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Design and techno-economic analysis of Hydrogen refueling stations: Scenarios developed in Torino and Palermo.

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Abstract

This thesis explores the feasibility and economic viability of various hydrogen refueling station layouts across two distinct urban settings, Torino and Palermo. Six scenarios were meticulously designed and analyzed, with a focus on sustainability, cost-effectiveness, and risk assessment.

The three layout options considered for each city are:

1. On-grid refueling station with integrated photovoltaic (PV) panels.
2. Off-grid refueling station with PV panels and a lithium-ion battery storage system.
3. Hybrid off-grid refueling station with PV panels and a hydrogen fuel cell to produce electricity from hydrogen.

All the scenarios were designed and analyzed through the software HOMER Pro, which optimizes micro-grid designs across all industries to minimize the costs and to calculate important economic indexes such as the Levelized Cost of Hydrogen (LCOH) and Levelized Cost of Energy (LCOE) to compare the various layouts to each other. The simulations showed that the on-grid layout emerged as the most cost-effective option in terms of initial capital cost and operational expenses. In the scenario developed for Torino, the Levelized Cost of Hydrogen (LCOH) was determined to be 10.38 €/kg, with a Net Present Cost (NPC) of 7209536 €. Meanwhile, in Palermo, the on-grid station exhibited an even lower LCOH of 8.91 €/kg and an NPC of 6190773 €. Even if the system is on-grid the hydrogen produced is considered green because just 1% of the total electricity produced comes from the grid, so the emissions generated yearly hovers around 20000 kg which is a negligible value compared to the yearly emissions produced by traditional combustion engine vehicles. In addition to the economic analysis, a comprehensive risk assessment was conducted to evaluate the robustness of these scenarios. The analytical hierarchy process (AHP) decision-making method was employed to quantify and prioritize risks associated with each scenario. The risk analysis results consistently favored the on-grid scenario as the most profitable option for the Torino location. Conversely, the hybrid refueling station with a hydrogen fuel cell emerged as the optimal choice in Palermo, demonstrating the adaptability of hydrogen infrastructure solutions to the specific characteristics of each urban environment.

This thesis contributes to the ongoing discourse surrounding sustainable hydrogen infrastructure by providing valuable insights into the design, economic viability, and economic risk assessment of hydrogen refueling stations. The outcomes emphasize the importance of tailoring hydrogen infrastructure solutions to the unique conditions of each urban setting, while also highlighting the potential for on-grid systems to be a cost-effective choice, especially in regions with grid infrastructure advantages. Moreover, the study underscores the significance of risk analysis in decision-making processes related to hydrogen infrastructure projects, promoting informed and strategic choices for future hydrogen development initiatives.

Keywords: Hydrogen, Hydrogen Refueling Stations, Levelized Cost of Hydrogen, Electric charging stations, Fuel Cell, Sustainability, Decarbonization, Greenhouse gas emissions.

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Nomenclature

Abbreviations and acronyms

GHG: greenhouse gas

ANAS: Azienda Nazionale Autonoma delle Strade Statali (National Autonomous Company of State Roads)

GHI: Global horizontal Irradiance

PV panels: Photovoltaic panels

AC: Alternate current

DC: Direct current

O & M cost: Operating and maintenance cost

STC: Standard condition

AHP: Analytic Hierarchy Process

ANP: Analytic Network Process (ANP)

HRS: Hydrogen refueling station

ERS: Electric refueling station

FCV: Fuel Cell Vehicle

BEV: Battery Electric Vehicle

1. Introduction – Overview of the greenhouse gas emissions in transportation sector and sustainable alternatives to traditional combustion engines.

1.1 Greenhouse gas emissions

In recent decades, the issue of global carbon emissions has garnered significant attention as a critical environmental challenge that necessitates immediate and concerted action. The continuous rise in greenhouse gas (GHG) emissions, predominantly carbon dioxide (CO2) emissions (about 74.4 % [1]), has led to adverse impacts on the Earth's climate system, exacerbating the threat of climate change. Recognizing the urgency of this issue, the international community came together to forge an unprecedented agreement known as the Paris Agreement. This treaty, adopted in December 2015 at the 21st Conference of the Parties (COP 21) to the United Nations Framework Convention on Climate Change (UNFCCC), represents a global commitment to combat climate change and limit global warming to well below 2 degrees Celsius above pre-industrial levels, while striving for a more ambitious target of 1.5 degrees Celsius [2].

Following these guidelines, many countries have committed themselves to reducing GHG emissions as much as possible, and most of them reached this goal. The Carbon emissions reduction rates range from -0.5% to -3% depending on the country, but we have to distinguish CO2 emissions from GHG emissions, indeed, for example, the US has a reduction of -1.1% in CO2 emissions since 2005, but only a -0.5% in GHG, and this trend is common also among the other states [3]. Despite these improvements, in the figure below we can see that the trend of global GHG emissions over years is always increasing due to emissions of the countries in the rest of the world (except in 2020 where we have a sharp decrease for the Covid-19 pandemic).

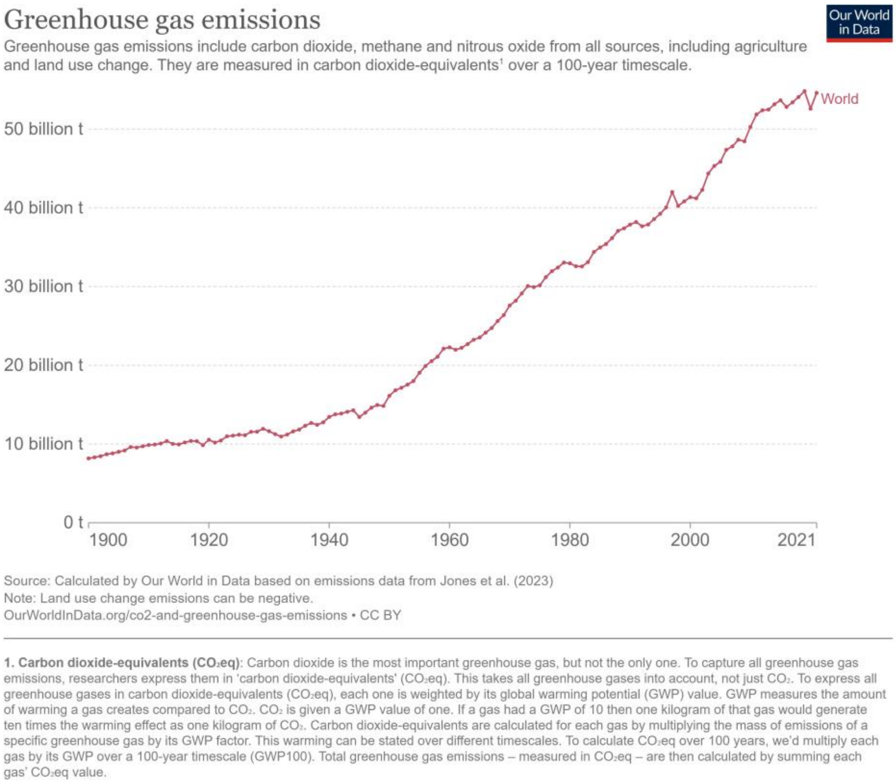

Figure 1 - Global greenhouse gas emissions, from 1900 to 2021 [4].

Emissions are categorised by sector to help understand where the emissions came from and how to minimize them. With their respective consumption, four macro-sectors are identified:

- Energy, 73.2%
- Agriculture, 18.4%
- Industry, 3.2%
- Waste, 5.2%

However, energy emissions are separated into three main sectors: energy use in industry (24.2%), energy use in buildings (17.5%), and transportation (16.2%). The emissions are schematized in the pie chart below.

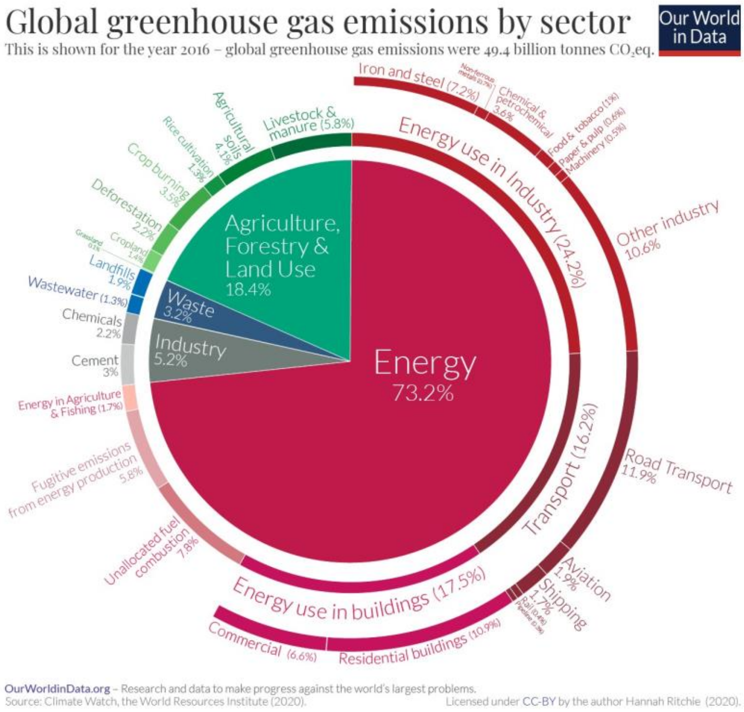

Figure 2 - Global greenhouse gas emissions by sector [5].

If we look at the preceding discussion of emission reductions by sector, we can see that the transport sector has not demonstrated any significant improvements in terms of emissions in recent years [3], this is the reason why the global transport sector has faced increasing challenges related to carbon emissions, air pollution, and energy sustainability. As a result, there has been a growing interest in alternative fuels and technologies that can mitigate these issues and pave the way for a cleaner and more sustainable future.

1.2 Hydrogen: a sustainable source

Hydrogen is increasingly seen as a promising and sustainable energy source, particularly in the transportation sector, where it has the potential to play a significant role in reducing greenhouse gas emissions and addressing environmental concerns. Here are some key aspects of hydrogen as a sustainable source of energy in transportation:

1. **Zero Emissions:** One of the most significant advantages of using hydrogen in transportation is that it produces zero tailpipe emissions when used in fuel cell vehicles (FCVs). Hydrogen fuel cells generate electricity through a chemical reaction between hydrogen and oxygen, with the only byproduct being water vapor. This makes FCVs an environmentally friendly alternative to traditional internal combustion engine vehicles powered by fossil fuels [6].
2. **Energy Density:** Hydrogen has a high energy density, which means it can store a large amount of energy in a relatively small volume or weight. This characteristic makes it suitable for applications

where energy storage capacity is critical, such as long-range transportation. Its energy storage capacity is awesome since 1 kg of hydrogen has an energy content of roughly 120 MJ (=33.33 kWh) which is more than double that most conventional fuels, for example conventional gasoline has an energy content of 43.44 MJ/kg, and conventional diesel just 42.78 MJ/kg [7].

3. **Fast Refueling:** Refueling a hydrogen vehicle is similar to refuel a gasoline or diesel vehicle in terms of time, taking just a few minutes. This stands in contrast to battery electric vehicles (BEVs), which generally have longer charging times. Fast refueling is crucial for the widespread adoption of hydrogen vehicles, as it offers convenience to consumers.
4. **Range:** Hydrogen fuel cell vehicles typically have a longer driving range compared to many battery electric vehicles. This extended range is important for applications such as commercial trucks, buses, and other heavy-duty vehicles that need to cover long distances between refueling.
5. **Versatility:** Hydrogen can be produced from a variety of sources, including natural gas, biomass, and water using renewable energy sources like wind or solar power. This versatility in production methods allows for a diverse and potentially sustainable supply chain. In Table 1 below are shown the several ways to produce hydrogen with their commercial availability.

Table 1 - Hydrogen production [8].

	Commercial availability	Feedstock/energy source	Production model
Steam reforming	Most common	Natural gas	Centralized or decentralized
Electrolysis	Special applications	Electricity	Centralized or decentralized
Gasification	R&D stage	Biomass	Centralized
Biological	R&D stage	Solar energy and/or organic waste	Centralized
Photochemical	R&D stage	Solar energy	Centralized
Thermochemical	R&D stage	Solar or nuclear energy	Centralized

We can notice how the electrolysis is used just for special application like in our case for the hydrogen refueling station.

6. **Infrastructure Challenges:** One of the significant challenges in adopting hydrogen for transportation is the development of a comprehensive refueling infrastructure. Building hydrogen refueling stations can be expensive and requires investment in both technology and infrastructure development. Governments and private companies are working together to address this challenge and expand the hydrogen infrastructure [9].
7. **Cost Considerations:** Currently, the cost of producing and storing hydrogen, especially from renewable sources, can be relatively high compared to fossil fuels. However, ongoing research and development efforts are aimed at reducing these costs, making hydrogen more competitive in the transportation sector. Moreover, the hydrogen price strongly depends on the singular station and on its production cost, “which depends on the feedstock and the technology used, and their delivery cost” [10].

In summary, hydrogen has the potential to be a sustainable energy source in the transportation sector, offering zero emissions, fast refueling, and long driving ranges. However, challenges remain, particularly in building the necessary infrastructure and reducing production costs. The adoption and success of hydrogen in transportation will depend on continued advancements in technology, infrastructure development, and supportive policies that promote clean and sustainable energy sources.

1.3 Sustainable alternatives to the transportation sector

The transportation sector is a significant contributor to greenhouse gas emissions and air pollution. To address environmental concerns and promote sustainability in transportation, various alternative technologies and modes of transportation have been developed. Two of the most attractive alternatives are: Fuel Cell vehicles (FCV) and Battery Electric vehicles (BEV).

1.3.1 Fuel Cell Vehicles (FCVs)

Fuel cell vehicles (FCVs) are a type of electric vehicle (EV) that use hydrogen gas as a fuel source to generate electricity through a chemical process in a fuel cell. They use hydrogen as a fuel to directly transform chemical energy from a reaction into electrical energy. An electrolyte layer in contact with an anode and a cathode on either side make up the fundamental physical components of a fuel cell (Figure 3). The most typical categorization of fuel cells is based on the electrolyte type and operating temperature of the cells:

1. Proton Exchange Membrane Fuel Cell (PEMFC), 80 °C
2. Alkaline Fuel Cell (AFC), 100 °C
3. Phosphoric Acid Fuel Cell (PAFC), 200 °C
4. Molten Carbonate Fuel Cell, 650 °C
5. Solid Oxide Fuel Cell (SOFC), 650–1000 °C
6. Direct Methanol Fuel Cell (DMFC), 80 °C.

