027			-283,995	-283,995			-161,958	<b>-161,958</b>
20	0.553675754			-283,995	-283,995			-157,241	<b>-157,241</b>
21	0.537549276			-283,995	-283,995			-152,661	<b>-152,661</b>
22	0.521892501			-283,995	-283,995			-148,215	<b>-148,215</b>
23	0.506691748			-283,995	-283,995			-143,898	<b>-143,898</b>
24	0.491933736			-283,995	-283,995			-139,707	<b>-139,707</b>
25	0.477605569			-283,995	-283,995			-135,637	<b>-135,637</b>
<b>Total</b>		<b>-2,810,134</b>	<b>-848,967</b>	<b>-7,099,864</b>	<b>-10,758,965</b>	<b>-2,810,134</b>	<b>-544,920</b>	<b>-4,945,239</b>	<b>-8,300,293</b>

Table 23 Net Present Cost of Regular\_MG

## 6.2 Results and Discussion

Using the same procedure, the Net Present Cost is computed for every scenario except the Minimum Grid, which is not a viable option. The results indicate that the smallest net present cost is always in the scenarios where the majority of the electricity is produced by the PV plant size. For this strategy, we can only compare expenses for items of identical size. Even though the initial cost for the Low Grid scenarios is more than twice that of the Full Grid scenarios. (Small Plant Size 55 percent more, Regular Plant Size 57.3 percent more, and Large Plant Size 60 percent more) In contrast, the Net Present Cost over 25 years is lower in the Low Grid scenarios, indicating that the Plant size possibilities with the largest PV installation are the most cost-effective over a 25-year period, with a reduction of almost 25% compared to the full grid scenarios. Figure 40 depicts difference between the Net Present Cost and Initial cost for each scenario. Which of the three Low Grid capacities is presently the greatest?

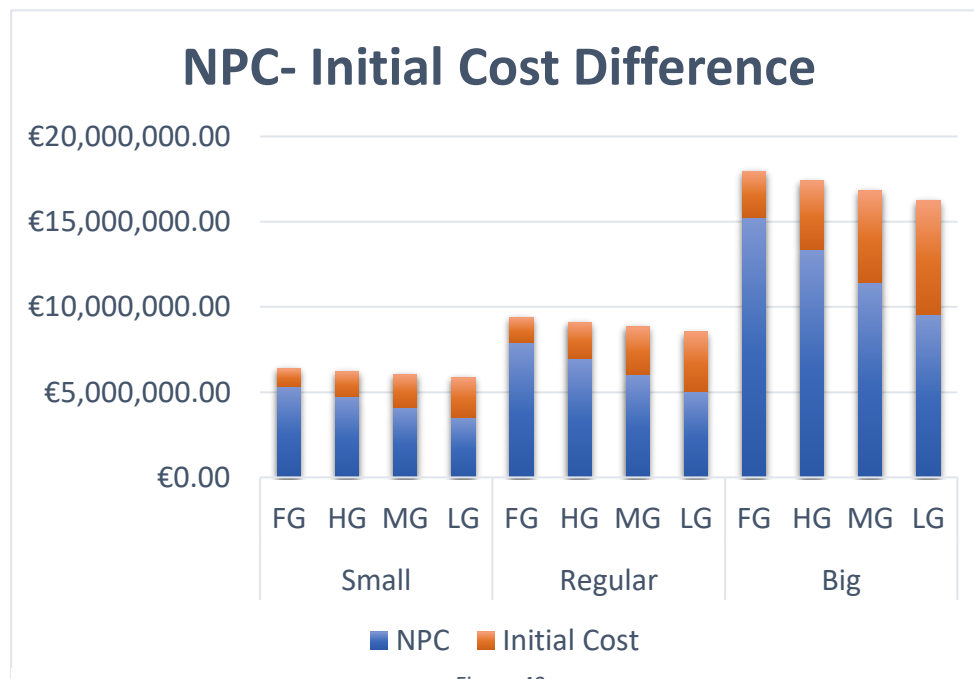


Figure 40

The LCOH has been calculated by applying Equations. (6-14). Figure 41 shows the results for all the studied plant configurations. It is worth noting that, as expected, the influence of the plant size is significant: the Big HRS shows a LCOH reduction of about 10% with respect to the Small HRS for each electricity mix. Moreover, by analysing the annual sharing of electricity supply by the grid and the PV plant, the optimal configuration is reached for the Low Grid energy management strategy (25% Grid). The lowest value (5.16 €/kg) of the LCOH is achieved for the Big\_LG system (430 kg/day, 25% Grid) while the highest value (7.83 €/kg) is obtained for the Small\_FG system (136.58 kg/day, 100% Grid). At a constant daily production, the LCOH varies of 26% for the small size, 28% for the regular size and 29% for the big size, by varying the electricity mix.

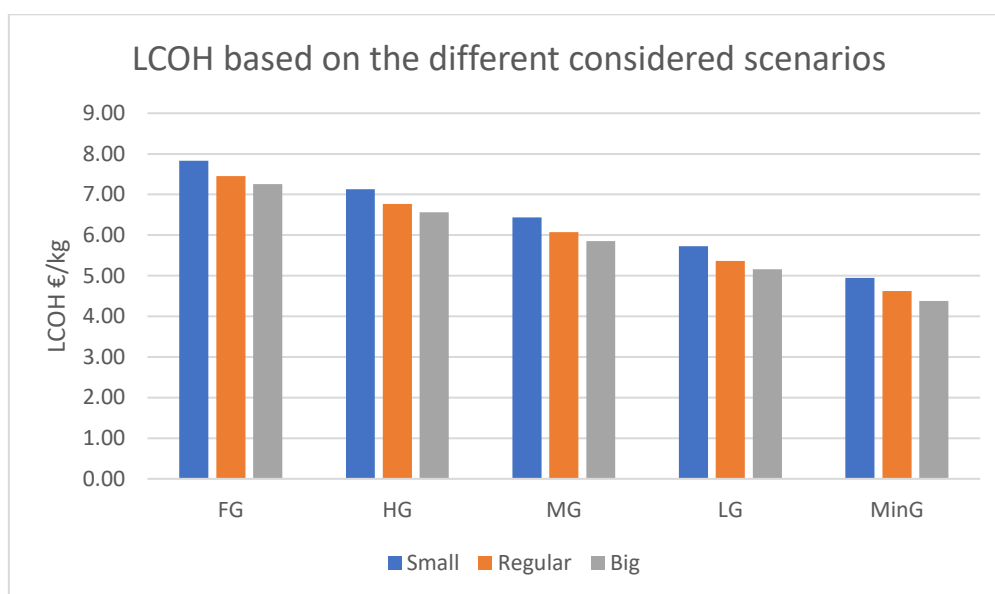


Figure 41

Solar hydrogen is a clean alternative fuel, is capable of substituting fossil fuels, and decreases the addiction to oil and gaseous fuels, abating CO<sub>2</sub> emissions to save the world from global warming. The problem is the components for PV hydrogen are still expensive to be competitive but is closing the gap to the piloting methods. Other methods such as SMR, CG, Dark fermentation are only 3-4 €/kg lower. In the past it was around 15 €/kg lower, shown a substantial growth in hydrogen technology. Table 24 indicates the hydrogen cost of different hydrogen studies from different hydrogen production processes.

Different hydrogen production processes	Energy Source	Feedstock	Hydrogen Cost €/kg	Year of Study
SMR with CCS	Standard fossil fuels	Natural Gas	2.27	2005
SMR without CCS	Standard fossil fuels	Natural Gas	2.08	2005
CG with CCS	Standard fossil fuels	Coal	1.63	2005
CG without CCS	Standard fossil fuels	Coal	1.34	2005
Dark fermentation	-	Food waste	3.20	2018
Current Study	Solar-Gird	Water	5.16	2022

Table 24

A sensitivity analysis is performed on the primary indicators that, if altered, will cause the LCOH to decrease or increase sufficiently. Principal indications include:

- The annual electricity prices
- The annual water prices
- The cost of the components
- The future cost of the components
- The efficiency levels of the electrolysis
- The efficiency levels of the PV panels

### 6.2.1 The Annual electricity prices

The Electricity bought from the grid has a huge impact on the operational and maintenance money used every year. Figure 42 summarizes the operational money paid every year in the Regular plant size for all the electricity mixed. The mind-blowing result is that even in the Low Grid electricity mixed which is 75% plant size in 25% purchase from grid, over 50% of the operational and maintenance money used every year is for the purchase of electricity. This mean that the electricity prices are very impactful.

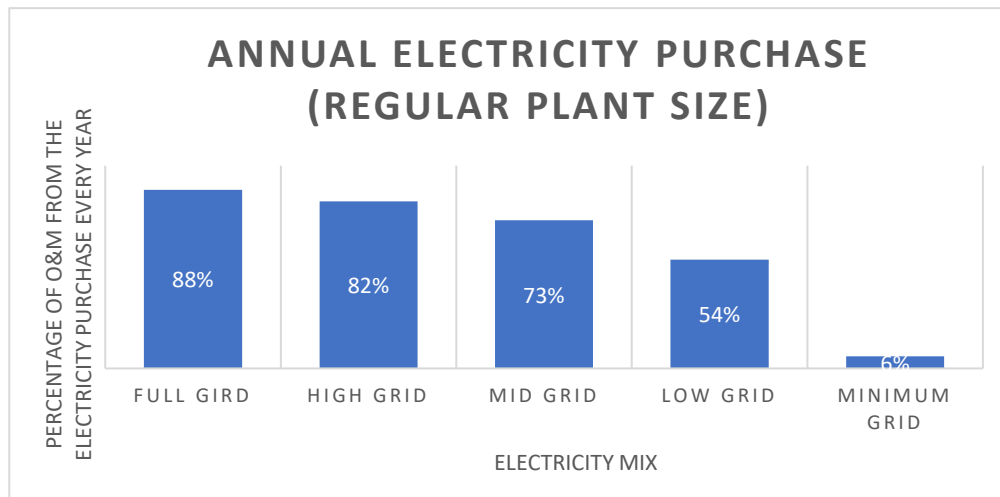


Figure 42

How much will the operation and maintenance of the station be impacted if the price of 0.08 €/kWh doubles or even quadruples, and what will happen if the price of 0.08 €/kWh falls in the same manner? The Regular Plant Size uses the prices of 0.02€/kWh, 0.04€/kWh, 0.08€/kWh, 0.16€/kWh, and 0.32€/kWh to determine the effect of a price shift on production. We will only conduct this analysis in the Regular Plant Size because it represents a middle ground in the hydrogen production capacity factor and the results will be comparable across all plant sizes. Figure 43 compares the various electricity acquisition costs. The most significant impact occurs in scenarios that use less electricity from the grid. Previously, for the low grid scenario with a price of 0.08€/kWh, the purchase of energy had a 54% impact on the size of the plant's operation and maintenance (O&M). Now that the purchase price is 0.32 euros per kilowatt-hour, the impact is 46% greater than it was previously, and for the low grid scenario that uses 75% PV technology, having to spend 82% of all operation and maintenance costs annually to the energy purchase is a major worry.

When the price of power decreases, it has a comparable impact on all types of electricity, resulting in a 22 to 32% decline. The difference in electricity reduction is greater for the Mid

Grid scenario, which uses 50% of the grid and 50% of the plant size. How this price shift affects the LCOH hydrogen and which of the four new power purchase prices offers the greatest solution for plant size.

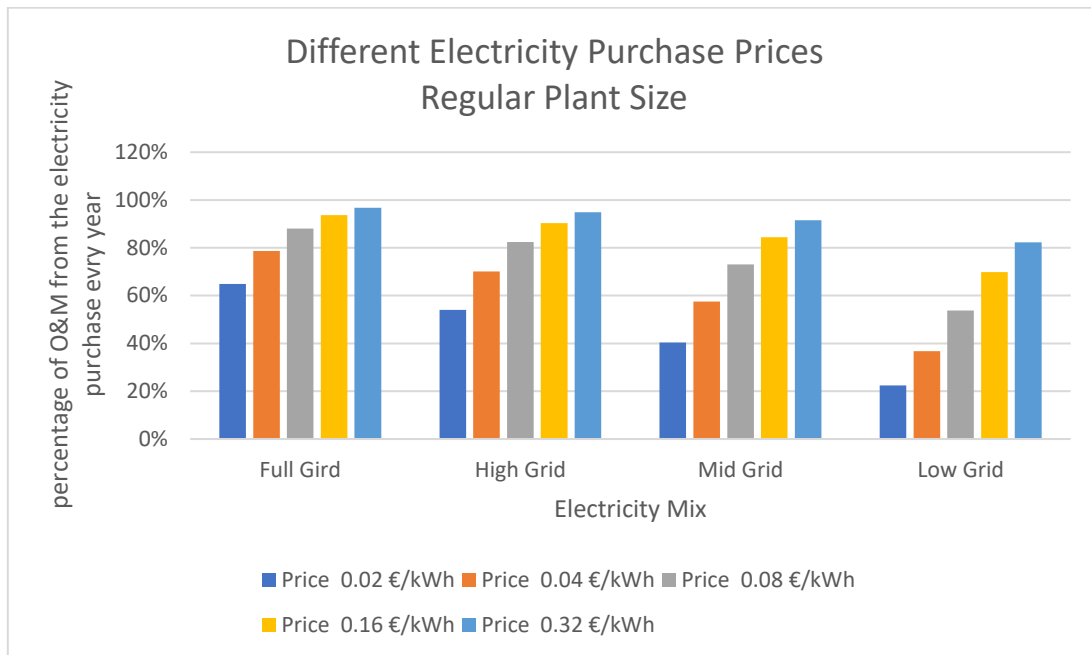


Figure 43

As expected, the Full Grid scenario is the best option with the lowest cost of 0.02€/kWh and 3.51€/kg. This is a significant decrease of 3,94 €/kg compared to the Main Full grid price of 7,45 €/kWh. The most significant observation is that PV insulation is unnecessary when electricity costs are so cheap. Figure 44 provides a summary of the levelized costs of hydrogen at a price of 0.02€/kWh.

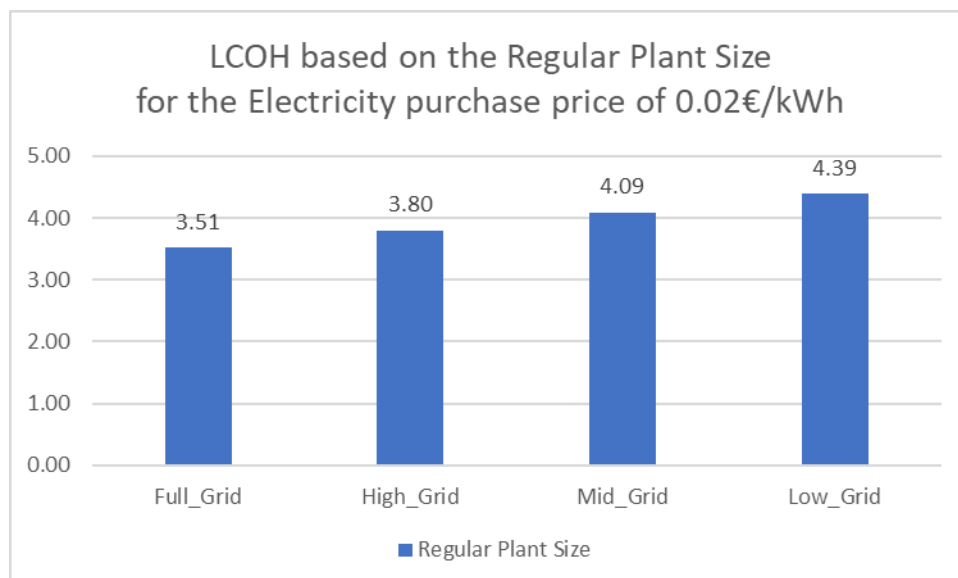


Figure 44

Y Axis (LCOH €/kg) X Axis (electricity Mix)

When the price is half of the actual purchase price (0.04 euros per kilowatt-hour), the Low Grid scenario is again the optimal alternative, but with a negligible advantage over the other

electricity mixes. Each scenario has a levelized cost price of around 4,78 €/kg. The illustration of figure 45 makes the observation even clearer.

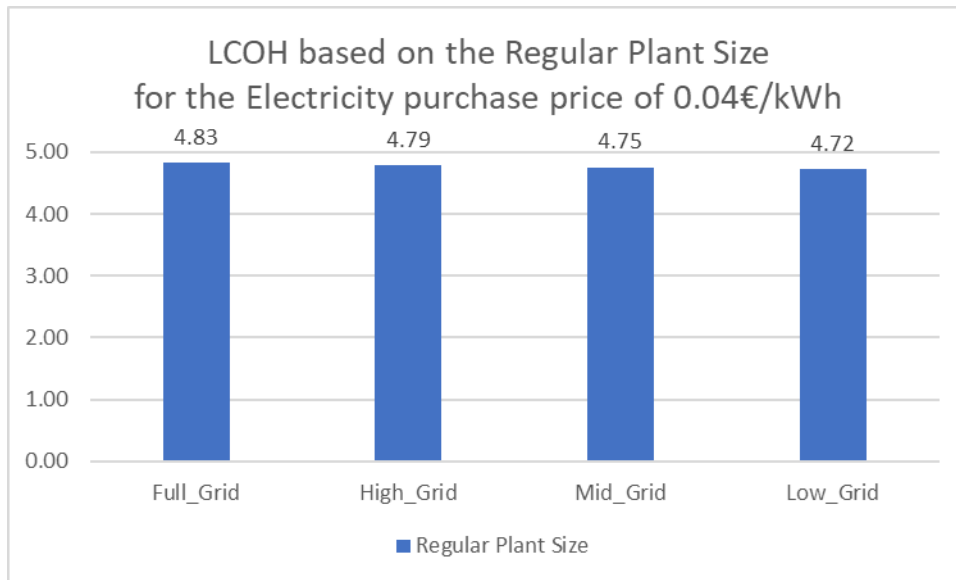


Figure 45  
Y Axis (LCOH €/kg) X Axis (electricity Mix)

In the situation that the electricity purchase is doubled from the actual one (0.16€/kWh). The LCOH prices skyrocketed in the Full Grid and now is almost double from the original one. In the low grid scenario, the levelized cost price increased normal in an increment of 1.3 €/kg. The price of the Low Grid scenario is not the best but still approachable in fuel price market. The difference is showed clearly in figure 46.