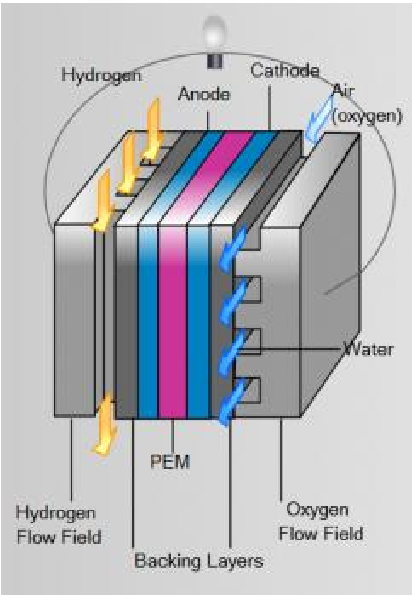

Figure 3 – PEMFC [11].

Compressed hydrogen gas is fed into a fuel cell stack onboard a fuel cell vehicle, which converts the chemical energy of the fuel into electrical energy rather than burning the gas. The electric motors of the automobile are then driven by this electricity. There are no emissions from the tailpipe, and the only waste generated is clean water. The fuel cell's design is comparable to that of a battery. A catalyst that encourages the division of hydrogen atoms into an electron and a proton is in touch with the hydrogen as it reaches the anode. The onboard batteries and/or the motors that spin the wheels are fed with the electrons collected by the conductive current collector, which is coupled to the high-voltage circuitry of the vehicle.

The main components of a fuel cell car are (Figure 4) [12]:

Fuel Cell Stack: A collection of multiple fuel cells that use oxygen and hydrogen to produce electricity and power an electric motor.

Fuel Tank (hydrogen): To supply fuel to the fuel-cell stack, hydrogen gas is kept in carbon fibre-reinforced tanks.

Electric Traction Motor: which propels the vehicle with the energy generated in the fuel cell stack.

Battery Pack: Stores energy from regenerative braking and gives the electric motor more power.

Power Electronic Controller: It plays a crucial role in managing and optimizing the flow of electricity between the fuel cell stack, the electric motor, and the vehicle's battery.

Thermal System (cooling): It is responsible for maintaining the proper temperature of the fuel cell stack, managing water produced during the fuel cell reaction, providing cabin heating and cooling, and optimizing the overall efficiency and safety of the vehicle. Moreover, it ensures that the fuel cell operates within its ideal temperature range.

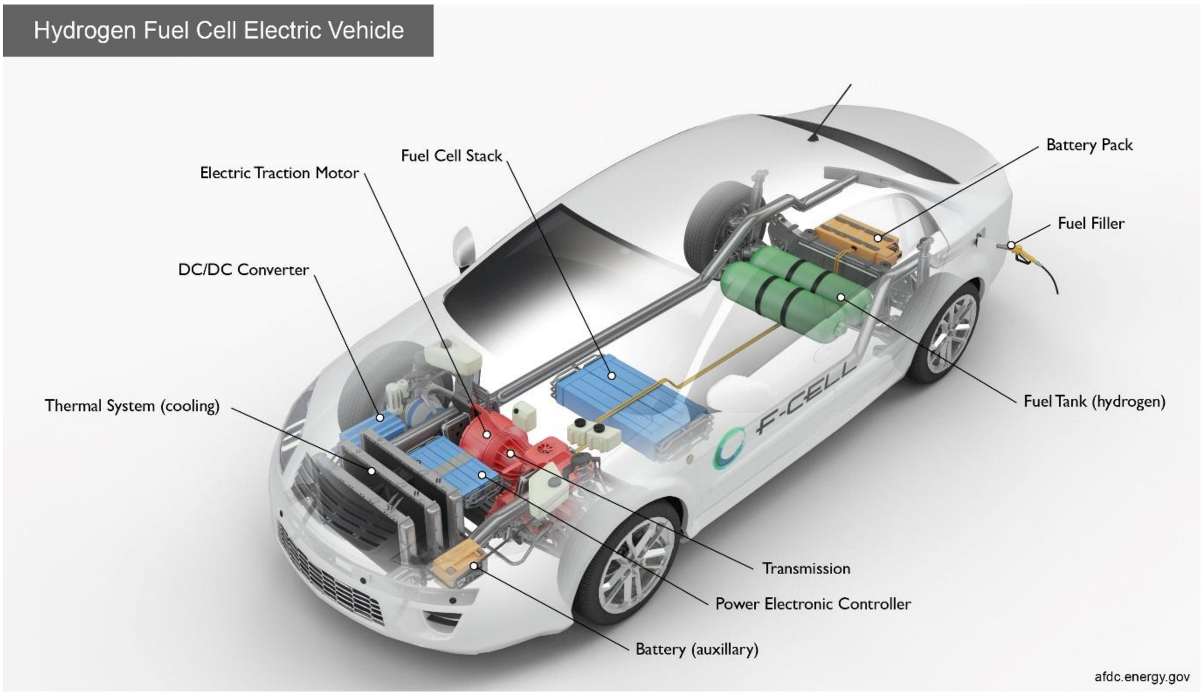

Figure 4 - Hydrogen Fuel Cell Electric Vehicle. (U.S. DOE)

The growth of fuel cell vehicles is closely tied to the spread of hydrogen infrastructures like HRSs which are expected to increase as hydrogen technology matures on hydrogen refueling stations. Taking a look at the international scenario, at the end of 2022, there were 814 hydrogen refueling stations operating globally [13]:

- 254 in Europe (105 in Germany)
- 455 in Asia (165 in Japan and 149 in South Korea)

- 89 in North America (70 in California)
- 315 are in progress all over the world.

Moreover, automobile manufacturers are putting money into fuel cell technology as a result of the aggressive targets set by world leaders to reduce greenhouse gas emissions. Furthermore, advances in fuel cell technology are bringing down the price and raising the efficiency, which is enticing more companies to the market. Many of them are among the most important and established companies in the world such as: General Motors Company, Honda Motor, Audi AG, BMW Group, Hyundai Motor Group, Toyota Motor, Volvo Group and many others [14].

The most widespread hydrogen car on the market is the Toyota Mirai with a 182 HP engine and 300 Nm of torque. It is powered by three hydrogen tanks of 141 L that store 5,6 kg of hydrogen (this represent the high energy density of hydrogen) and the autonomy with a full tank is 629km; moreover, the maximum speed of the car is 175 km/h and its cost is around 70000 € which is quite high for an utility car [15].

Risk of explosion

A false myth that concerns FCVs is the high risk of explosion. It is true that hydrogen is a high flammable gas and it carries the risk of explosion when certain condition are met. Its characteristic related to explosion are: wide flammability range, low ignition energy, rapid flame spread, it tends to disperse quickly in the atmosphere (Actually this property can help prevent the buildup of dangerous concentrations, it also means that leaked hydrogen can spread rapidly in the presence of air, potentially increasing the size of a fire or explosion) and an finally it has an invisible flame. However, hydrogen fuel cell vehicle are designed with a strong emphasis on safety, and they have several features and systems in place to minimize the risk of explosions or other safety hazards associated with hydrogen. While no technology is entirely risk-free, it's essential to understand the safety measures that are in place to mitigate potential risks [16] [17].

1. **Hydrogen Storage**: FCVs store hydrogen gas in high-strength, lightweight tanks that are designed to withstand various stressors, including collisions. These tanks are typically made from composite materials that can absorb and dissipate energy during an impact [18].
2. **Leak Detection**: FCVs are equipped with sophisticated hydrogen leak detection systems. If a leak is detected, the system can shut down hydrogen flow and take appropriate safety measures, such as venting the gas safely to prevent buildup.
3. **Hydrogen Dispensing**: Hydrogen refueling stations also have safety measures in place. They dispense hydrogen at high pressures, but the connectors and nozzles are designed to prevent leaks or disconnections while fueling. Safety interlocks ensure that the vehicle and station are properly connected before hydrogen is dispensed [19].
4. **Hydrogen Sensors**: Hydrogen sensors inside and outside the vehicle continuously monitor for the presence of hydrogen. If a leak is detected, the vehicle's fuel cell system can shut down, and the hydrogen can be vented safely.
5. **Crash Safety**: FCVs undergo rigorous crash testing to ensure their safety in accidents. The fuel cell stack and hydrogen tanks are designed to minimize the risk of rupture or release of hydrogen in a collision.

In conclusion, today the risks associated with hydrogen fuel cell vehicles are not significantly different from those associated with gasoline or natural gas vehicles [16].

1.3.2 Battery Electric vehicles (BEVs)

Battery electric vehicles, or BEVs, are exemplars of advanced engineering and sophisticated energy management. At their core, these vehicles rely upon a substantial lithium-ion battery pack to serve as a reservoir for electrical energy, analogous to the role of a fuel tank in conventional internal combustion engine vehicles. However, the energy is stored in a chemical form within the battery cells.

The operational sequence commences with the charging process. When a BEV is connected to an external power source, such as a residential or public charging station, it initiates the replenishment of its energy reserves. The incoming electricity, typically in the form of alternating current (AC), undergoes transformation into direct current (DC) to align with the requirements of the battery's chemical composition. Crucially, the Battery Management System (BMS) assumes a pivotal role in this context. The BMS exercises meticulous oversight by monitoring parameters such as voltage, current, and temperature to ensure the battery's safe and efficient charging. Following the charging phase, electrical energy is securely stored within the lithium-ion battery pack, ready for utilization during the upcoming vehicular operation. The central component within a BEV is its electric motor, the principal agent for converting the stored electrical energy into mechanical energy for the purpose of vehicle propulsion. It is worth noting that the BEV' characteristic attributes, including quiet and simple operation, are predominantly attributed to the electric motor's performance. The electric motor draws upon the energy stored in the battery pack via an electronic controller, commonly referred to as an inverter. The inverter's role is to govern the flow of electricity, effectively managing the motor's speed and direction. This precise organization allows the vehicle to accelerate, decelerate, and reverse with a high degree of efficiency and smoothness [20].

During the acceleration phase, electrical energy flows from the battery to the electric motor, conferring power to the wheels. A noteworthy feature of BEVs, known as regenerative braking, merits special mention. In this scenario, the electric motor assumes an alternative role, functioning as a generator. Instead of dissipating kinetic energy as heat, it harnesses it and transforms it back into electricity. This recaptured energy is subsequently redirected into the battery, replenishing the charge and amplifying overall operational efficiency. Regenerative braking stands as an exemplar of BEV's commitment to efficiency and environmental sustainability [21].

In matters of transmission, BEVs often incorporate a single-speed transmission or may avoid a transmission altogether. This comes from the electric motor's capacity to deliver substantial torque at low speeds, rendering the need for multiple gears redundant. The outcome is a simplified and inherently efficient powertrain [22].

Of paramount significance is the driving range of a BEV, a parameter contingent upon the battery pack's capacity and the efficiency with which energy is utilized. In contemporary BEVs, driving ranges frequently exceed 300 km on a single charge, with certain premium models surpassing the 450 km threshold [23].

Safety considerations extend to the battery pack, with specialized thermal management systems playing a crucial role. These systems are tasked with maintaining the battery's operating temperature within an optimal range, thereby precluding deleterious effects such as overheating or excessive cooling, which might otherwise compromise performance and longevity [24].

In Figure 5 below the BEV components are shown; In the front part of the vehicle is located the traction system as seen for the FCV, but here the car is powered by a big traction battery pack, positioned at the bottom of the vehicle, giving more stability thanks to its heavy weight.

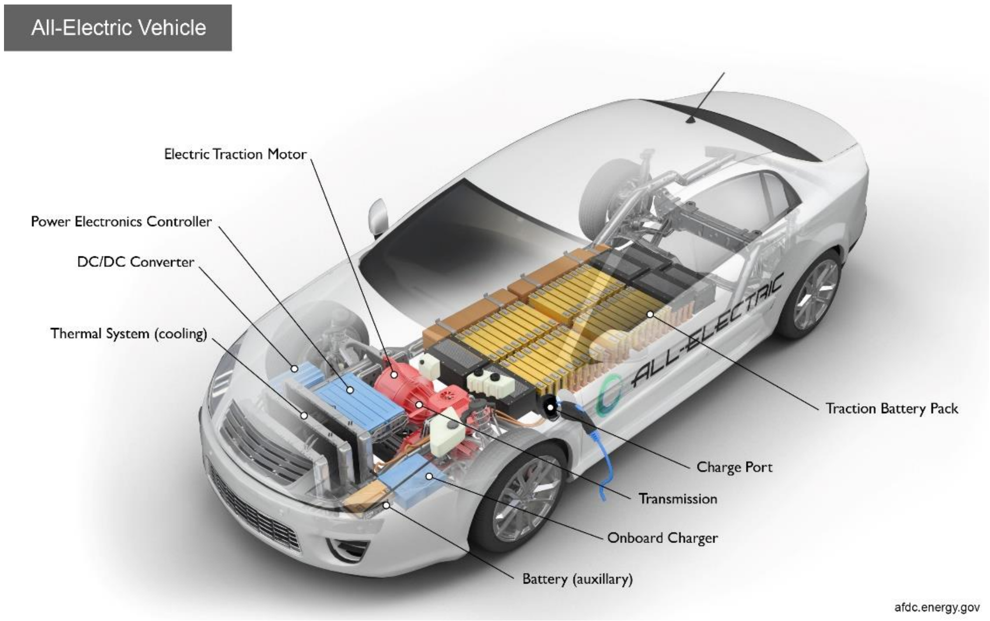

Figure 5 - Battery Electric vehicle. (U.S. DOE)

A point of strength of battery electric vehicles is the already established market that counts 26 million of electric cars (including Plug-in Hybrid Electric Vehicles (PHEV)) on the world's roads. In 2022, BEVs accounted for almost 70% of the worldwide electric vehicle stock. The global electric car stock is shown in the graph below [25].

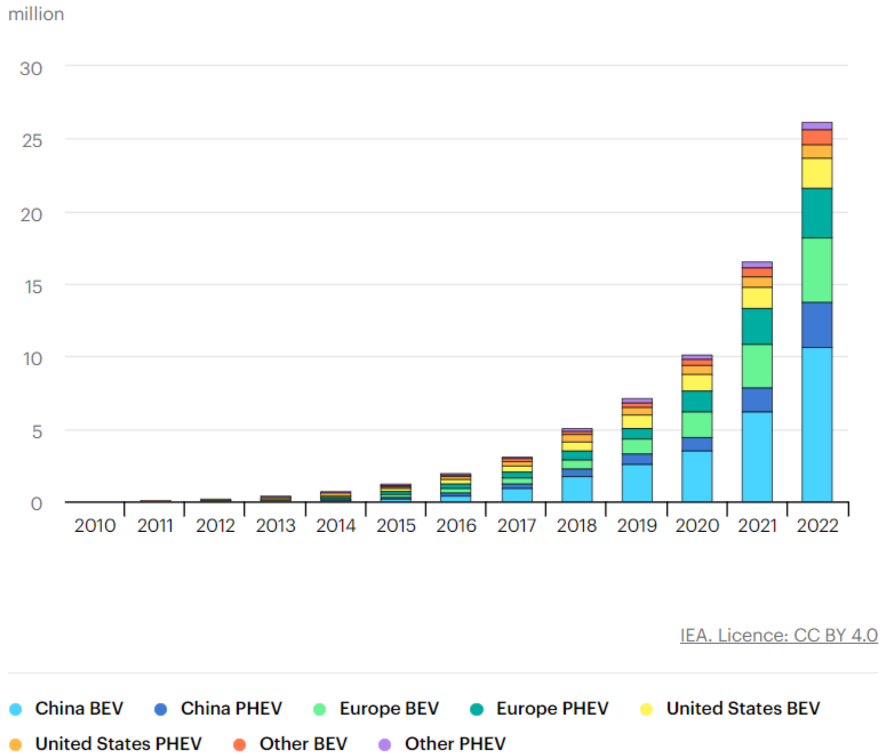

Figure 6 - Global electric car stock, 2010-2022 [25].