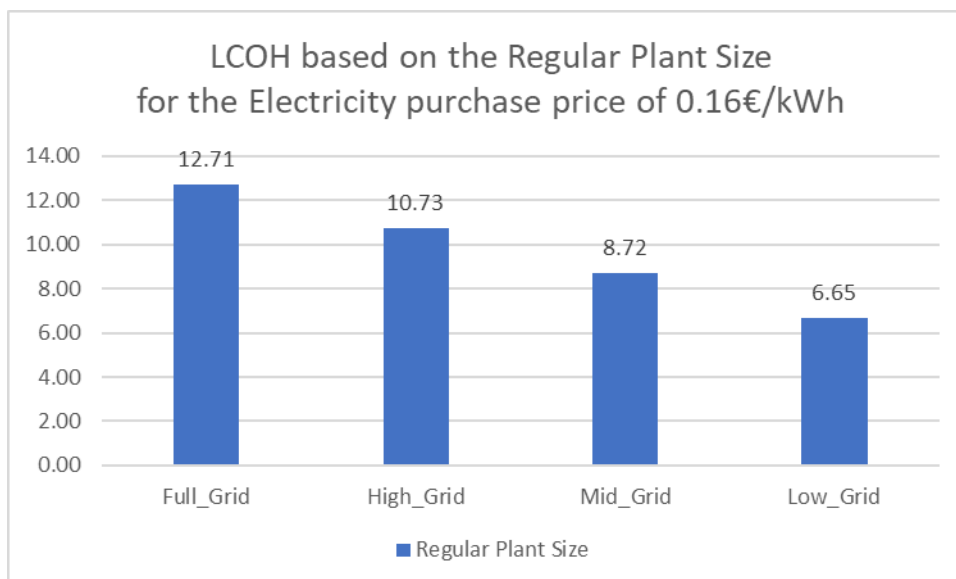


Figure 46  
Y Axis (LCOH €/kg) X Axis (electricity Mix)

In the final choice, the price is quadruple the base rate (0.32€/kWh). Due to the astronomical LCOH prices depicted in figure 47, refuelling becomes an unfeasible subject of investigation. Even the finest solution costs almost 10 € per kilogramme. For the study to become viable

once more, the other components of the installation must be reduced, or even better, the grid connection must be severed, and the marine refuelling station must be a solar installation that operates independently.

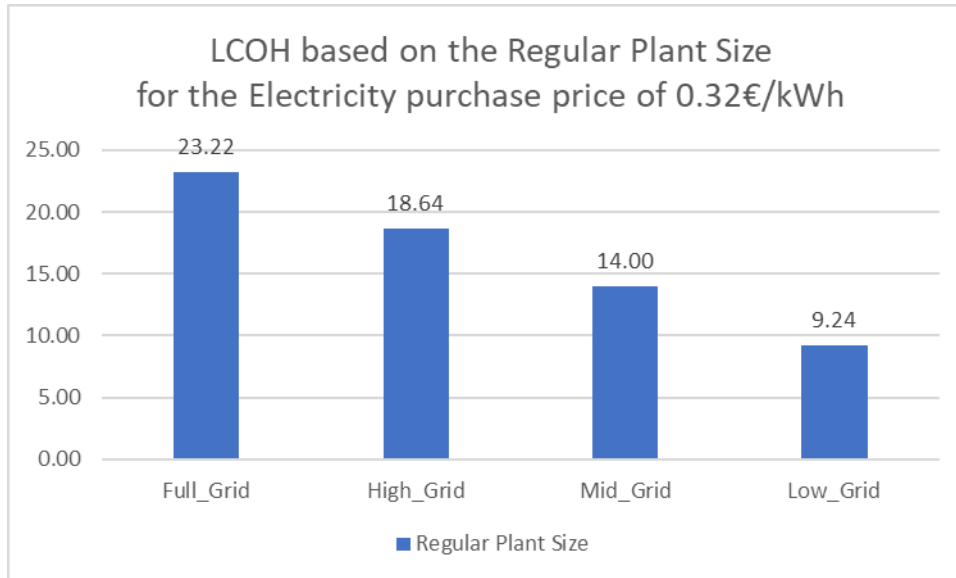


Figure 47  
Y Axis (LCOH €/kg) X Axis (electricity Mix)

## 6.2.2 The Annual water prices

Regarding the purchase of water, the standard rate in Greece is  $2 \text{ €/m}^3$ . Now, if there is an increase of  $6 \text{ €/m}^3$  and the annual water price rises to  $8 \text{ €/m}^3$ , the LCOH will experience little price adjustments. Figure 48 illustrates the assumption that the purchase of water has a negligible effect on the pricing of LCOH.

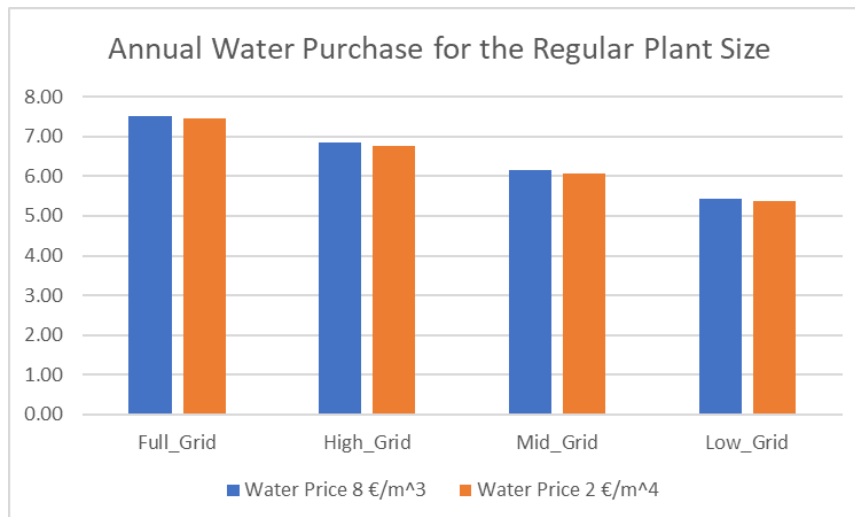


Figure 48  
Y Axis (LCOH €/kg) X Axis (electricity Mix)

### 6.2.3 The cost of the components

The initial and operational cost of the electrolyser and PV panels, as well as the cost of maintaining the compressor, also have a substantial effect on the price of hydrogen. The electrolyser costs approximately 45 000 euros each year and has an initial cost of 1.133.000 million euros for the optimal plant size (Big LG), which represents 28% and 17% of the total cost of all items, respectively. The compressor also has a substantial impact, contributing around 32,000 euros per year, or 20% of all components. Lastly, the efficiency and longevity of the PV panels are crucial due to their extremely high purchasing price. The operational and maintenance cost of the PV modules is forty percent of the total, or nearly fifty percent of the operation of the components. Even more significant is the initial cost of the photovoltaic panels, which exceeds fifty percent of the total initial cost of the naval station's components. Figures 49 and 50 provide the percentages of the O&M and Initial costs for the ideal maritime refuelling station (Big LG), respectively. Moreover, the dispenser unit and the hydrogen tanks have a minor but considerable impact on the O&M and initial cost of nearly 10% of all components.

PV technology is currently quite well established hence the price of solar technology may have less room for decline in the coming years. The most significant contribution must be made to the new technology that evolves around hydrogen components.

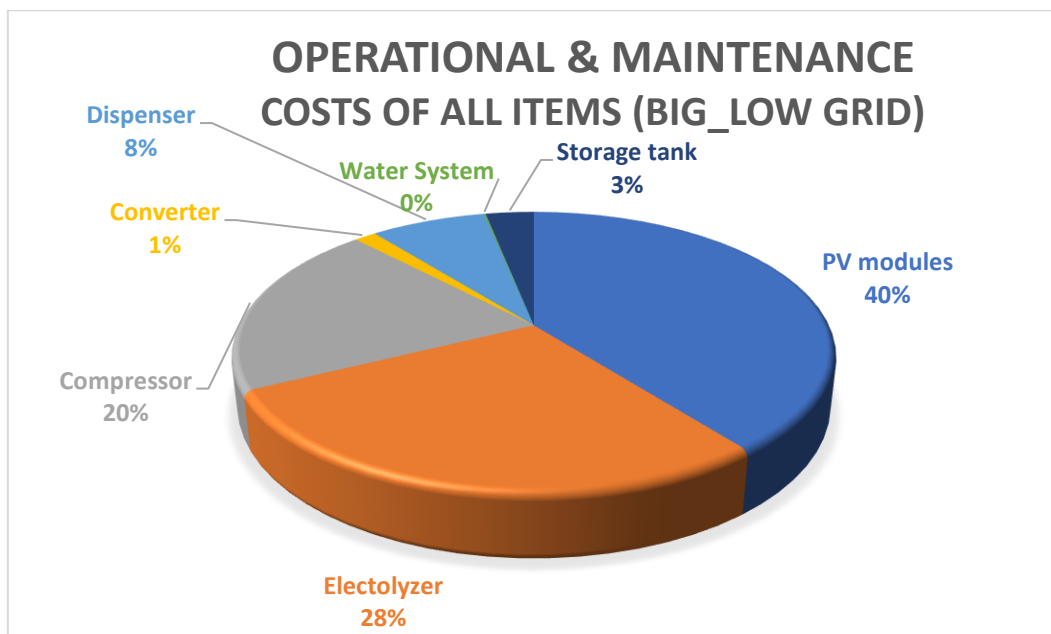


Figure 49

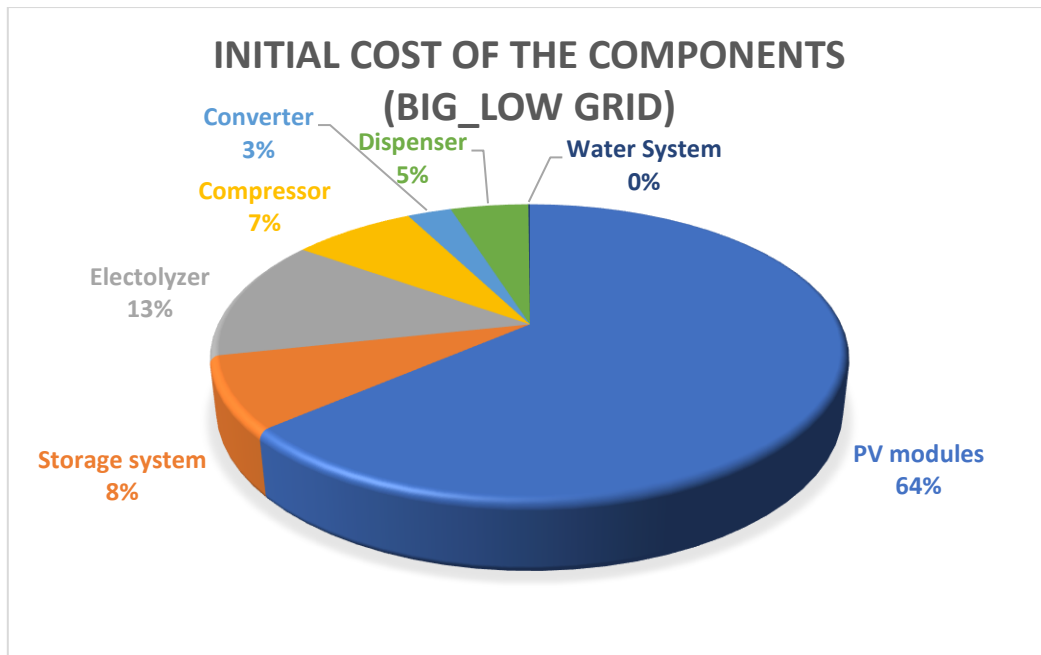


Figure 50

#### 6.2.4 The future cost of the components

An estimation is created regarding the marine refuelling station's production in 20 years. The price of electrolyzers will reduce by 30%, the price of PV panels by 10%, the price of the hydrogen tank and dispenser combined by 20%, and the price of the compressor by 35%. The updated costs are shown in table 25.

Economic assumptions and costs data in 2042		
Pv plant cost	767.19	€/kW
Compressor cost	405,783.16	€
Electolyzer cost	770.00	€/kW
Storage system cost	900.00	€/kgH2
Dispenser	135 000	€/kW

Table 25

After comparing the current and future potential LCOH the decline in the price is not very impactful. On all electricity mixed the decrease was about 12%, that proves that a grid connect refuelling station will mainly depend on the electricity prices. Figure 51 shows the results of LCOH between the comparison of present and future prices. However, the most significant factors have yet to be tested.



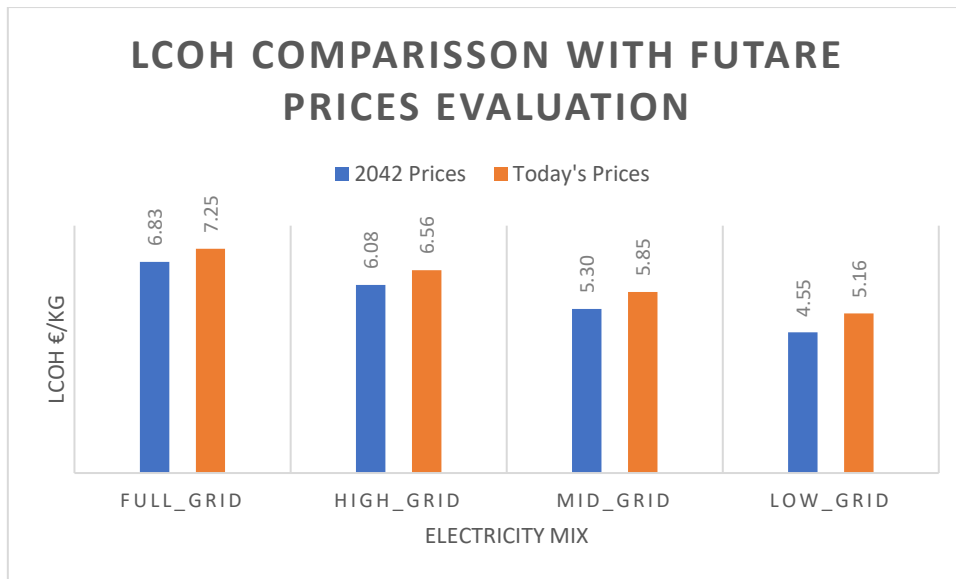


Figure 51

### 6.2.5 The efficiency levels of the PV panels

Solar panels efficiency throw time is one of the most important instigators. Solar panels must be produced so the efficiency is not dropped, and they last longer. If the efficiency drops that means the grid will be needed more so the LCOH will increase throw time.

The great thing about solar panels is that they require very little maintenance. Regular solar panel cleaning is generally unnecessary unless the area is highly susceptible to dust, dirt, pollen, or sand due to an arid climate. While solar panels generally require little maintenance, it's still important to inspect your solar panels from time to time and monitor their performance.

### 6.2.6 The efficiency levels of the electrolysis

The efficiency of the electrolyser is an additional assumption that has a significant bearing on the marine refuelling station. The modern PEM electrolyser has an efficiency of 5,1 kWh/Nm3 H2. In ten years, electrolysers will become more efficient. Notably, in order to lower this consumption, it may be advantageous to select a more efficient technology, such as commercial (4.5 or 4.8 kWh/Nm3) or revolutionary (3.8 kWh/Nm3) electrolysers. Thus, the existing electrolysis efficiency will be compared to 3,8 kWh/Nm3 electrolyser.

Under the same economic assumptions, only the original Full Grid scenarios will be compared against the more efficient electrolyser. We only utilise the 100% grid-connected HRS scenario since we wish to avoid the impact of the solar connection.

Annual Electric energy Consumption is affected by the use of a more efficient electrolyser. Approximately a 25% reduction in energy use across all capabilities. The precise total energy consumption of both electrolysers is indicated in Table 26. Consequently, the purchase of electricity will also be impacted, as the need for energy is now lower for the same amount of hydrogen production.

### Annual Electric energy Consumption (MWh/year)

Plant Capacity	EL60N	EL100N	EL200N	
Electrolysis Unit	2107.13	3328.80	6657.60	MWh/year
Compressor	170.71	251.41	509.48	MWh/year
Convertor	177.83	257.54	496.69	MWh/year
<b>TOTAL</b>	<b>2455.67</b>	<b>3837.76</b>	<b>7663.77</b>	<b>MWh/year</b>

Due to the lower energy need, the levelized cost of hydrogen decreases by approximately 1.5 €/kgH<sub>2</sub> and the Small FG, which was the most expensive technique at 7.83 €/kgH<sub>2</sub>, now costs 6.14 €/kgH<sub>2</sub>, closing the gap with the optimal configurations of the current study. Therefore, the electrolyser's efficiency is crucial for the development of hydrogen technology. Figure 52 compares the LCOH of hydrogen refuelling station between the innovative method and the current method.

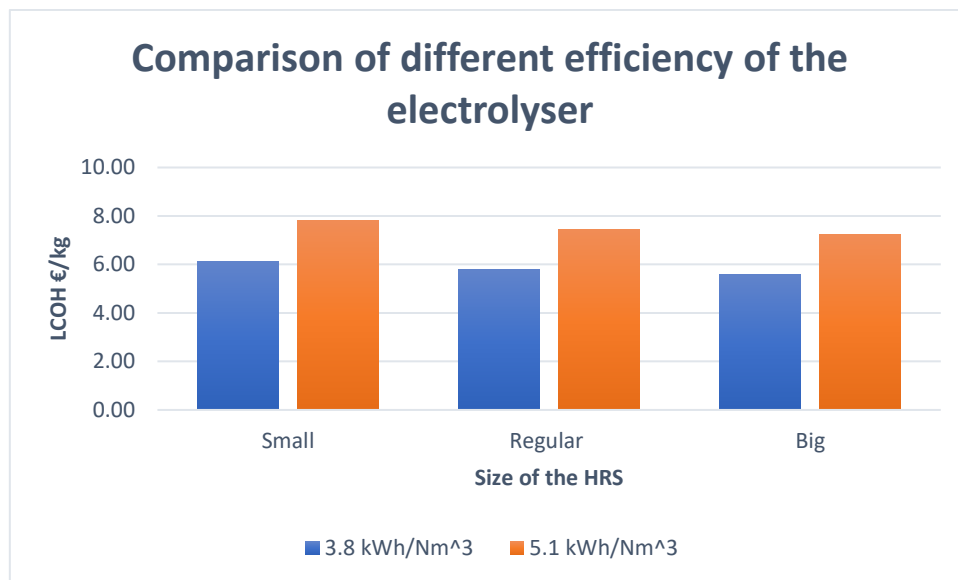


Figure 52

## 7. Techno-economic assessment of a fuel Cell ferry connected to the hydrogen Refuelling station

### 7.1 Marine-engine pollution

Ships have various impacts on the environment, and they are divided in three categories Air emissions, physical impacts, and discharges to water. The air emissions are consisting of GHG, Ozone-depleting substances, Sulfur oxides (SO<sub>x</sub>), Particle matter (PM), Nitrogen oxides (NO<sub>x</sub>) and volatile organic compounds (VOC). The physical impacts have to do with erosion, wildlife collisions, noise, resuspensions of sediments and grounding. Finally, the discharges of wastewater, antifouling paints, marine litter, oil and cargo effect the Water for Wildlife substantially (Figure 53).