China, Europe, and USA are the three main electric car markets (they count about 95% of global sales in 2022), but in other counties like India, Indonesia and Thailand the interest for electric car is growing.

To compare price and performance of a BEV with a FCV we always chose a Toyota car, in this case the bZ4X XLE that is a common model sold by the brend. The price of this car is about 45000€ with an autonomy of

400 km. The electric engine has 201 HP with 265 Nm of torque and the maximum speed reachable of 160 km/h [26].

Electric charging stations:

The electric charging stations are totally different from the hydrogen charging stations and there are several types of ERS with different level of power. Charging times of the charging station depend on a multitude of factors, one of the most important is the power at which the charging take place.

The first subdivision regards the current of the station; there are DC and AC charging stations. Moreover, the most common powers for the Electric charging stations are:

- 3 kW car charging station.
- 7.4 kW car charging station.
- 11 kW car charging station.
- 22 kW car charging station.
- 50 kW Fast car charging station.
- 350 kW Ultra-fast car charging station.

To calculate the charging times simply divide the battery capacity (in kWh) by the charging power (in kW).

The maximum power for an AC charging station is 22 kW, while the DC ones today can reach 350 kW, but the higher the power of the charging station, the higher the costs of charging. Fast charging stations located on public roads and highways with power up to 50 kW can recharge a 40 kWh battery in less than an hour, while Ultra Fast Stations with power up to 350 kW can provide a full charge in under 25 minutes. However, Italy does not yet have a large number of these last types of charging stations, and there aren't many vehicles that can charge more quickly [27].

You can also charge your vehicle at home with a 3 kW station, it is really convenient in term of cost but a fully charge can take more than 8 hours.

1.3.3 Comparison between Fuel cell vehicles and Battery electric vehicles.

Hydrogen fuel cell vehicles face competition from battery electric vehicles, which have gained more widespread acceptance in recent years. Both technologies have their advantages and disadvantages, and the choice between them often depends on specific use cases, infrastructure availability, and consumer preferences. All the considerations seen for both FCVs and BEVs can be summarized and compared to understand which technology is the best and in which scenario. The advantages and disadvantages of both Hydrogen and Electric cars are listed below [28]:

Fuel Cell Vehicles:

Advantages:

1) No tailpipe emissions.
2) Rapid refueling times.
3) Greater driving range in comparison to electric vehicles.
4) Lighter weight due to smaller battery packs.

Disadvantages:

1) Limited infrastructure for refueling.
2) The vehicle’s cost is higher due to the high expense of fuel cell technology.
3) Few vehicles on the market.

Battery Electric Vehicles:

Advantages:

1) No tailpipe emissions.
2) Cheaper operational expenses due to fewer moving components and reduced energy expenditures.
3) Less noisy operating.
4) Widespread infrastructure for charging.

Disadvantages:

1) Longer charging times.
2) Low driving range in comparison to FCVs.
3) Vehicle performance may be impacted by heavy batteries.

In Table 2 below is shown a comparison of the cost to ride 100 km with a FCV, with a BEV and with traditional combustion engines vehicles.

Table 2 - Cost comparison between FCVs, BEVs, and traditional vehicles

	Efficiency [km/kg or km/L or km/kWh]	Specific Cost [€/kg or €/L or €/kWh]	Cost to ride 100 km [€]	Source
Hydrogen [kg]	100	13.7	13.7	[29]
Gasoline [L]	13	1.939	14.91538462	[30], [31]
Diesel [L]	16	1.827	11.41875	[30], [31]
Electric [kWh]	6	0.86	14.33333333	[32], [33]

We can notice how the cheapest technology is the diesel one, while hydrogen results the second cheapest alternative. This is due the really high taxes imposed on traditional fuel from the Italian government. Regarding the electric station price, it is actually high variable, and it ranges from 0,20 to 0,90 €/kWh, here we considered the price of a pay-per-use rate of the brand A2A for fast charging station.

There are other advantages of the hydrogen over the lithium-ion batteries used as a storage energy mean. The first one regards the environmental sustainability of lithium, since it is extracted from quarries and for every tonne of lithium mined 2.2 million litres of water are needed. Otherwise, the transportation of these critical materials adds another layer to the environmental equation. Given that approximately 90% of global trade relies on sea transport, it is worth noting that maritime shipping generates approximately 3% of the world's greenhouse gas emissions.

The second one regards political reasons concerning energy independence: China, despite being primarily an investor in numerous cobalt mines, wields significant influence, controlling a staggering 70% of the capacity for the transformation of cobalt ore into essential cobalt chemicals used in the battery industry. This dominant role in the supply chain cannot be underestimated. Similarly, Australia possesses a noteworthy distinction, housing five out of the world's top ten largest lithium deposits. However, it is worth noting that more than 60% of lithium processing activities are concentrated within China, underlining its pivotal role in the lithium production landscape [34].

2 Literature review

2.1 Electrolysis of water

It is a chemical process that involves the decomposition of water molecules (H20) into hydrogen (H2) and oxygen (O2) gas through the application of an electric current. The process is performed in an electrolysis cell made up of two electrodes, an anode and a cathode, immersed in an electrolyte solution. The materials used for the electrolytes are inert to avoid unwanted reactions or contamination.

Anode is the positive electrode in the electrolysis cell, it attracts negative ions (anions) from the electrolyte. The materials usually used for the anode are resistant to oxidation, such as Platinium (Pt), graphite, or other metals like titanium coated with a thin layer of noble metal oxide. The anode reaction involves the oxidation of water molecules releasing oxygen gas (O2) and protons (H+).

Cathode is the negative electrode, so it attracts the positive ions (cations). The materials used for the cathode can efficiently catalyze the reduction reaction and facilitate the production of hydrogen gas, such as Platinium (Pt), Nickel (Ni), or stainless steel. The cathode reaction involves the reduction of water molecules, leading to hydrogen gas (H2) formation.

The electrolysis cell is set up, typically using a container filled with water that acts as the electrolyte. Water must be pure to avoid unwanted reactions, so deionized or distilled water is commonly used to ensure the purity of the electrolyte solution. The anode is connected to the positive terminal of the power source, while the anode is connected to the negative one.

The electrochemical process is the following:

When the electric current is applied the water molecules dissociated. Water is composed of two atoms of hydrogen and one of oxygen. Due to the electric current, water molecules near the anode lose electrons leading to the formation of positively charged hydrogen ions (H+) and oxygen gas at the anode (oxidation reaction). At the cathode, hydrogen ions gain electrons and are converted to hydrogen gas through a reduction reaction. The reactions will be the following:

Anode reaction: 2H2O(l) → O2(g) + 4H+(aq) + 4e-

Cathode reaction: $4\ H^{+}\ (aq.) + 4\ e^{-} \rightarrow 2\ H_2\ (g)$

Overall reaction: $2\ H_2O(l) \rightarrow 2\ H_2(g) + O_2(g)$

These reactions occur in Proton Exchange Membrane electrolyzers, which is a peculiar kind of electrolyzer, but as we will see we have different partial reactions in the anode and cathode, even if the overall reaction will be always the same.

Oxygen gas O2 is produced as a byproduct of the reaction and it can be released into the atmosphere or collected and used for other purposes.

Following the stoichiometric proportion every two moles of water produce two moles of hydrogen and one of oxygen.

The efficiency of the electrolysis depends on several factors, including the voltage applied, the distance between the electrodes, the electrode materials, and the concentration of the electrolyte. Increased electrolysis rates are often associated with higher voltage and greater electrode proximity. [35].

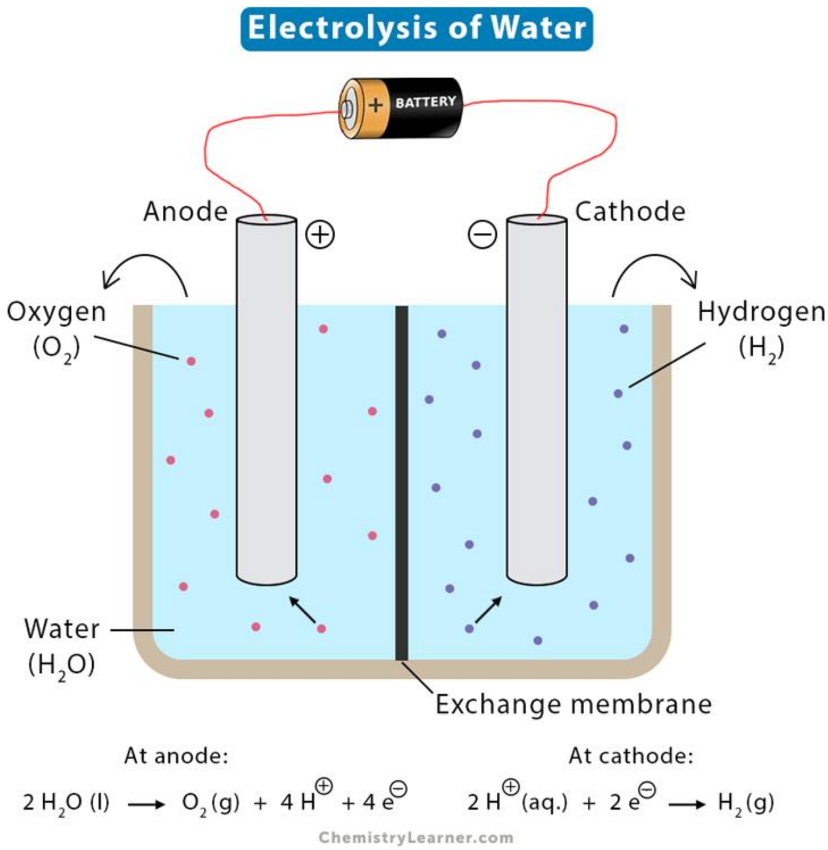

Figure 7 - Electrolysis of water [35]

2.2 Electrolyzers

The electrolyzer is the component that produces hydrogen by the electrolysis of water. There are numerous methods of producing hydrogen as we can see in Figure 8, but we can reduce the action area because our analysis is focused on green hydrogen, which means that the electricity comes from renewable sources, moreover, the technique under consideration is water electrolysis, which is a zero-emission process; only hydrogen and oxygen will be produced. Furthermore, the Proton Exchange Membrane (PEM) electrolyzer was chosen for various reasons discussed in the next pages.

Before explaining why a PEM electrolyzer is chosen, an overview of different kinds of electrolyzers is exposed. The overall reaction will be always the same, through which water is dissociated in hydrogen and oxygen, but depending on the electrolyte used and the design of electrodes, we have different partial reactions to the anode and cathode which involves other ions and molecules.

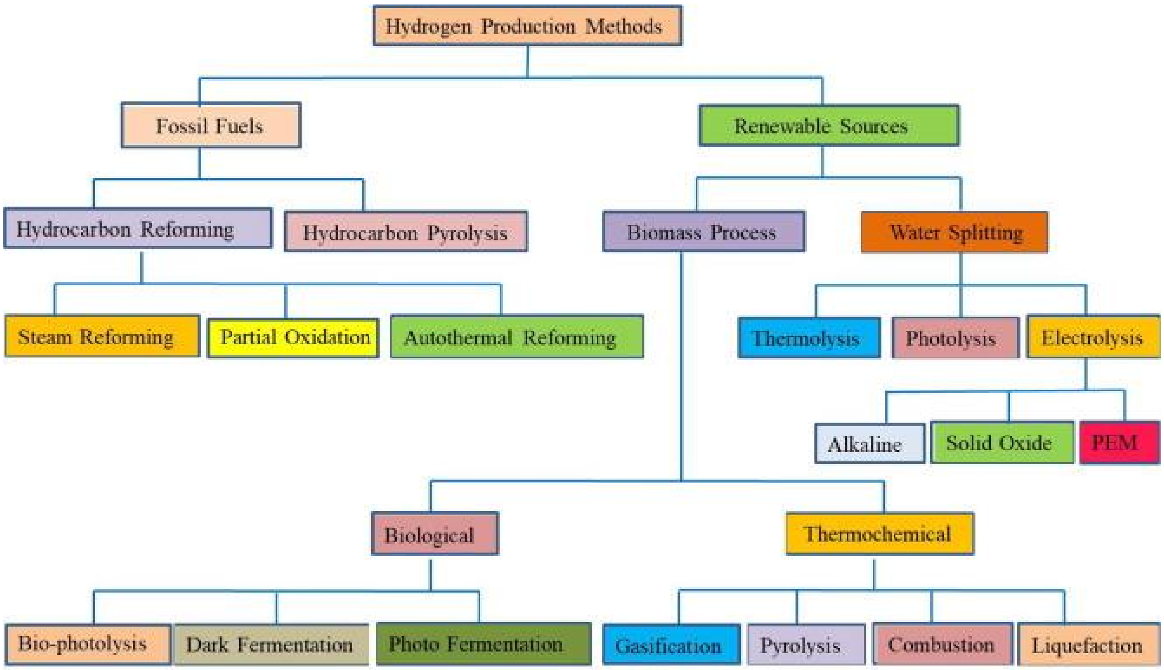

Figure 8 - Hydrogen production methods [36]

Alkaline water electrolysis:

This is the first typology of electrolyzer used; today this technology is spread also for commercial level up to the megawatt. This electrolyzer uses 30% wt potassium hydroxide (KOH) solution or 25% wt sodium hydroxide (NaOH) solution as electrolyte; it has a working temperature between 30°C and 80°C and as the division between anode and cathode uses a diaphragm of asbestos, a naturally occurring mineral fiber widely used for his heat resistance, strength, and insulating properties [37]. This material separates the product gases and allows the passage of hydroxide ions (OH^-). The principle of the electrochemical reaction is always the same, but we introduce the alkaline solution at the cathode (KOH/NAOH), where the reduction reaction occurs thanks to the passage of current, and it forms one molecule of hydrogen and two hydroxyl ions (OH^-). These ions pass through the diaphragm to the anode where the oxidation reaction will take place, so half a molecule of oxygen and one of water will be produced. The schematic reaction is illustrated in Figure 9. The limitations of this technology are: low energy efficiency and pressure and limited current densities, as well as difficulties in working with variable energy sources [36].