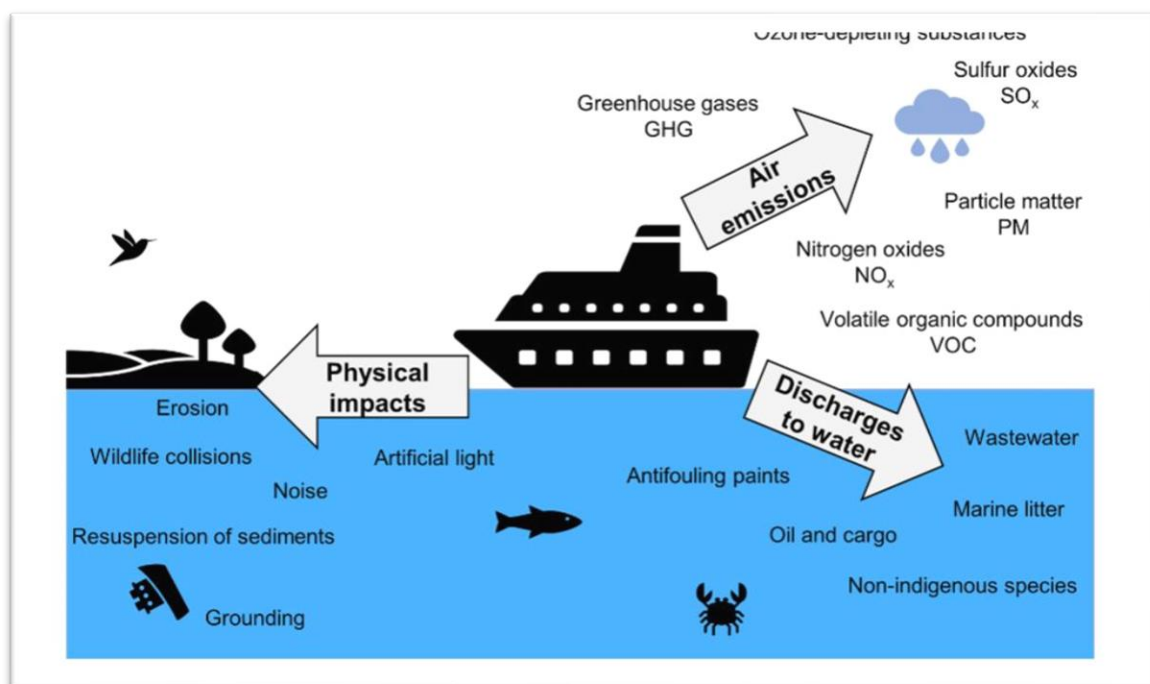


Figure 53 Classification of the environmental impacts of shipping on the aquatic environment into three main categories of discharges to water, physical impact, and air emissions.

[Annika K. Jägerbrand 2019]

Marine fuels contribute to both main categories include discharges into the sea and air pollution of the impacts on the environment from the vessels. These marine fuels pollution is caused by oil spills and emissions to the air from ships {e.g., CO<sub>2</sub>, carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), hydrocarbons (HCs), sulfur dioxide (SO<sub>2</sub>), and particulate matter (PM)} (Annika K. Jägerbrand 2019). More specifically, ship movement through water requires thrust, which is generated in several methods. Most of the commercial fleet is converting the chemical energy contained in fuel into ship thrust. More specifically, the process involves the conversion of the chemical energy of the fuel to thermal energy through the combustion of the fuel-air mixture and in turn, the conversion of the thermal to mechanical energy based on a thermodynamic cycle that ultimately manifests itself as ship thrust. The technologies that are used as prime movers for ships to produce mechanical power are mostly diesel engines, gas turbines, and steam turbines. Prime mover generates mechanical power, then mechanical

power is transferred to the propeller by the propeller shaft and the thrust bearing and then the thrust shaft transmits the thrust generated by the propeller to the hull. (Andersson et al., 2016)

Marine propulsion engines cause environmental impacts with reference to the atmospheric environment. Namely, most exhaust emissions from ships are produced by the combustion process and are dependent on the combustion process, the fuel used, and the engine. On the other hand, operational oil pollution originates from various sources, such as bilge water, propeller shaft bearings, and accidental oil spills from the transportation of fuels in tanker vessels and from fuel used for propulsion. Marine propulsion has changed throughout the years (Figure 54). The first fuels at the beginning of the nineteenth century were made from coal and were used for steam engines and steam turbines (Andersson et al., 2016). Before that, shipping was powered by wind and manpower (Fridell, 2019). Over the years, most steam engines were replaced with marine engines fuelled by diesel and residual oil or heavy fuel oil (HFO) (E. Λόης, Φ. Ζαννίκος, Δ. Καρώνης 2014).

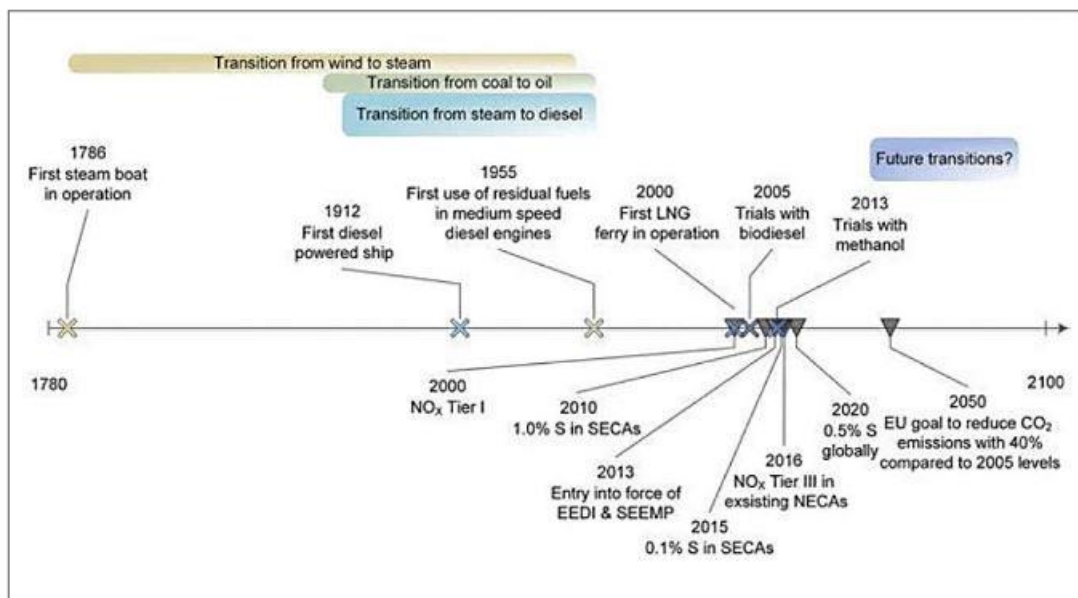


Figure 54 Transition of marine fuels from 1780 to 2100 (Andersson et al., 2016)

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

Hence, alternative fuels and energy sources are expected to play a vital role as a synergistic solution for reductions of SO<sub>x</sub>, NO<sub>x</sub>, PM and CO<sub>2</sub> emissions. Apart from innovative technologies and systems for traditional engines, fuel cell power system is proposed to be an important option to improve the use of alternative marine fuels. High energy efficiencies make fuel cells very attractive compared to marine combustion engines and gas turbines (GTs), though the power capacities of fuel cells cannot cover all maritime applications. However, the efficiencies and power capacities of fuel cells continue to be a focal point of research and

development, leading to constant improvements that bring the technology closer to widespread adoption with every passing year. [Xing 2021].

## 7.2 Operation procedure of a Fuel Cell

A fuel cell is composed of an anode, a cathode, and an electrolyte, and it turns the chemical energy from a fuel into electricity via an electrochemical reaction. Figure 55 depicts a fundamental schematic diagram of a hydrogen fuel cell. The various possible ion transport properties across the electrolyte depending on the fuel cell variety About 0.7 volts (V) of electrical potential is created by a capacitor. an individual fuel cells. Consequently, cells are connected in series to generate enough voltage to suit the requirements. A prerequisite for an application that produces a "fuel cell stack." Fuel cells are usually grouped based on the type of electrolyte they employ.

Fuel cells are likened to an engine with no moving parts and can be defined as an electrochemical energy conversion device. The particles of hydrogen and oxygen are converted into water through this process as well energy is produced. The operation is similar to a conventional galvanic battery, but in this case as long as fuel (hydrogen) is supplied the operation does not stop. Fuel cells convert chemical energy into electrical energy without the presence of thermal energy. It is a chemical process that turns the high purity hydrogen fuel to electricity. It's like a battery but you don't need it re-charging because the fuel source is provided through the system. The fuel cell system is the reverse process of electrolysis. A fuel cell consists of the anode, the cathode, and a membrane electrolyte. It works by passing hydrogen through the anode and oxygen through the cathode. At the anode, the hydrogen molecules split into electrons and protons. The protons pass through the electrolyte membrane, while electrons are pushed through the circuit, generating electric current (direct current) and heat. At the cathode, the protons, electrons, and oxygen combine to produce water molecules. The DC voltage we get at the output of a fuel cell it is converted into a direct voltage or alternating voltage of variable amplitude and frequency through the boost converters and inverters. [ Zohuri, B., 2019]

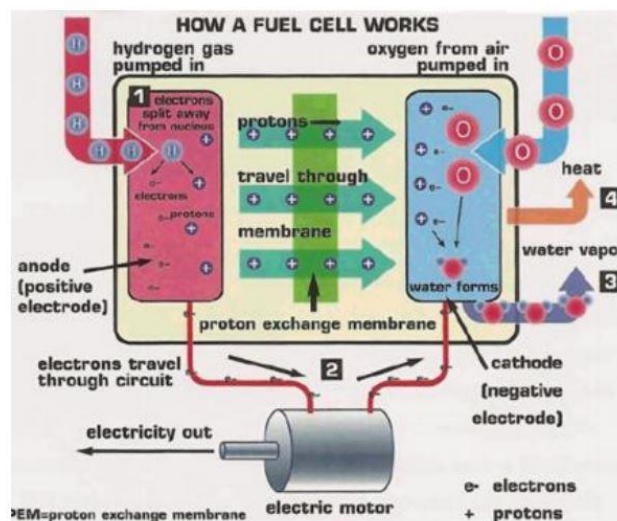


Figure 55 Operation procedure of a Fuel Cell  
[ Zohuri, B., 2019]

## 7.2.1 Types of Fuel Cells

There are six dominant types of FCs. The most common criterion for classification must do with the electrolyte used. They are divided into the following types:

- AFC, “Alkaline Fuel Cell”
- PEMFC, “Proton Exchange Membrane Fuel Cell”
- DMFC, “Direct Methanol Fuel Cell”
- PAFC, “Phosphoric Acid Fuel Cell”
- MCFC, “Molten Carbonate Fuel Cell”
- SOFC, “Solid Oxide Fuel Cell”

Nevertheless, there is another, more generic division which, refers to the temperature in which the fuel cells operate, creating three large groups:

- Low temperature fuel cells that work at approximately 80 C: the AFC, PEMFC and DMFC
- Intermediate temperature fuel cells that work at approximately 200 C: the PAFC
- High temperature fuel cell whose working temperature is between 650 C and 1000 C: the MCFC and SOFC [Alvarez 2016]

To select the optimal cell, it is required to consider the following characteristics:

1. PEMFC. The PEMFC's low operating temperature enables speedy start up without the need for corrosive ingredients in the cells. Due to its zero-emissions, high power density, and rapid start-up, the PEMFC is mostly used in transportation and commercial applications. Submarine propulsion is another successful application of PEMFC for transportation.
2. AFC. The electrolyte in this type of fuel cell is KOH operating between 50 and 250 degrees Celsius. Operating at low temperatures, the fuel cell features a rapid start-up. A major disadvantage of the AFC is that the KOH solution is extremely sensitive to the presence of CO<sub>2</sub>. It requires extremely pure H<sub>2</sub> as the fuel. It is utilised widely in both space applications and computers.
3. PAFC. This mechanism functions at temperatures between 50 and 250 degrees Celsius. The chemical reaction is identical to that of PEMFC, with the exception that pure hydrogen must be utilised as its fuel. This solution requires both anode and cathode platinum as an electrocatalyst.
4. MCFC. These cells operate at temperatures between 600C and 700C, which are extremely high. Due to the high working temperature, hydrocarbons that react with CO in the stack can be transformed into hydrogen. Platinum is not required as a catalyst in MCFC, but nickel and nickel oxide are required for the anode and cathode. MCFC can reform typical hydrocarbon fuels due to its high working temperature. The development of MCFCs has concentrated on large stationary applications. This technology is also suited for naval applications in which the comparatively large size and weight of the MCFC and its sluggish start-up time are not a concern.

5. SOFC. These types of fuel cells typically function at temperatures between 600C and 1000C. SOFC function in a high efficiency range, often between 40 and 60 percent. In addition, if integrated into a gas turbine, they can attain an efficiency of 70 to 80 percent. Due to the high working temperature, carbon monoxide and some hydrocarbons can be utilised as fuel directly. High operating temperature, slow start up, high cost, and corrosion of metal stack components are among the primary downsides of SOFC. Because of this, they are only employed for auxiliary power units as well as medium and large power generation applications.
6. DMFC. DMFCs function between 50C and 120C with up to 40% efficiency. As a liquid, methanol is more easily integrated into current transmission and distribution networks. Directly reforming methanol within the FC stack necessitates that the electrodes include substantial quantities of platinum. DMFC appears to be a promising contender for extremely tiny to mid-sized applications, such as mobile phones and other consumer products, due to its high energy density and safer handling. Additionally, the automotive sector utilises this cell. [Alvarez 2016].

In this study, a deeper analysis is needed for the PEMFC, because the ferry used is based on a concept design for the high-speed light craft (HSLC) that uses a PEM fuel cell.

### 7.2.2 PEMFC system

The PEMFC is the most commercialized fuel cell, which is available in many applications, including in the maritime sector. It can reach an efficiency of 50–60%, but its main drawback is its intolerance to impurities and the requirement for pure hydrogen. It contains a proton-conductive polymer electrolyte membrane placed between electrodes. Pure hydrogen as a fuel and oxygen are engaged in electrochemical reactions. The hydrogen is oxidized, the formed electrons result in electricity, while the formed protons due to the electrochemical gradient diffuse through the electrolyte up to the cathode. On the cathode, the oxygen is reduced, and its ions react with protons and form water. The onboard PEMFC system fuelled with pure hydrogen is presented in Figure 56 [Perčić 2022].

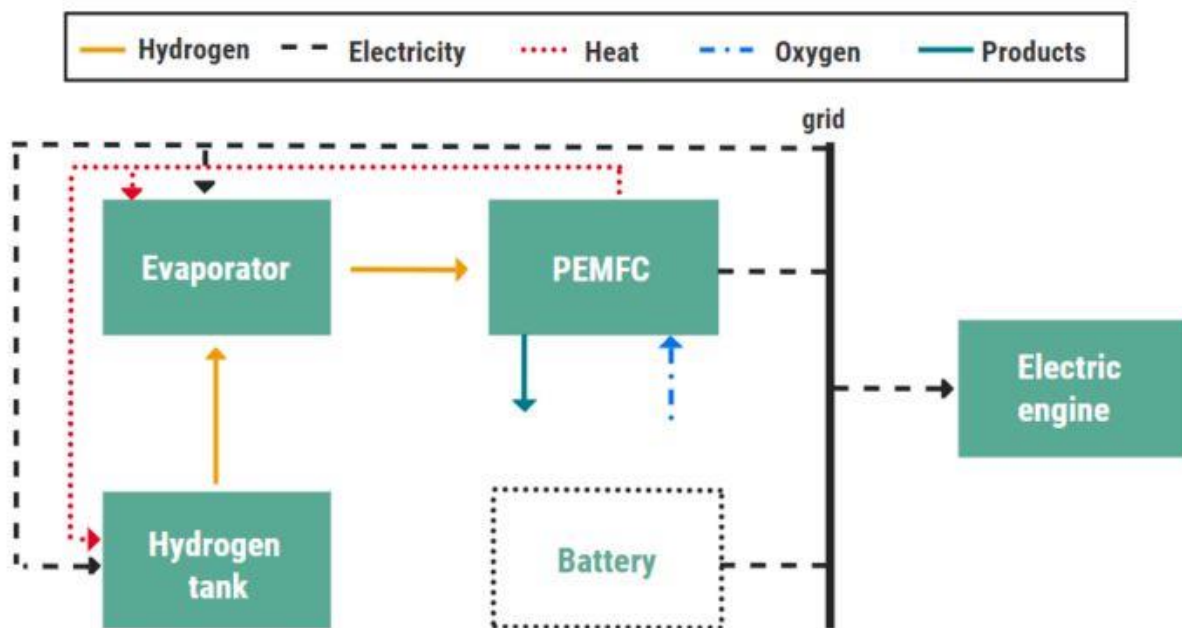


Figure 56 on board PEMFC system with pure hydrogen [Perčić, M., Vladimir, N., Jovanović, I. and Koričan, M., 2022]

## Fuel Storage

Due to the low volumetric energy density of hydrogen and limited power range of PEMFCs, PEMFC power systems are only available for small-scale ships operating for domestic and short-sea shipping. Correspondingly, hydrogen storage is typically achieved in a compressed state at a pressure of 350 bar or 700 bar rather than in a liquefied state at a temperature of  $-253\text{ }^{\circ}\text{C}$ . The storage tanks for compressed hydrogen usually comprise a thin aluminium liner and carbon fiber–plastic composite materials [Durbin 2013].

## Durability and Operability

Durability primarily means the lifetime of a fuel cell stack. The lifetimes of a PEMFC for stationary and transportation applications are expected to be 40,000 and 5000 h, respectively, by the U.S. Department of Energy. The lifetime of a fuel cell stack is mainly dependent on the degradation of electrolyte, electrode, and bipolar plate. For instance, the degradation mechanisms of PEMFC include loss of catalyst, reduced conductivity of electrolyte, corrosion, poisoning, and flooding [Shabani 2019]. Operability could be reflected by start-up time and transient dynamic response. Considering the fuel cell stack, the start-up time ranges from a few seconds for a PEMFC to tens of minutes. However, for maritime applications, a long start-up time is not a significant flaw and could be accepted to some extent. After all, several hours are normally required for engine standby of large maritime ships powered by diesel engines at present. Dynamic response characteristics reflect the response of fuel cell power systems to external load changes. The transient response time ranges from less than 10 s for PEMFC to 15 min for SOFC [Ellamla 2015].

## 7.3 High-speed light weight passenger ferry

The pilot project GKP7H2 is part of DNV GL Green Coastal Shipping Program. Brødrene has designed a 30-meter-long high-speed vessel with hydrogen propulsion as part of the project (figure 57) [Ocean Hyway Cluster].



*Figure 57 Illustration of a concept design (GKP7H2)*  
[<https://www.oceanhywaycluster.no/projectlist/project-1>]

The ship is a medium sized passenger ferry with a capacity of 100 passengers, has a lightweight carbon fibre hull, rated speed of 28 knots without refuelling, hydrogen storage capacity of 450 kg, and installed propulsion power of 1.2 MW. The reference route goes from Florø in the Western part of Norway and has a distance of 113 nautical miles (209km) per day,



which yields a hydrogen consumption of about 380 kg per day. The exact ship characteristics are illustrated in table 27 [Aarskog 2020].

We then determined the maximum hydrogen storage capacity for other vessels based on the known lengths and widths of their decks. The theoretical time required to fully bunker with hydrogen between routes was calculated by allowing 40 minutes per 450 kilogrammes of hydrogen, which was found to be achievable with one nozzle, plus an additional 10 minutes to account for the fact that bunkering locations are likely to be located outside of central harbour areas where passengers embark/disembark. By utilising two nozzles during the refuelling procedure, we can reduce the time required in 20 minutes [Sundvor 2021].

GKP7H2 Passenger ferry specs		
Capacity	100	passengers
Speed	28	knots
Storage capacity	450	kgH <sup>2</sup>
Power	1.2	MW
Distance	120	Nm
Fuel consumption	0.07	kg/kWh
Refuelling time	22.5	kgH <sup>2</sup> per minute

Table 27

## 7.4 Ferry time schedule

As seen in Figure 45, the ferry will make round journeys from the port of Piraeus to the islands of Aegina and Agkistri, before returning to Piraeus.