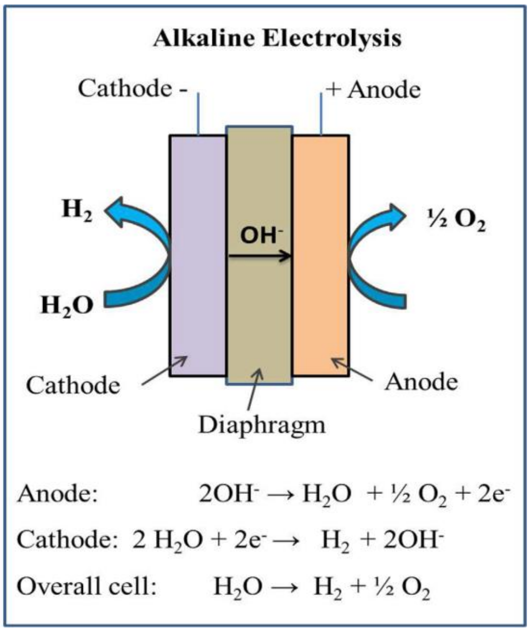

Figure 9 - Alkaline water electrolysis [36]

Solid oxide electrolysis (SOE)

This is the most recent method of generating hydrogen by electrolysis, and it is also one of the most efficient in terms of producing high-purity hydrogen. The peculiar characteristic of this technology is that it dissociates vapor instead of liquid water since its operating temperature is between 500 and 850 °C. The membrane is made up of a solid oxide electrolyte (usually yttrium-stabilized zirconia(YSZ) with the addition of Yttrium oxide (Y_2O_3)) [38]; this material owns the O^{2-} conductor. The reactions will be always the oxidation at the anode and the reduction at the cathode as shown in Figure 10 below. But the greatest limit of this electrolyzer is the high operating temperature, which causes many mechanical and chemical issues to the materials. Moreover, it causes long times of start-ups and break-ins [38].

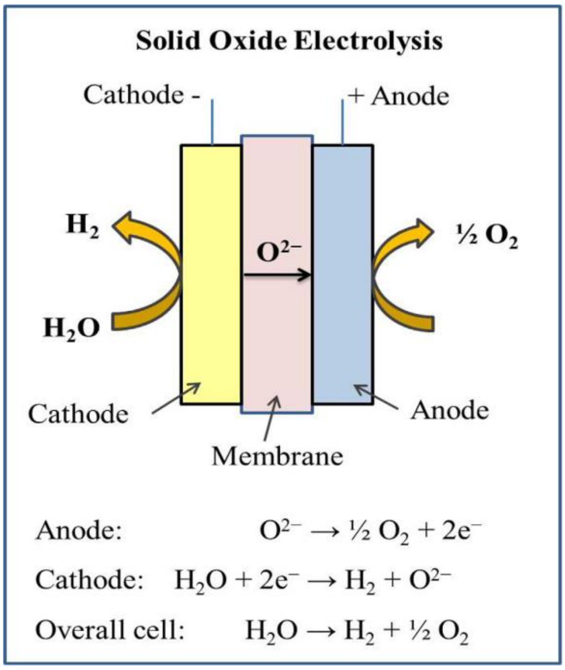

Figure 10 - Solid Oxide Electrolysis [36]

Proton exchange membrane (PEM) water electrolysis

This method employs a solid polymer electrolyte (SPE) that has multiple functions, including carrying protons from the anode to the cathode electrically insulating the electrodes, and separating the anode and cathodes. The most often utilized membrane material is fluoropolymer (PFSA) Nafion, which is widely accessible commercially. This type of electrolyzer was created to overcome the limitations of the alkaline water electrolyzer, so it has high current densities and produces high-pressure hydrogen (up to 20-30 bar) with high purity (it can rech 99.99% of purity [36]); this is why it is an ideal solution for refueling fuel cell vehicles, which require high purity hydrogen to function properly. Furthermore, they have a fast dynamic reaction, allowing them to be powered by renewable sources like sun or wind which have aleatory peaks in energy inputs [39] [36].

The reaction is exactly that described in the "Electrolysis" paragraph, and it involves always oxidation at the anode and reduction at the cathode (Figure 11).

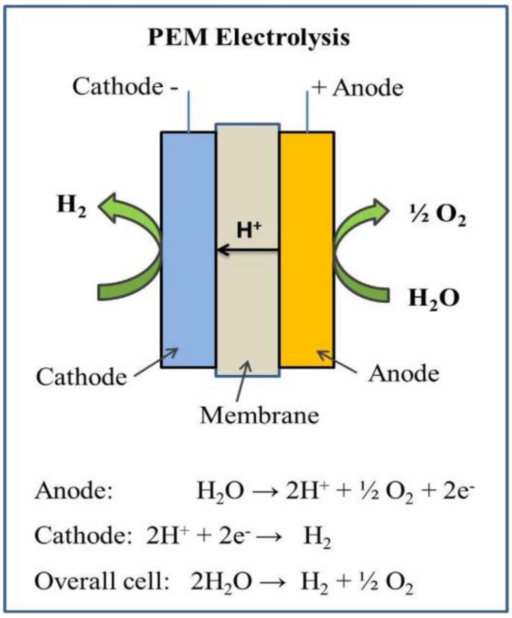

Figure 11 - PEM water electrolysis [40]

2.3 HYDROGEN SUPPLY CHAIN NETWORK (HSCN)

In Figure 12 we can see the overall Hydrogen supply chain network (HSCN), from the feedstock to the refueling station [41]. There are different combinations that we can adopt to produce, stock, and finally deliver Hydrogen to feed refueling stations, but in our case of study, the attention is focused on the production of green Hydrogen. This kind of Hydrogen is produced through renewable energy sources (wind, solar, or hydropower) with zero emissions of greenhouse gases through the electrolysis of water. An interesting analysis to lead is the comparison between on-grid and off-grid systems also considering the CO2 emissions due to the production of electricity coming from the grid. For various reasons described below, the product further narrows the range of our analysis to solely deal with gaseous hydrogen. The Transportation and Distribution parts will be incorporated into a unique system, skipping the terminal part, because the H2 production center is supposed to be located close to or within the analyzed city.

Finally, different kinds of refueling stations will be considered by comparing the existing layouts and the new ones proposed with a techno-economic analysis.

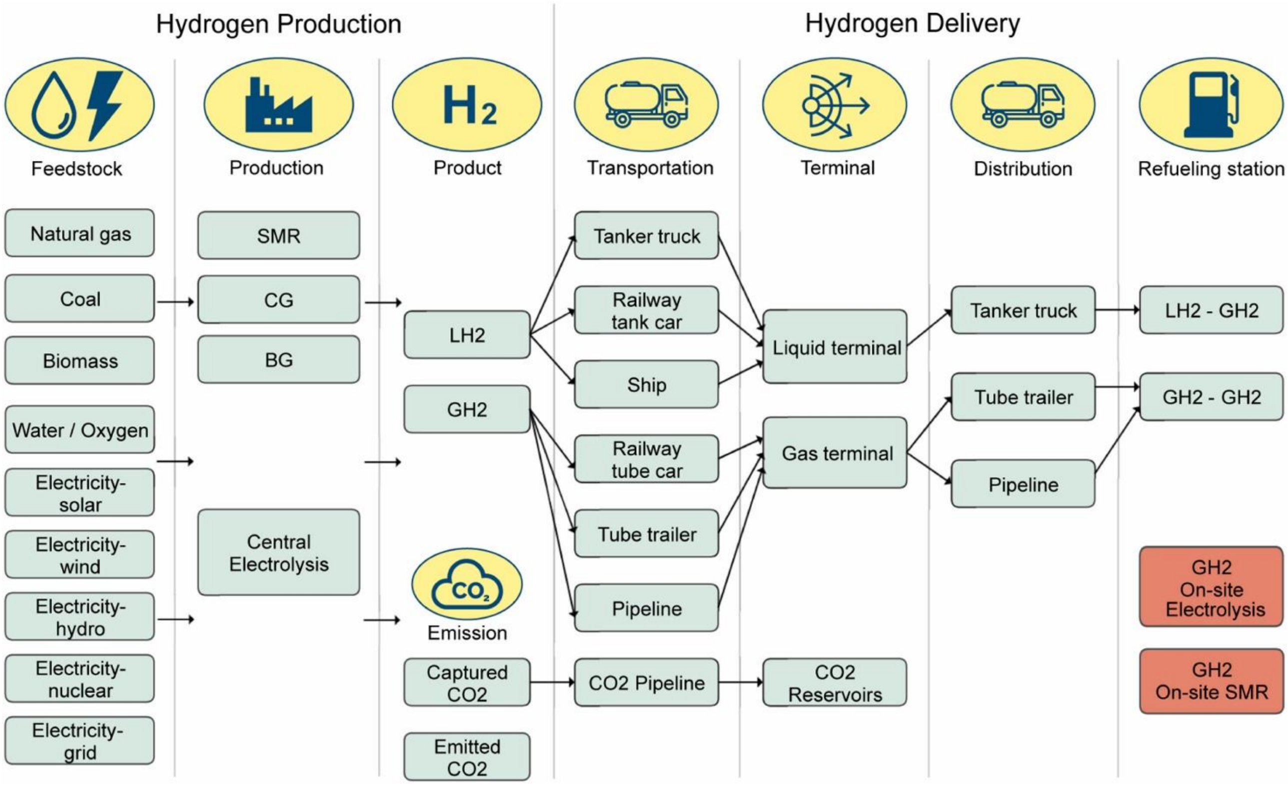

Figure 12-Superstructure of HSCN in the transportation sector. HSCN: Hydrogen supply chain network - SMR: Steam methane reforming - BG: Biomass gasification - CG: Coal gasification - LH2: Liquid Hydrogen - GH2: Gaseous hydrogen [41]

CLASSIFICATIONS OF GREEN HYDROGEN REFUELING SYSTEMS

Classification based on Hydrogen supply chain:

- Off-Site Stations:

Hydrogen is produced in remoted hydrogen generation plants and delivered by trucks or by a hydrogen pipeline network. The layout is simple, and they usually have capacities between 100 kgH2/day to 520 kgH2/day. The cost analysis of this kind of station includes the cost of hydrogen purchased from the hydrogen production plant.

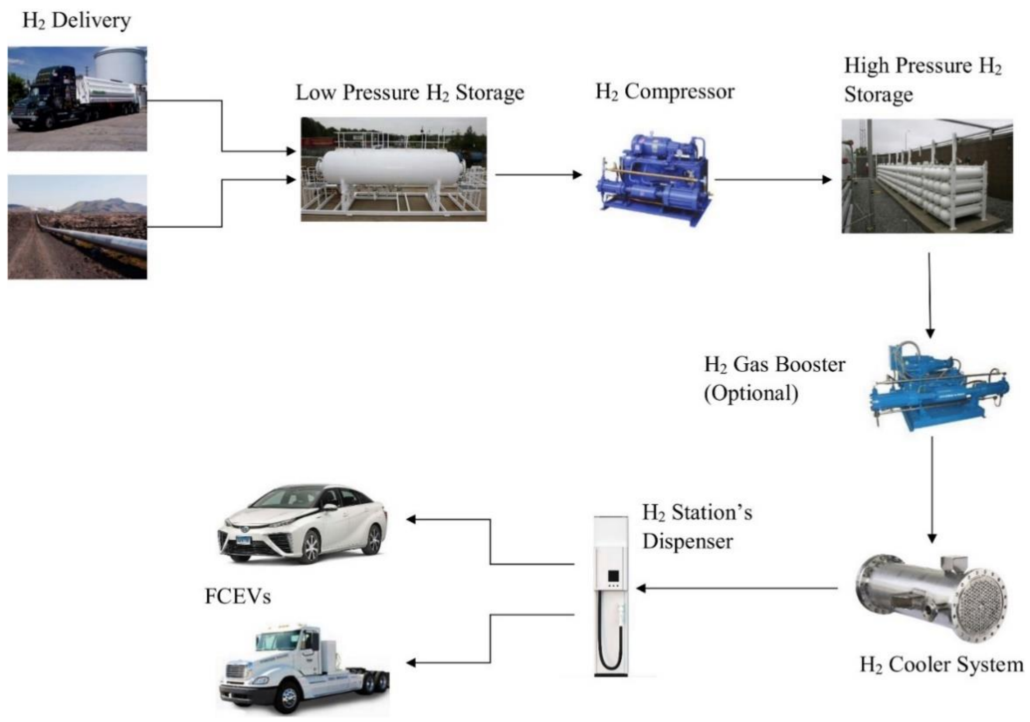

Figure 13 - Off-site H2 production hydrogen gas refueling station's main components [42].

- On-Site Stations:

Hydrogen is produced in situ through an electrolyzer. The presence of the electrolyzer makes the layout more complicated and significantly raises the capital cost, however, hydrogen is auto produced by the station. They also have a lower capacity: between 100 and 400 kgH2/day.

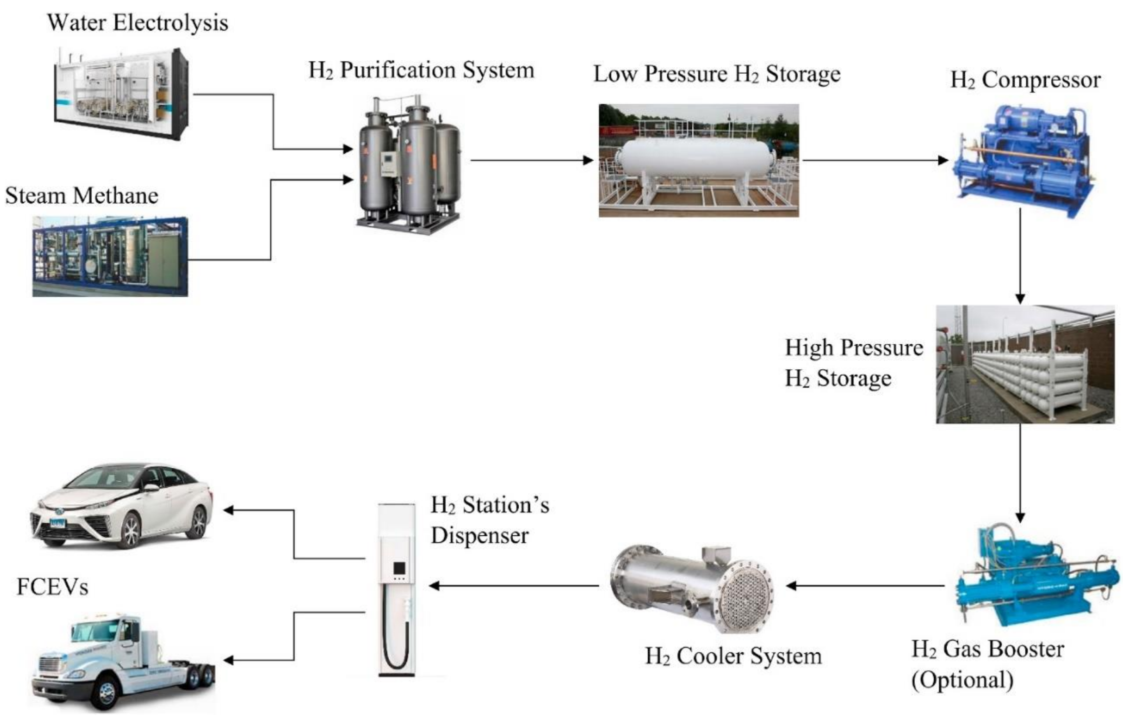

Figure 14 - On-site H2 production hydrogen gas refueling station's main components [42].