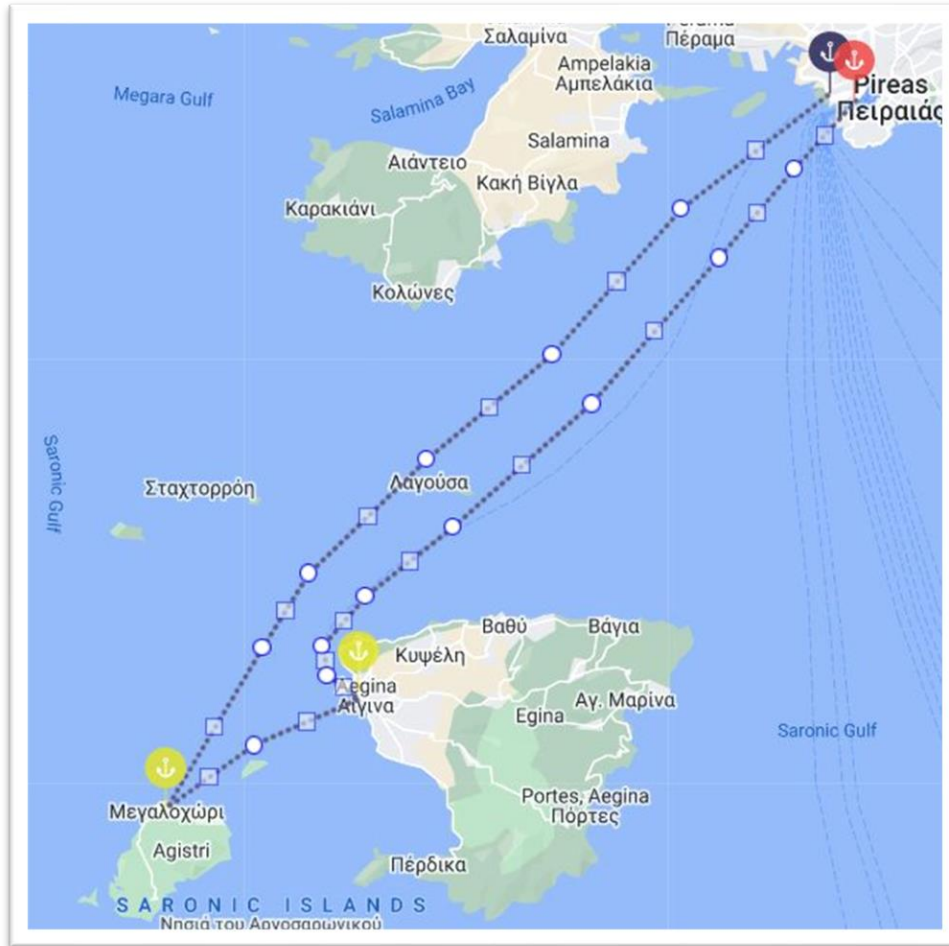


Figure 58 The Round-trip route of the ferry  
[the BednBlue Sailing Distance Calculator]

According to the BednBlue Sailing Distance Calculator, the distance of the journey is 21.4 nautical miles. With an average speed of 28 Knots, the ferry requires 38 minutes and 17.8 nautical miles to reach the port of Aegina from Piraeus, and an additional 12 minutes and 3.6 nautical miles to reach the port of Agkistri. Therefore, the total time required for cruising is 50 minutes. A single round voyage requires 140 kg of hydrogen. This implies the ferry can make three full journeys without refueling. The trip characteristics are shown in Table 28.

Pireaus	to	Aegina-Agkistri
Distance	21.4	Nm
Speed 28kn	0.83	Hours
Power	1000	KWh
Fuel consumption	70	Kgh <sup>2</sup>
Round Trip	140	Kgh <sup>2</sup>
Number of Trips	420	OK
without Refuling	3	

Table 28 Trip Characteristics

In every port, an additional 10 minutes for boarding and debarking. In addition, the refuelling station has two nozzles, requiring a refuelling time of 20 minutes plus an additional 10 minutes to account for the fact that bunkering locations are likely to be outside of the harbour areas where passengers embark/disembark. Daily, the boat may complete six successful excursions. The exact scheduling of the ferries is detailed in Table 29. The ferry requires 420 kg of hydrogen per day. Therefore, the required hydrogen refuelling station needed is 200 Nm<sup>3</sup>/h (430 kg/day). The example is a possible idea for the use of the marine hydrogen refuelling and also proves that the hydrogen marine infrastructure already exists.

GKP7H2 hydrogen time-table							
	Pireus	Aegina		Agkistri		Pireus	
Trip	Departure	Arrival	Departure	Arrival	Departure	Arrival	
1	7:00	7:38	7:48	8:00	8:10	8:55	
2	9:05	9:43	9:53	10:05	10:15	11:00	
3	11:10	11:48	11:58	12:10	12:20	13:05	
Refuelling	13:25	20 min Refuelling of 420kgH <sub>2</sub> 10 min boardng					13:35
4	13:45	14:23	14:33	14:45	14:55	15:40	
5	15:50	16:28	16:38	16:50	17:00	17:45	
6	17:55	18:33	18:43	18:55	19:05	19:50	

Table 29

For instance, assuming a single GKP7H2 ship is operational. Normal tickets will cost 10 euros, while high season tickets will cost 15 euros. The peak season is between May and September. The total number of journeys each year is 2,190. The trips are divided into three categories: summer, spring-fall, and winter. This distinction is formed due to the differing ticket prices throughout the summer months and the fluctuating seasonal demand. Table 30 displays the precise number of seasonal travels.

Number of GKP7H2 ships	1	ships
Passenger normal Ticket	10	euro

Passenger Ticket Summer	15	euro
Number of trips per day of a Ship	6	trips/day
Overall trips/day	6	trips/day
Overall trips	2190	trips/year
Summer trips	930	trips/year
Fall-Spring trips	360	trips/year
Winter trips	900	trips/year

Table 30 Ticket Prices & Number of Trips

The passenger capacity varies during the three seasons. The ship can accommodate a maximum of 100 passengers. Summer season capacity is approximately 90%, while fall spring season capacity is 70%. During the winter season, the capacity dropped to 50%. Table 31 depicts the capabilities.

MAX Capacity	100	Passengers
Summer Capacity (May-Sept)	90	90%
Fall-Spring Capacity (April+Oct)	70	70%
Winter Capacity(Nov-Mar)	50	50%

Table 31 Passenger Capacity

The profit per season is estimated annually. Obviously, the summer profit is approximately three times that of the other two seasons combined, with an annual estimate of 1,255,500 euros. The annual total profit is 1,77,500 euros. In addition, the maximum profit displayed in table 32 is merely a comparison to the general average. The maximum profit is determined when all trips are full capacity. An ideal circumstance that is unattainable to achieve.

Summer Profit	1,255,500	€/year
Fall-Spring Profit	252,000	€/year
Summer Profit	270,000	€/year
Normal Profite	1,777,500	€/year
MAX Profite	2,655,000	€/year

Table 32 Profits of the Ferry

## 7.5 Economic evaluation

Net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period. By contrast, the internal rate of return (IRR) is a calculation used to estimate the profitability of potential investments.

Both of these measurements are primarily used in capital budgeting, the process by which companies determine whether a new investment or expansion opportunity is worthwhile. Given an investment opportunity, a firm needs to decide whether undertaking the investment will generate net economic profits or losses for the company.

*The net present value (or “discounted cash flow”) method takes the time value of money into the account, by:*

- *Translating all future cash flows into today’s money*
- *Adding up today’s investment and the present values of all future cash flows*

*If the net present value of a project is positive, then it is worth pursuing, as it creates value for the company.*

*IRR is the discount rate at which the net present value becomes 0. In other words, you solve for IRR by setting NPV at 0. Equation 14 illustrates the NPV formula.*

$$NPV = \sum_{t=0}^n \frac{Rt}{(1+i)^t} \quad (16)$$

where:

R<sub>t</sub>=Net cash inflow-outflows during a single period, t

i=Discount rate or return that could be earned in alternative investments

t=Number of timer periods

Initial cost, O&M costs, and replacement cost comprise the cash outflow for the ideal hydrogen refuelling station (Big LG 430 kg/day). Also include the work by Frederik G. Aarskog and Janis Danebergs entitled Energy and economic analysis of a high-speed passenger ferry powered by hydrogen. This study provides the additional start up, operational, and replacement costs required to complete the cash outflow. The additional cost for the high-speed passenger ferry is summarised in Table 33. Regarding the cash inflow, the ticket price will complete this portion of the equation.

Estimated Purchase cost of a hydrogen powered HSC		
Item	Lifetime	€
<b>Investment Cost</b>		
Fuel cell system (permanent installations)	25	€1,234,800
Fuel cell system (degradable components)	10	€1,234,800
Hydrogen storage	25	€599,760
Power electronics and electric motoros	25	€882,000
TOTAL (HRC)		€3,951,360
<b>Operetional Cost</b>		
		€/year
Fuel cell system (permanent installations)		€125,440
Fuel cell system (degradable components)		€196,000
Hydrogen storage		€61,054
Power electronics and electric motoros		€89,866
Maintenance		€130,340
FEE		€49,000
TOTAL (HRC)		€651,700
<b>Repex</b>		
Fuel cell system (degradable components)	10	€1,234,800

Table 33

Using the costs of Big\_Low grid power plant which the most efficient one for the period of 25 years and the discount rate of 3%. Figure 59 presents the 25-year cash flow forecast for the entire system. Since the projected NPV is negative ( $<0$ ), it is anticipated that the project would result in a net loss. The payback period is estimated in 18 years and NPV is zero when the IRR is 2% (Figure 60 shows the NPV as a function of the discount rate). As a result, and in accordance with the rule, the business should not proceed the project, despite the fact that High speed craft have very high emissions of around 904 g/km. The reduction of these emissions has a significant impact, as the HSC is the main source of emissions from public transportation in all Mediterranean region. For the project to have its own hydrogen-powered boats, funding must come from the government or the European Union. Therefore, the net present value must be positive and close to the initial cost, and the discount rate should be around 20%. A "good" IRR would be greater than the initial investment made by a corporation in a project.