Classification based on Hydrogen Thermodynamic Status:

- Gaseous Hydrogen technology.
- Liquid Hydrogen Technology

This classification implies radical changes between the storage methods of HRS, moreover, liquid Hydrogen stations can be only off-site. The great advantage of Liquid H2 over gaseous one is its high storage density, making it suitable for aerospace applications, but the phase transition from gas to liquid hydrogen involves a high energy consumption (40% of its energy content) due to the cryogenic temperature request of -253°C [43].

An energetic evaluation of HRS with liquid and gaseous stored hydrogen was done by Bauer et al. [44]. They analyzed the energy consumption of the main components of the refueling station calculating the specific energy demand and dividing the supply chain network into 3 parts: One associated with the production of Hydrogen, another with transportation, and finally the last associated with refueling. As we can see in Figure 15 below the Liquid Hydrogen refueling station itself is more convenient in terms of specific energy demand In the field of transport and dispensing, but what makes it non-competitive compared to the gaseous technology is the storage and distribution field, since the liquid hydrogen is stored in a cryogenic tank at -253 °C; moreover, it is still a developing technology that is trying to reduce the boil-off losses due to the evaporation of hydrogen.

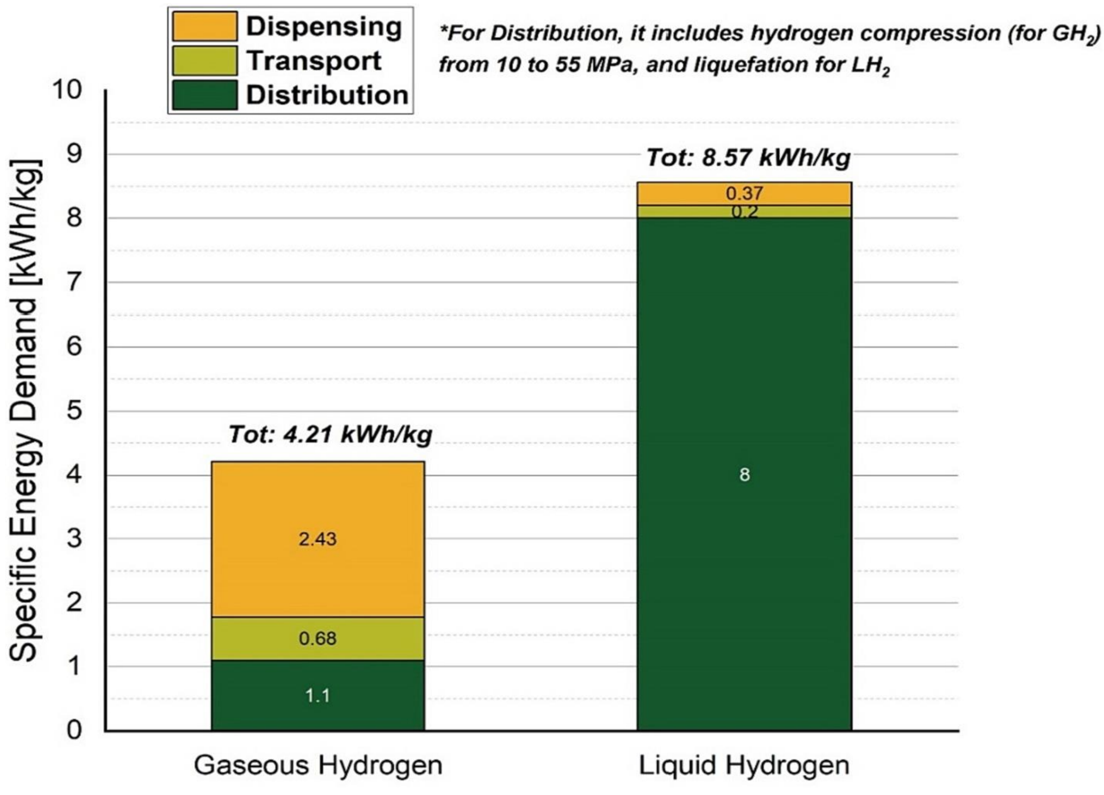

Figure 15-Energy demand for GH2-HRS and for LH2-HRS, from production to dispensing [43]. (Data elaborated from [44])

The result is that the liquid technology in this experiment involves 8.57 kWh/kg against the 4.21 kWh/kg of the gaseous one. So gaseous HRS are widespread due to the lower energy load spent for the storage (we need about 20% of its energy content to compress the gas), however, bigger storage tanks are needed [43].

HYDROGEN REFUELING STATION (HRS)

Regardless of the type of HRS, we can always find the following components:

- Compressor: there are different kinds of compressors such as reciprocating compressors (which is the most used, with a piston used to compress hydrogen) or diaphragm compressors
- Storage tanks (liquid tank, gas tank, or medium-pressure storage)
- Cooling unit
- Safety equipment
- Dispensers

Compressor

Even though the electrolyzer produce high pressure hydrogen, as we said before, these levels of pressures are around 20 or 30 bar, but we need higher pressures to reduce hydrogen’s volume and store it in the vehicle’s tank:

- 350 bar for high duty vehicles
- 700 bar for low duty vehicles

Moreover, to guarantee a fast refueling of the vehicle, usually in 3 or 5 minutes, the pressure must be rise to 150-200 bar more then the pressure values listed before. So, the refueling station requires a compressor linked to the outlet of the electrolyzer which leads hydrogen to high pressure storage tanks. In high efficiency HRSs the compressor is coordinated with the storage system forming a cascade refueling system which allows a lower consume of energy and which we will discuss in the following paragraphs.

Gaseous hydrogen, like every gas, can be compressed in several ways which are more or less efficient due to the physical characteristics of hydrogen. The main four technologies are:

- Reciprocating compressor:
  Is the classic compressor made of a piston sliding into a cylinder. It is used for very high compression ratio.
- Rotary compressor:
  Here hydrogen is compressed by screws, lobes, or gears.
- Ionic compressor:
  This is an upgrade of the reciprocating compressor since it works always with the same principle but with an ionic liquid instead of the piston. They are the most spread compressors in HRSs.
- Centrifugal compressor:
  They use the centrifugal force to compress the gas rotating at high speed. The peculiar characteristic of this technology is the high flow rate that they can process but at the same time, the typical compression ratio is quite low, especially for a low molecular weight gas like hydrogen which needs high speed to reach adequate compression ratios [45].

2.4 GASEOUS HYDROGEN TECHNOLOGY

The most common configurations for HRS with gaseous hydrogen technology are:

- Cascade refueling.
- Direct refueling with the use of a hydrogen compressor.

2.4.1 Cascade refueling

This layout is the simplest one which involves the minimum number of components. The structure is described in Figure 16 below:

The first component is the high-pressure compressor which rise the Hydrogen pressure up to 90-95 Mpa. This high pressure is required for a quick refueling time of roughly 3-5 minutes. It is also possible to reduce at the minimum the use of the compressor if the station is fed by an external tube trailer that transports hydrogen directly at 90-95 MPa pressure, but this increases the cost of transport and emissions. Hydrogen is often trucked at the pressure of 20-50 MPa, so the compressor is needed. Other situations in which the existence of a compressor is necessary are when the HRS is fed by an H2 pipeline (pressure of 2-5 MPa) and when we have an on-site station where hydrogen is produced in situ (pressure of 1-3 MPa) [43].

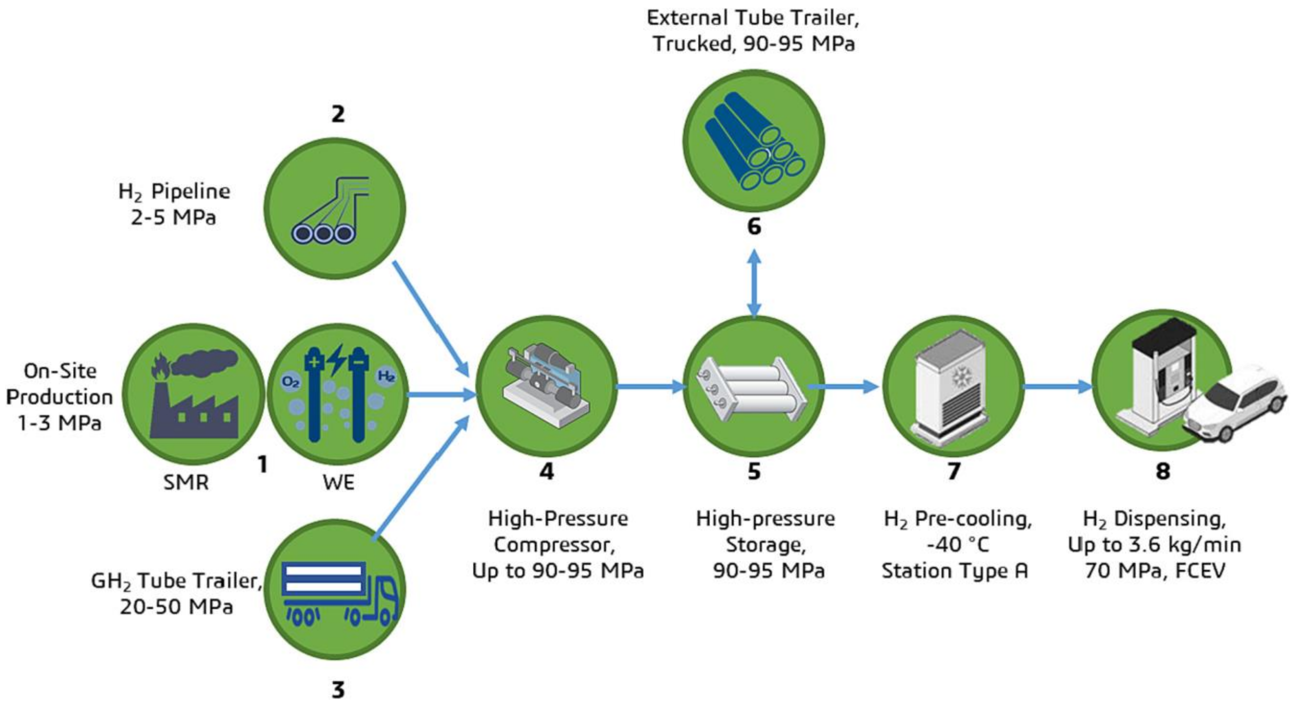

Figure 16 - Gaseous Hydrogen Storage: HRS layout with cascade refueling process [43].

Regarding High-pressure storage, it is usually made up of three high-pressure tanks which work in succession. In Figure 17 below the layout of a classic cascade refueling process is shown:

We have three tanks at high pressure (usually between 90 and 95 MPa) fed by the High-pressure compressor. The compression at that high pressure causes a rise in the Hydrogen's temperature so a heat exchanger is located right after the compressor to lower it. The initial pressure of the vehicle's tank is used to set the average pressure ramp rate (APRR) that avoids excessive pressure. When the reduction valve opens Tank 1 (called low-pressure tank) starts to release hydrogen and we obtain a certain mass flow due to the gap of pressure between the vehicle's tank and Tank 1; at the same time the compressor refills Tank 1. When the pressure in the reduction valve decreases until a value that cannot keep up the APRR, the flow distributor closes Tank 1 and opens Tank 2 (medium-pressure tank) which now is a higher pressure than Tank 1. Finally, the process is repeated with the same logic between Tank 2 and Tank 3 (high-pressure tank), in this way, we ensure a continuous and fast flow with a considerable saving of energy compared to a system with a single tank. [46]

After the reduction valve, we have another heat exchanger called precooling unit. This can be of different types (A, B, C, or D) depending on the temperature at which hydrogen is led (respectively -40°C, -20°C, 0°C, no-precooling). This unit is critical because the vehicle tank, according to specified safety rules, must not exceed 85°C. The A type is the most often used cooling unit, and it can cool gaseous hydrogen to -40°C [43].

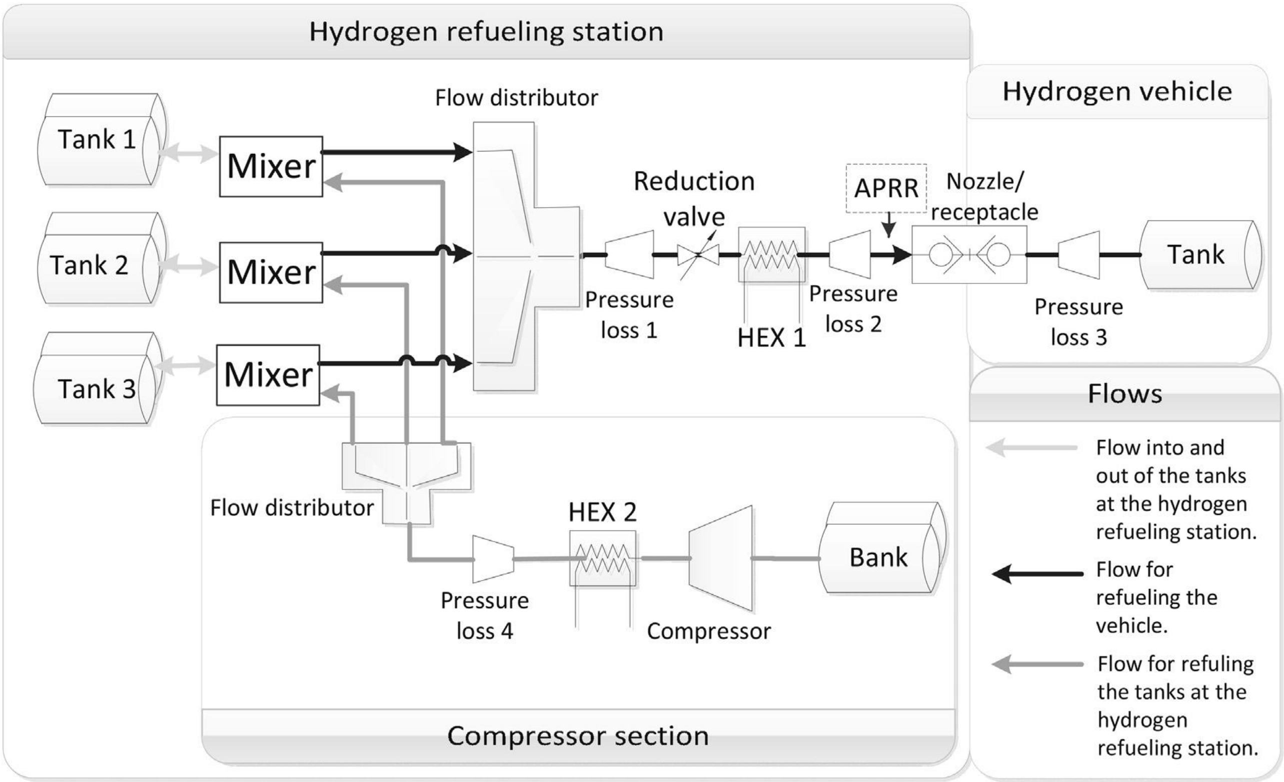

Figure 17 - Sketch of a hydrogen refueling station with three tanks in a cascade setup and a compressor section to refuel the station [46].