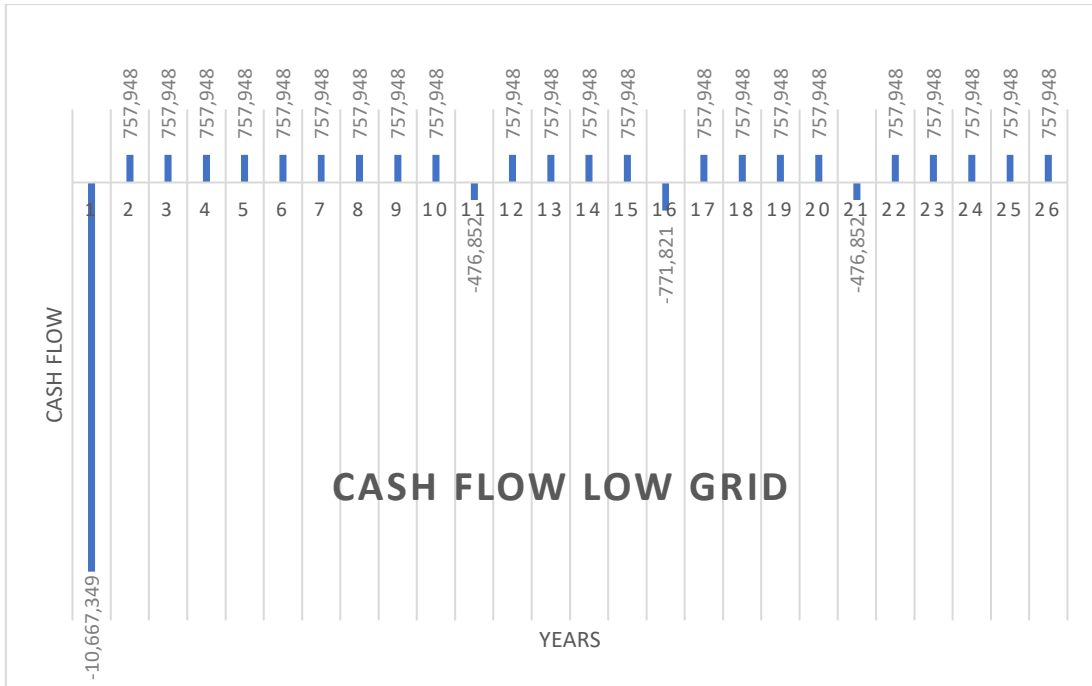


Figure 59

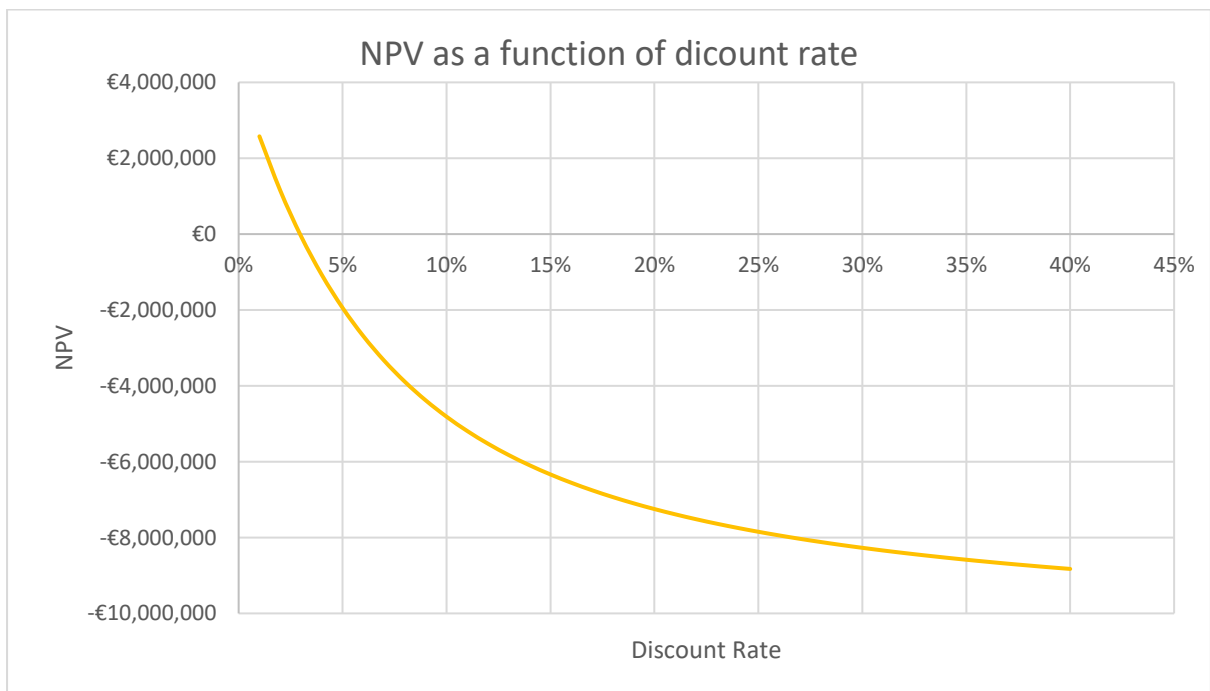


Figure 60

## 8. Conclusion

In summary, the techno-economic assessment of on-site hydrogen refuelling stations based on electrolysis units integrated with grid-connected PV plants has been carried out.

To start with, a sensitivity analysis based on the hydrogen production capacities and on the electricity mix (electricity from PV plant and grid) has been performed. Three hydrogen production capacities and four Electric Energy Supply Management Strategies, in terms of annual sharing of electricity supply by the grid and the PV plant (from full grid to the low grid supply and even a minimum grid for experimental purposes) have been selected.

The economic assessment has been performed by calculating the levelized cost of hydrogen (LCOH), and Net Present Cost that are considered the most important indicator among the economic evaluation indexes.

The results indicate that the lowest net present cost is always in the scenarios where the majority of the electricity is produced by the PV plant size, despite the fact that the initial expense for Low Grid scenarios is more than double that of Full Grid scenarios.

In fact, the plant with the highest hydrogen production capacity (420 kg/day) displays a 10% reduction in LCOH compared to the plant with the smallest hydrogen production capacity (136.58 kg/day). Consequently, central PV hydrogen systems are a means of closing the gap between carbon-intensive methods with low levelized costs.

The LHC depends on the IC and OM costs of the PV panels, electrolyzers, compressors, convertor, and storage tanks. Moreover, by analysing the annual sharing of electricity supply by the grid and the PV plant, the optimal system configuration is achieved when the grid supply is equal to 25%. The best configuration has a LCOH equal to 5.16 €/kg (Big\_LG).

In addition, by analysing the impact of plant costs on the LCOH calculation, it is determined that operational and maintenance costs are the most significant contributors. The annual cost of grid-purchased is the largest contributor. Despite the fact that the Low Grid electricity mixed consists of 75% plant size and 25% purchase from the grid, over fifty percent of operating and maintenance funds are spent annually on the purchase of electricity.

*Various electricity rates (0.02€/kWh, 0.04€/kWh, 0.08€/kWh, 0.16€/kWh, and 0.32€/kWh) were evaluated. Providing evidence that the lowest electricity price of 0.02€/kWh rendered PV insulation unnecessary. The 0.04 euros per kilowatt-hour subsequently demonstrated that there were negligible variations in the electricity mixture. Most significantly, the other three values demonstrated that the PV decreases the LCOH price. With a price difference of 0.32€/kWh between the Low Grid and the Full Grid, the Full Grid LCOH price was two times that of the Low Grid. The suggestions of a lower electricity price have a more positive effect with respect to the reduction of the investment costs of the more expensive components (i.e., compressor unit, electrolyser, PV panels).*

Regarding the purchase of water, the standard rate in Greece is €2/m<sup>4</sup>. Now, if there is an increase of 6 €/m<sup>4</sup> and the LCOH will experience little price adjustments. Consequently, the purchase of water has a minor impact on the cost of LCOH.

The electrolysis and photovoltaic (PV) panel efficiencies are a further key factor. Solar panels must be manufactured so that their efficiency does not decrease and so that they last longer. The LCOH will increase with time if the grid is utilized more due to a decrease in the efficiency of the pv panels. Regarding to the electrolysis's efficiency, the current PEM electrolysis has a



power consumption of 5.1% kWh/Nm<sup>3</sup> was compared to a future approach with a power consumption of 3.8% kWh/Nm<sup>3</sup>. This resulted in a 25% decrease in energy consumption across all the components and a €1.5/kgH<sub>2</sub> decrease in LCOH. Therefore, the efficiency of the electrolysis is essential for the development of hydrogen technology.

Moreover, an economic analysis for a regular zero-emission ferry route is conducted utilising the existing concept design of GKP7H<sub>2</sub>, which is already in use in Norway and whose hydrogen storage capacity corresponds to the optimal daily production of a maritime refuelling station. Calculating the net present value, internal rate of return, and payback period for a six-trip-per-day route from Piraeus port to Aegina Island, then Agkistri Island, and back to Piraeus utilising the Big Low refuelling station. The investment resulted in a net loss, with a payback period of 18 years and an internal rate of return of 2%. This plan was not practicable without a solid financial foundation.

Above all, the green hydrogen refuelling station is practical but costly. With its high energy density and solidly established technology, hydrogen offers the ability to decarbonize ferries. Numerous continuing studies are being conducted on hydrogen and ammonia, and the International Maritime Organization (IMO) has set a deadline for the globe to transition to a decarbonized solution. Consequently, the objective of this study is to contribute to the decision-making processes regarding the design of on-site hydrogen refuelling stations. Based on the present thesis and the above conclusions, some suggestions for further research are listed:

- A Techno-economic analysis off-grid Solar-powered Hydrogen Refuelling Station
- Integrated optimization model for hydrogen supply chain network design and hydrogen fuelling station planning in Greece
- Techno-economic analysis of green hydrogen ferries with a wind based marine fuelling station
- Cost Competitiveness of Electrolytic Hydrogen

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