Talpacci et Al. [47] investigated the thermodynamic characteristics of a cascade refueling system and presented their findings in the graphs shown in Figure 18 In Graph a) we can notice how the pressure of the vehicle's tank increases following the APRR in an almost linear way, while the pressure inside the tanks follows a discontinuous trend due to the cascade system which implies the opening and closing of the tanks during the refueling process, instead, in graph d) the single pressure of each tank is analyzed. In this specific analysis the 3 tanks are filled to the same pressure, but they usually have different pressures (low, medium, and high) as we can see in the analysis led by Cristina Blazquez-Diaz in Figure 19. Graph b) shows the temperature trend of both storage tanks (which follow the same trend of the pressure) and vehicle tanks, which rise from the ambient temperature to a higher value but stay under 85°C (358 K), and it is guaranteed by the cooling unit with a temperature of -40°C (these values are specified in the standardized protocol from the Society of Automotive Engineers, SAE J2601). So high-pressure Hydrogen increases its temperature when it expands in the vehicle's fuel tank, this is due to the positive Joule Thomson coefficient. Finally graph c) reports the mass flow rate and the cooling demand.

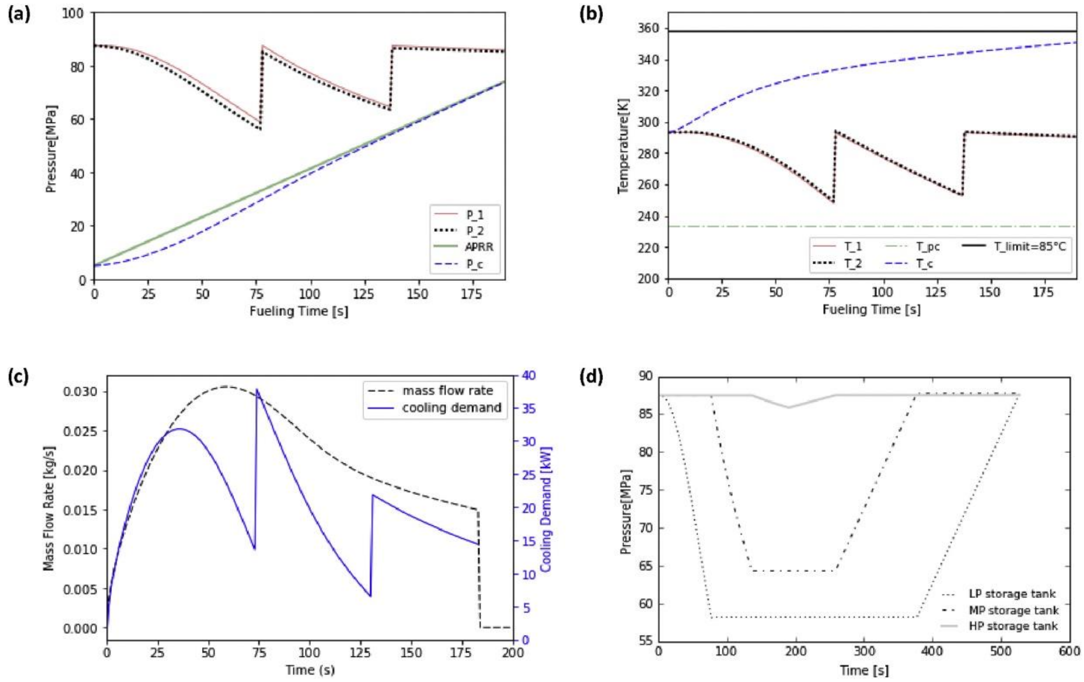

Figure 18 - The thermodynamics of hydrogen refueling station. (a) Pressures calculated in different components of the system pointed out in Figure 17: Pc is the pressure in the vehicle tank, P1 is the pressure in the storage tanks and P2 is the pressure before the reduction valve. (b) Temperatures calculated in different components of the system pointed out in Fig. 1: Tc is the temperature in the vehicle tank, T1 is the temperature in the storage tanks, T2 is the temperature before the reduction valve and Tpc is the pre-cooling temperature (c) Mass flow rate and cooling energy consumption behavior during the fueling time. (d) Pressure behavior in the cascade storage tanks [47].

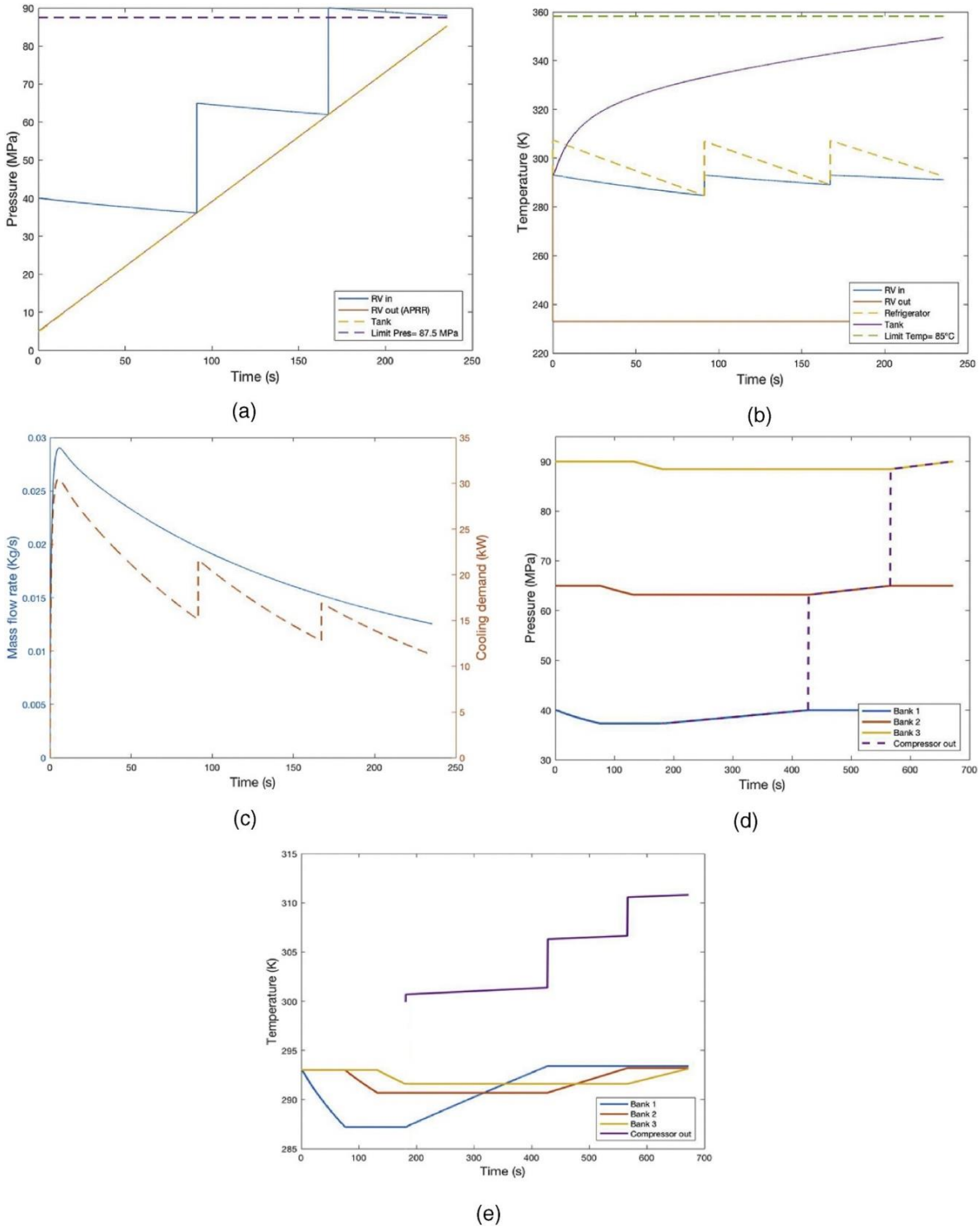

Figure 19 - Evolution of thermodynamic properties in the components shown in Fig. 2. (a) Pressure in the system when refuelling the vehicle (RV is the Reduction Valve). (b) Temperature in the system when refuelling the vehicle. (c) Mass flow and cooling demand when refuelling the vehicle. (d) Pressure inside the banks in the cascade system and compressor (Bank 1 = Low-pressure, Bank 2 = Medium-pressure, Bank 3 = High-pressure). (e) Temperature inside the banks in the cascade system and compressor (Bank 1 = Low-pressure, Bank 2 = Medium-pressure, Bank 3 = High-pressure) [48].

2.4.2 Direct refueling with the use of a hydrogen compressor

The other configuration of HRS is the one seen in Figure 20. This system includes the addition of a storage compressor which rises the pressure to 40-50 MPa and stores Hydrogen at this medium pressure, then it is sent to a booster compressor where pressure is increased up to 90-95 MPa. This system also required high-pressure buffer tanks to store hydrogen, send it to the cooling unit, and finally to the dispenser.

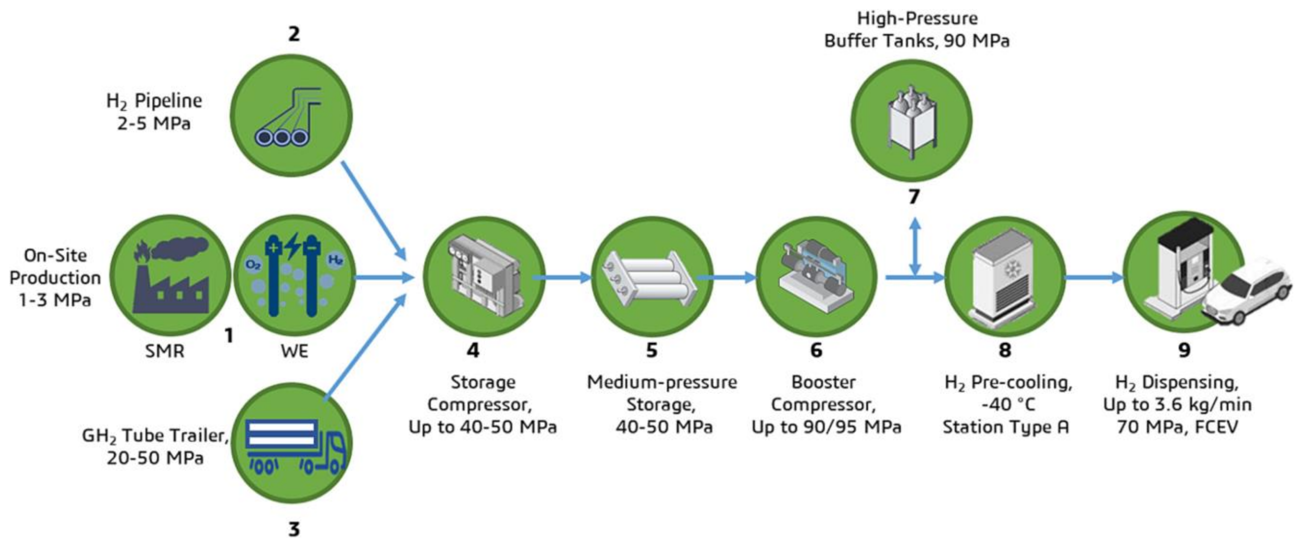

Figure 20 - Gaseous hydrogen storage: HRS layout with a booster dispensing compressor [43].

One of the major issues with this arrangement is that the interaction of the compressor and the mass flow regulator’s operation causes unusual vibrations between the dispenser and the final nozzle and this impact with the components’ life.

Making a comparison between the two systems, the cascade layout is cheaper both in term of operational cost (the levelized cost of hydrogen is lower) and capital cost (due to its simplicity). But the direct refueling system becomes more interesting when we need more flexibility in the station: it can be used both for a 350 bar or 750 bar HRS [43].

3 Concept design and models

In this chapter the overall methodology of the thesis is explained dividing the process in 3 levels, describing all the layouts with their design process, and identifying all the scenarios.

In Figure 21 the overall methodology is shown.

- On the first level we have the first choices and hypothesis such as the location choice. This is the first step because it identifies the natural resources available to power our station. Then the hydrogen load is assumed following a normal gasoline station demand, and once having the hydrogen load, we can find the electric load consumed by the compressor and the chiller.
- On the second level we start to consider all the component parameters and costs, to insert these data in the software HOMER and obtain the capacity and total cost of the components.
- On the third level we extract the data from HOMER to find the cost of the missing components like the compressor and the chiller, and to consider the land and water system cost.

Finally, the results are obtained so they are analyzed in energy and economic terms.

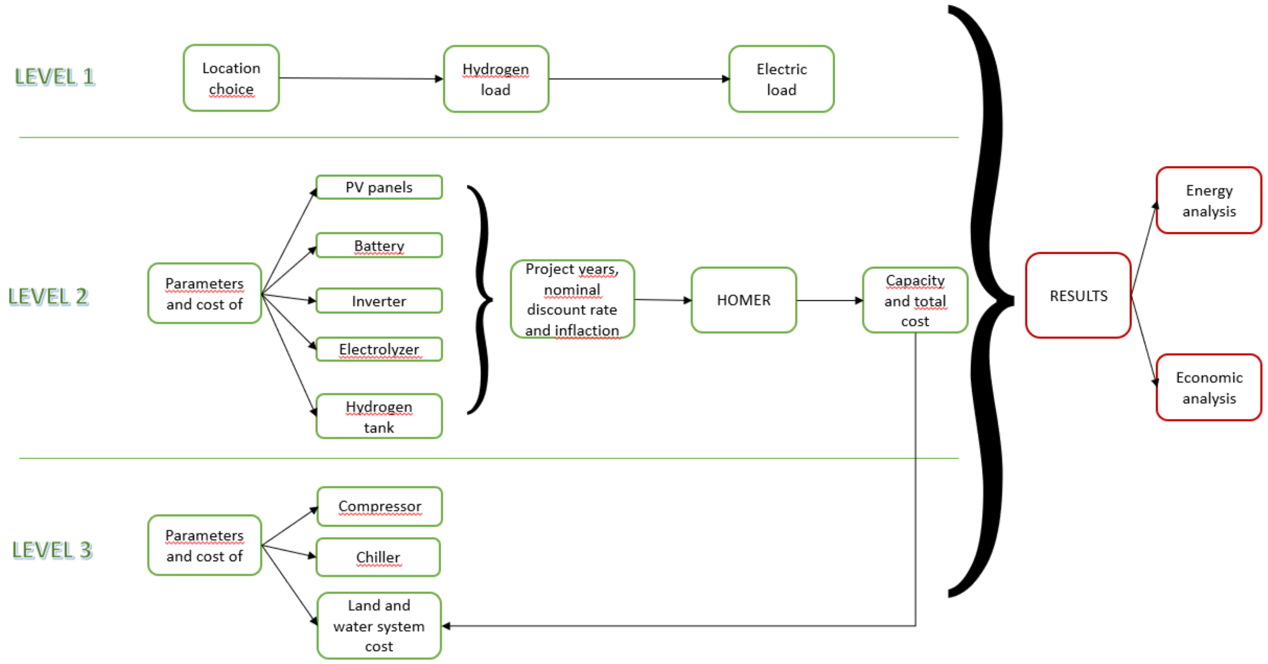

Figure 21 - Overall methodology

3.1 Proposed layouts

The layouts proposed are three:

1) On site, on-grid station with PV panels [49] [50] [51] [52].
2) On site, off-grid station with PV panels and lithium-ion battery [53] [50]
3) Hybrid, On-site, off-grid station with PV panels and fuel cell [54] [50]

<u>On site, on grid station with PV panels.</u>

In this layout the electrolyzer is powered by the PV panels, but we have a back-up system linked with the grid. It functions when PV panels are inoperative, such as on cloudy days or at night when we require electricity for producing hydrogen. However, the generation of power from the grid, specifically carbon and sulphur dioxide, and nitrogen oxides, implies an output of emissions. The largest portion of emissions is made up of CO2. The best feature of this system is its total autonomy because grid electricity is always available; but, despite this benefit, we made every effort to minimize the amount of grid power used to run the station in order to reduce emissions. By using large hydrogen storage tanks, we can generate a lot of hydrogen when the sun is out, store it, and use it when it is needed, reducing the need for the power grid.

As we can see in Figure 22 hydrogen is stored in low pressure storage tanks ready to be compressed, chilled and dispensed in the HRS.

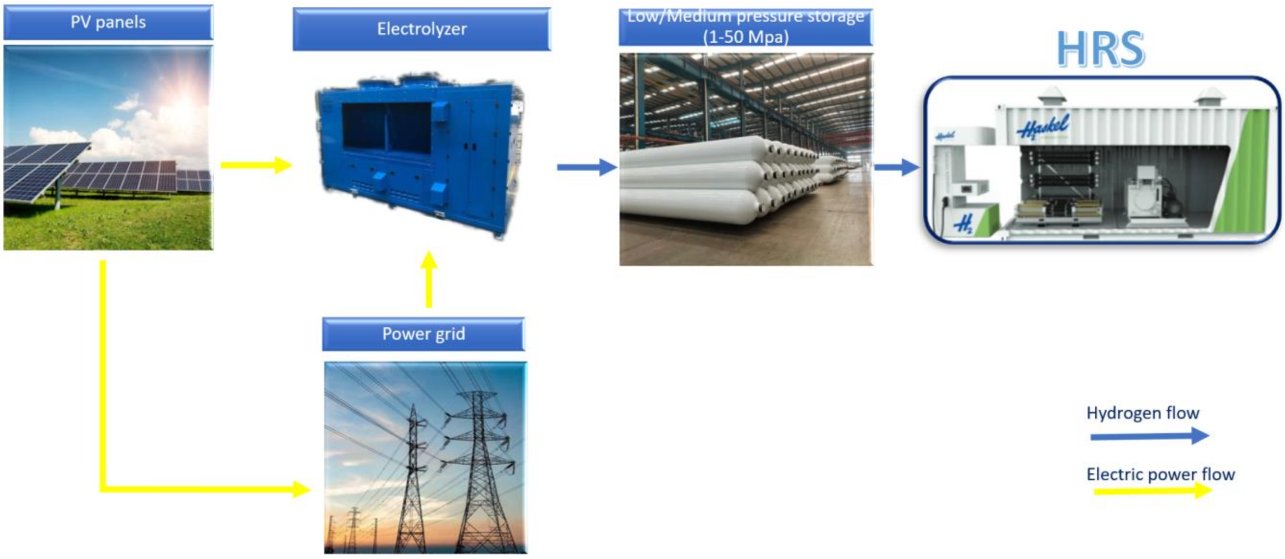

Figure 22 - On site, on-grid station with PV panels.

On site, off-grid station with PV panels and lithium-ion battery.

This arrangement was thought to make the station independent from the grid, so to have a zero-emission system where electricity can be stored in a lithium-ion battery and used during the hours when the PV system is inactive. However, in this case the system is less flexible than the previous one because it always depends on the electricity coming from the PV panels. Moreover, it must be considered that the cost of the battery and the possibility to have an unmet electric load during the year.

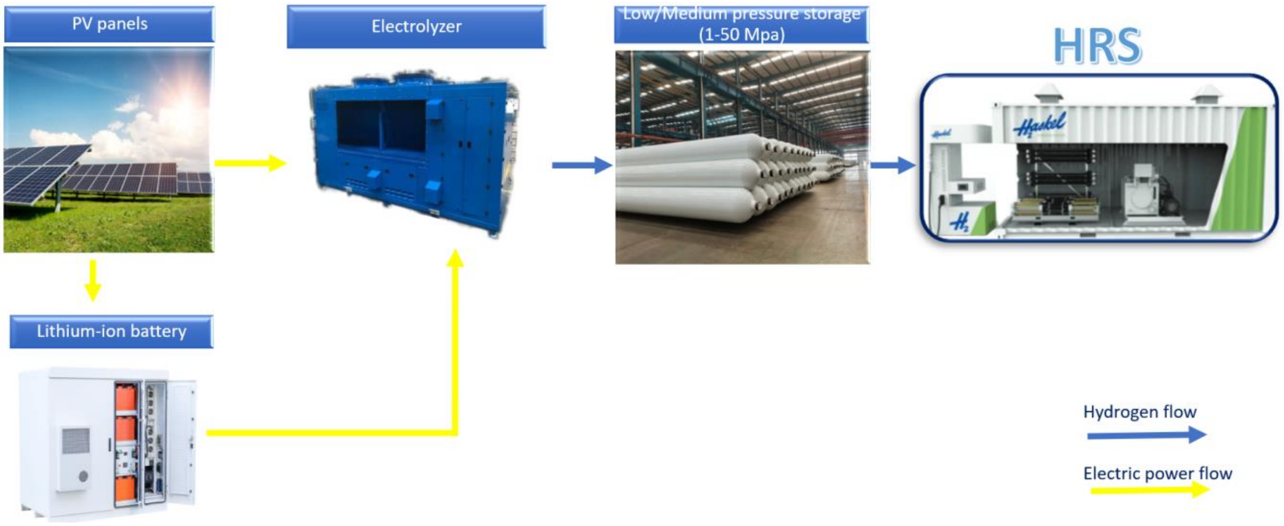

Figure 23 - On site, off-grid station with PV panels and lithium-ion battery.

Hybrid, On-site, off-grid station with PV panels and fuel cell.

The last design is the most innovative: a hybrid station where we have both hydrogen dispenser for fuel cells and electric charging stations for electric vehicles.

The main energy source is always the PV system, which power both the electrolyzer to produce hydrogen and the electric charging station, but in this case, energy is stored in form of hydrogen and transformed in electricity that can be used to feed the electric refueling station. Hydrogen produced from the electrolyzer is always stored in low pressure storage tanks and then it is distributed between the HRS and the fuel cell. Obviously, the hydrogen distributed to the fuel cell is only a small percentage compared to that requested from the HRS.

But for this third layout the hydrogen demand was slightly modified since we also introduce the demand of the electric vehicles.

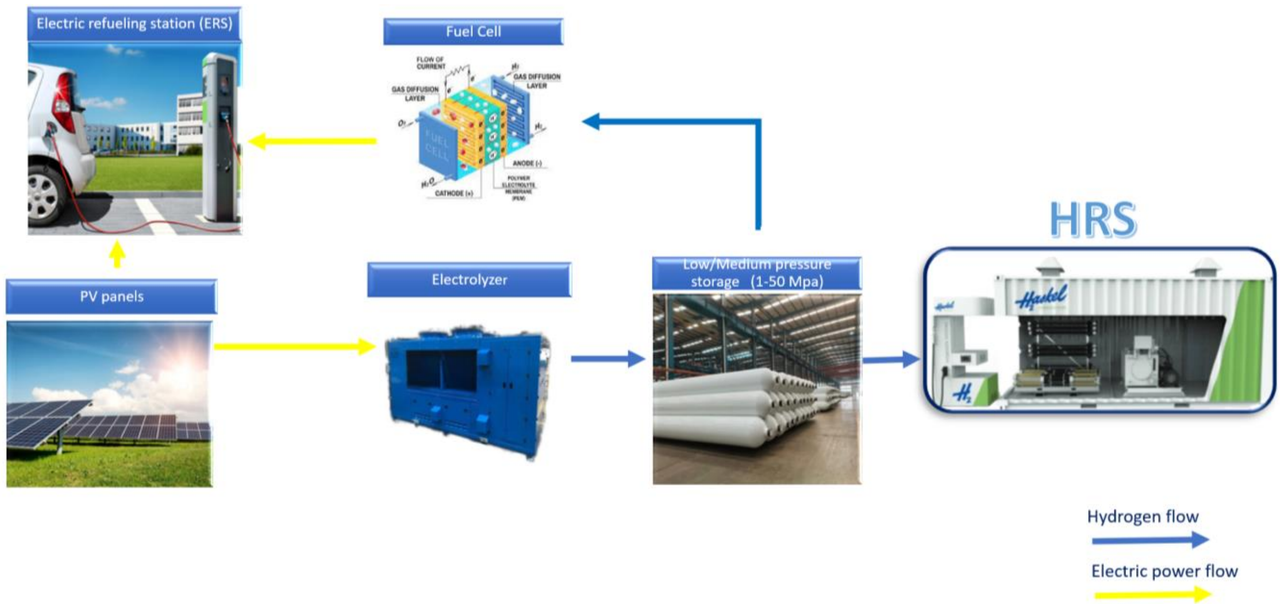

Figure 24 - Hybrid, On-site, off-grid station with PV panels and fuel cell.

3.2 Layouts design

The methodology used to design each layout is always the same. It starts with the choice of the hydrogen load and so the electric load to satisfy the hydrogen load. Then we proceed with the sizing of each components through the software Homer, which once insert the cost per unit of each component, it works making a sort of iteration: if the hydrogen and electricity produced are lower than the required quantities it will go back to the sizing step, otherwise if they are higher than the required quantities the software proceed with the calculation of the economic indexes like the Net Present Cost, The Levelized Cost of Hydrogen and the Levelized Cost of Energy.

The only difference that we can notice in the three layouts is in the last one where we have also to consider the ERS demand.

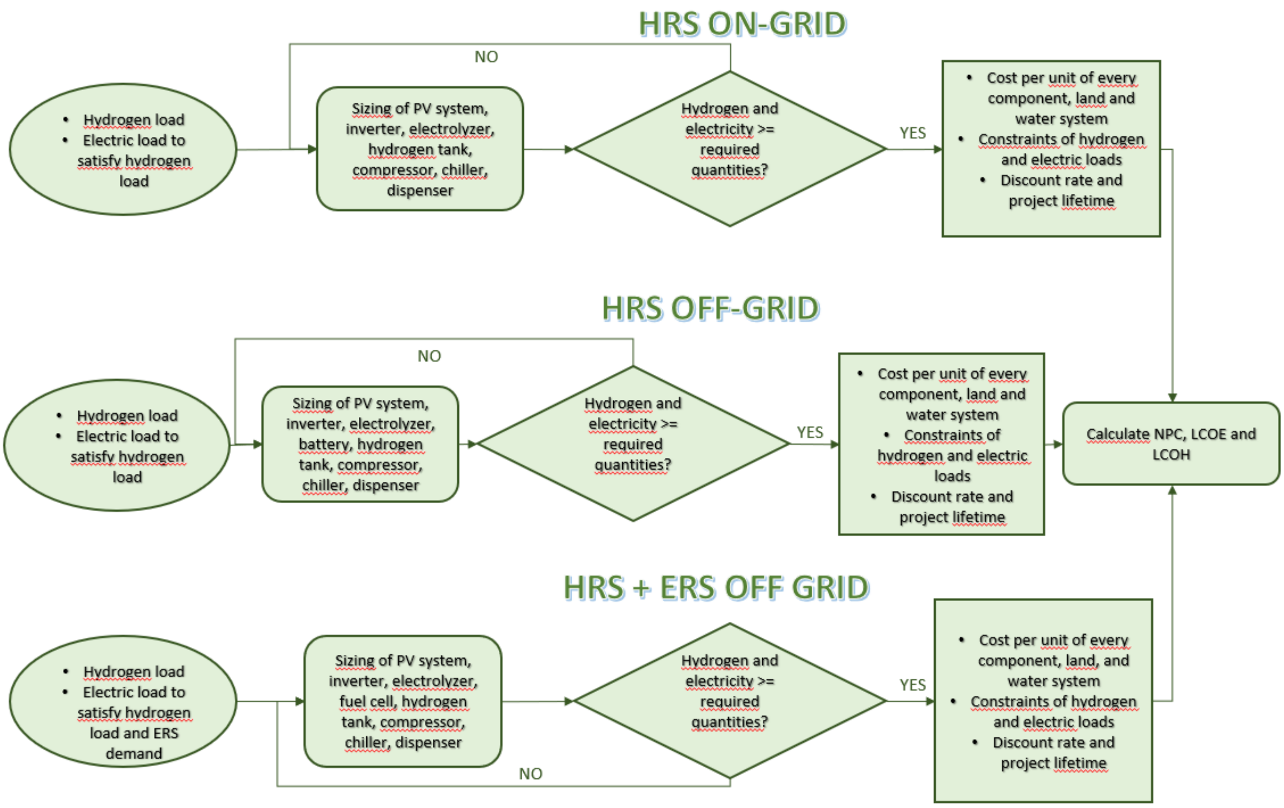

Figure 25 - Layouts design.

3.3 Homer PRO

HOMER PRO optimizes micro-grid designs across all industries to minimize the Net Present Cost (NPC) of the investment and to calculate important economic indexes, such as the Levelized Cost of Energy (LCOE) and the Levelized Cost of Hydrogen (LCOH).

As shown in Figure 26 the software HOMER receive some inputs, such as the project's location, the hydrogen load, Electric load (represented by the compressor and chiller electric work), the components with all parameters and costs and finally the economic parameters like the interest rate, inflation rate, the time life project and the system constrains. Given these inputs, the software returns as outputs all the energy and economic data.

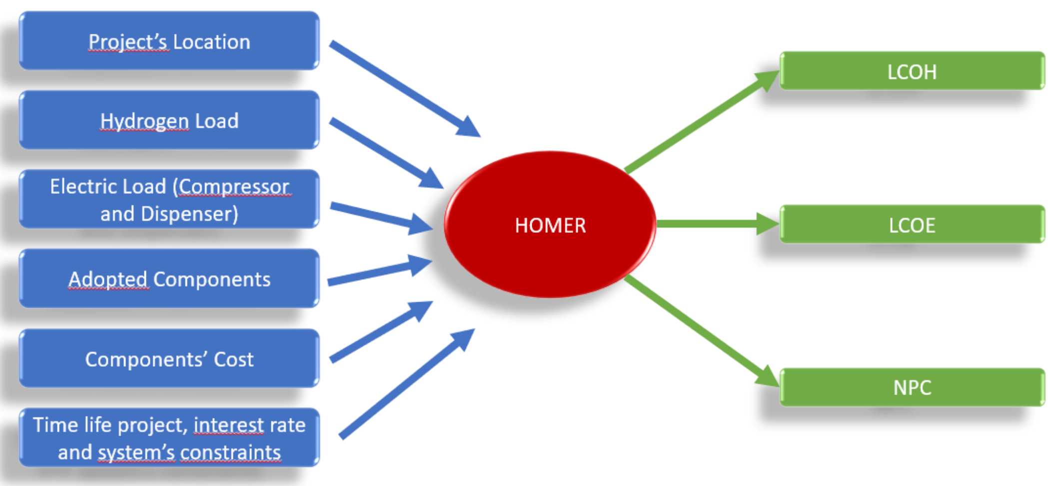

Figure 26 - Homer Pro methodology.

4 Detailed design

4.1 Locations

Turin, in the Piemonte region and Palermo, in Sicily, have been chosen as project locations. The selection of these two cities was not made casually, as the first lies in the far north of Italy and the second in the far south. We will compare these two locations for each plan evaluated to emphasize the importance of renewable energy depending on the longitude site selected.

Since on-site stations are being investigated, as shown in Figure 14, large areas are required, particularly for the component linked to hydrogen production. Furthermore, the project's primary purpose is to reduce, or better yet, eliminate greenhouse gas emissions, thus the hydrogen produced will be green hydrogen derived from renewable sources, which, as we all know, necessitates the occupation of vast areas. This is why they were placed near highways, which, in addition to having more available space, are also extensively traveled. However, the location was chosen to be close to the city so that residents could reach the station in a few minutes by car.

4.1.1 Turin

The location in Turin was chosen in the motorway junction Torino-Caselle, between the city and the Airport Torino Caselle. The chosen land is that shown in Figure 27.

Figure 27 - Site chosen for the Hydrogen refueling station. Torino-Caselle, 45°08'16"N 7°41'29"E.

It has a perimeter of 1213.7 m and an area of 82663.48 m^2.

In Table 3 below the traffic data taken by the National Autonomous Company of State Roads (ANAS) [55] are reported.

Table 3 - Traffic data per year RA10, Torino-Caselle.

Location	Road	Km	City	Year	Light vehicles	Heavy vehicles
2275	RA10	5057	Borgaro Torinese	2021	36283	1092
				2022	41083	1087

<u>Natural resources:</u>

The main natural resource of interest for the analysis is the solar global horizontal irradiance (GHI). We can see its monthly average value in Figure 28 below.

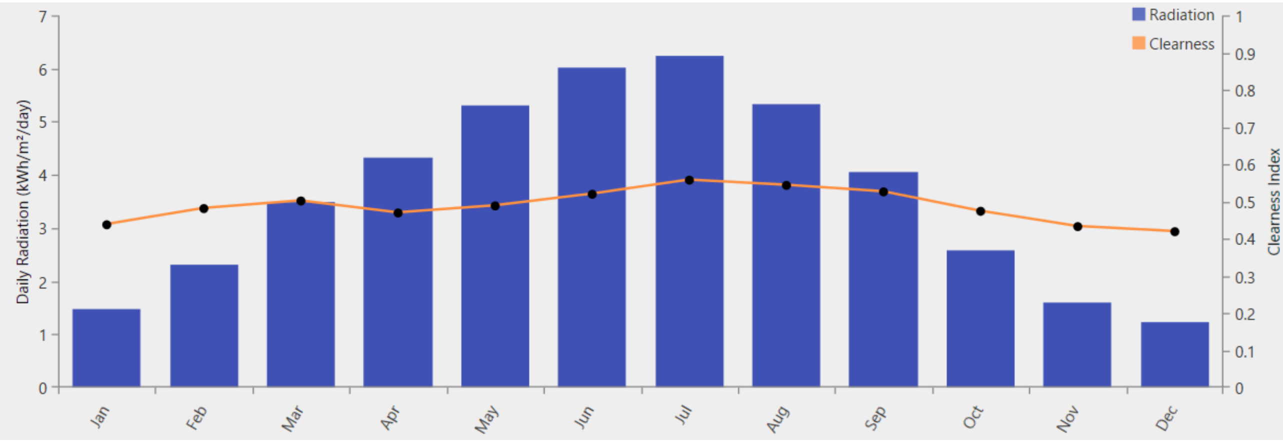

Figure 28 - Monthly average solar global horizontal irradiance (GHI) in Turin. Graph taken from Homer.

Also the daily average temperature of the site is reported below.

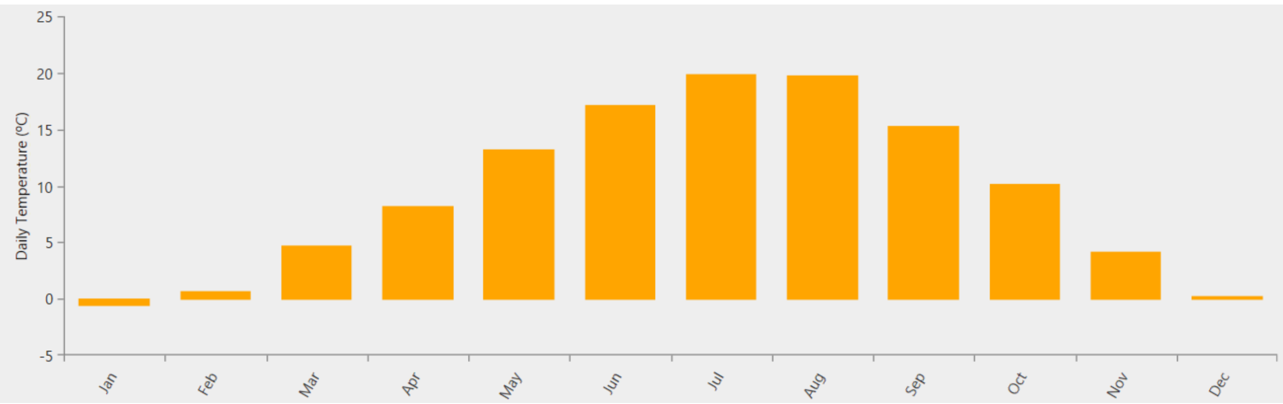

Figure 29 - Monthly average temperature in Turin. Graph taken by Homer.

The annual average of each resource is shown in Table 4.

Table 4 - Annual average resources values, Turin.

	global solar irradiance [kWh/m^2/day]	temperature [°C]
Annual average	3.66	9.49

These values will be crucial for the project because they are the guide values that will determine the size of each component and therefore also its economic value. The greater the values of irradiance, we will need smaller systems and therefore with lower costs.

4.1.2 Palermo

The location in Palermo was chosen along the highway A29, in a land belonging to the territory of Capaci, between the city of Palermo and the International airport Falcone e Borsellino.

Figure 30 - Site chosen for the Hydrogen refueling station. Palermo-Capaci, 38°10'42" N 13°13'41" E.

Area: 24.493,58 m²

Perimeter: 633,24 m

Coordinates: 38°10'42" N 13°13'41" E

Table 5 - Traffic data per year A29, Palermo,Capaci.

Location	Road	Km	City	Year	Light vehicles	Heavy vehicles
19080	A29	21537	Cinisi	2021	24917	1030
				2022	27466	1039

<u>Natural resources</u>

It is instantly apparent that Palermo experiences higher daily radiation levels than Turin. In contrast to Turin's 6 kWh/m2/day, here it reaches a maximum of 8 kWh/m2/day throughout the summer. This has a significant impact on the system's energy efficiency because it demonstrates that the same amount of hydrogen may be produced at a cheaper cost and with fewer component sizes.

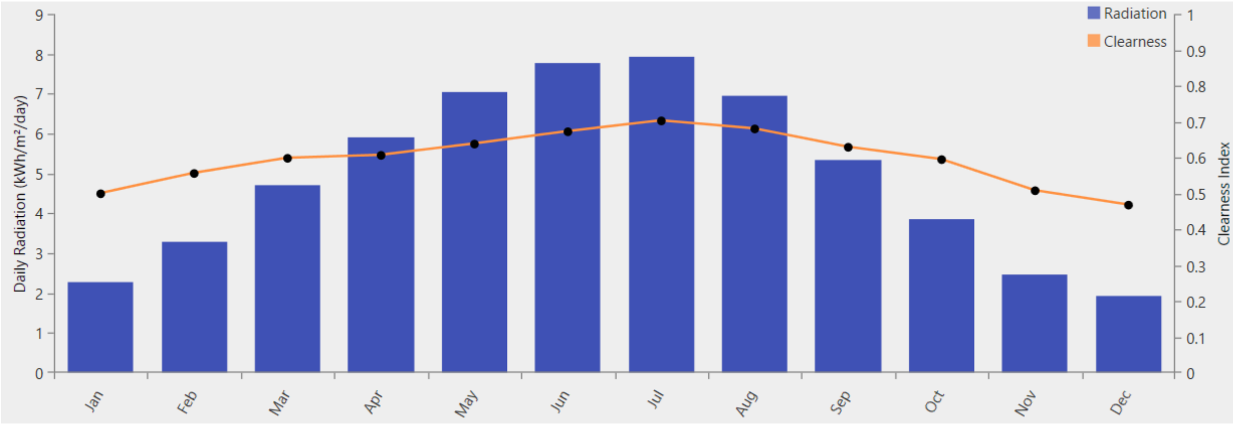

Figure 31 - Monthly average solar global horizontal irradiance (GHI) in Palermo. Graph taken from Homer.

Also the monthly average temperature in Palermo is higher than in Turin, but it is a drawback for the generation of power from the PV panels. Indeed, in monocrystalline PV cells the rise in temperature causes the decrease of both the current and the voltage, so an overall decrease of power. A slighter decrease of power is shown in polycrystalline and amorphous PV cells where an increase of the temperature causes an increase in current, but a sharp decrease of voltage, so the final effect is always a decrease in power [56].

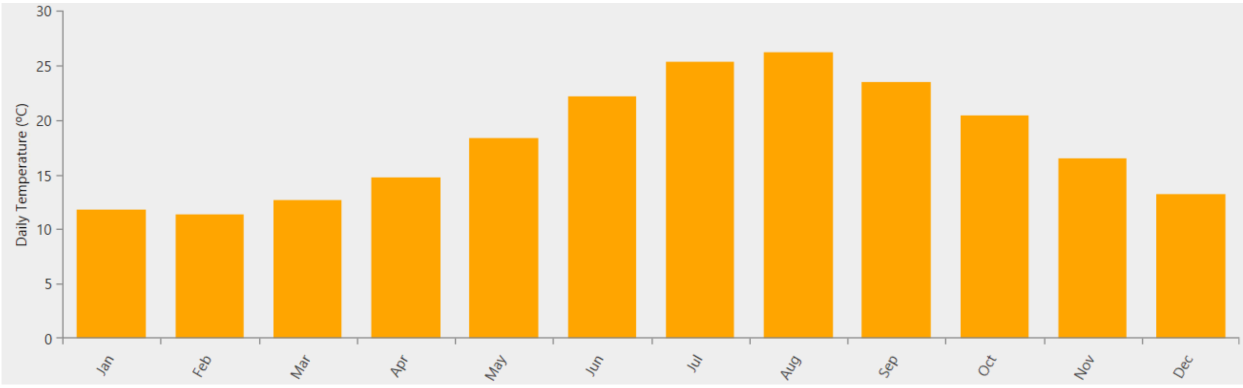

Figure 32 - Monthly average temperature in Palermo. Graph taken by Homer.

Although we have a simultaneous increase of the solar radiation and of the temperature, the prevailing phenomenon that affects the increase in power generated by the PV cells is always the increase of the solar irradiance, so we will se an higher efficiency for the station located in Palermo.

The annual average of each resource is shown in.

Table 6 - Annual average resources values, Palermo.

	global solar irradiance [kWh/m^2/day]	temperature [°C]
Annual average	4.95	18

4.2 Scenario 1: On grid HRS, PV panels, Electrolyzer in Turin.

The first scenario is the On-grid HRS with the PV panels and the electrolyzer. In Figure 33 we can see the scheme of the first scenario with all the components.

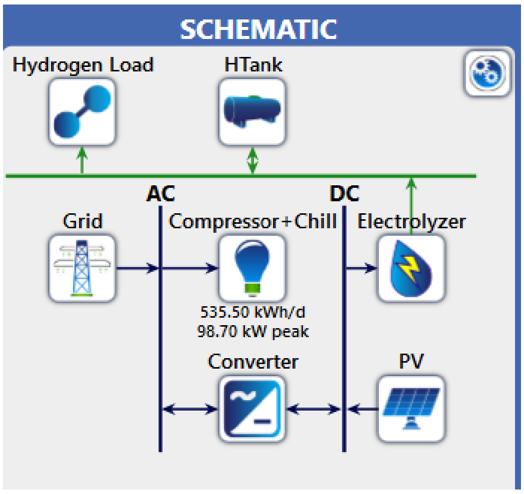

Figure 33 - Design of 1st layout. On grid, PV, Electrolyzer

4.2.1 Hydrogen load

The HRS Capacity is the first factor to be determined, thus the first query is: How many cars per day do we want to refuel? In this way, we can figure out how much hydrogen the HRS needs everyday.

In our analysis, we consider the design of a medium-capacity HRS with an average of 30 vehicles/day refueled (some HRSs can refuel up to 60 vehicles per day [57]). A fuel cell vehicle tank has an average capacity of 5kg of Hydrogen, so the requested amount of Hydrogen will be:

$$Daily\ Hydrogen\ Capacity = 30\,\frac{vehicles}{day} * 5\ kg = 150\,\frac{kg}{day} \qquad Eq.\ 1$$

Moreover, the software Homer ask to define a daily profile of the hydrogen load and it was defined following the demand of a standard gasoline or diesel refueling station. In Figure 34 we can notice a peak during the day, while the demand is almost zero during the night hours. As we can see, this trend will prove to be an advantage for the electric load which mirrors the hydrogen one. Indeed, having a more concentrated demand during the day means that the electrolyzer and the other components work during the sunny hours, so we don't need to purchase electric energy by the grid.

Homer also gives the possibility to modify some constrains like the unmet hydrogen load; in this analysis it has been set to 0% in order to satisfy the entire demand.

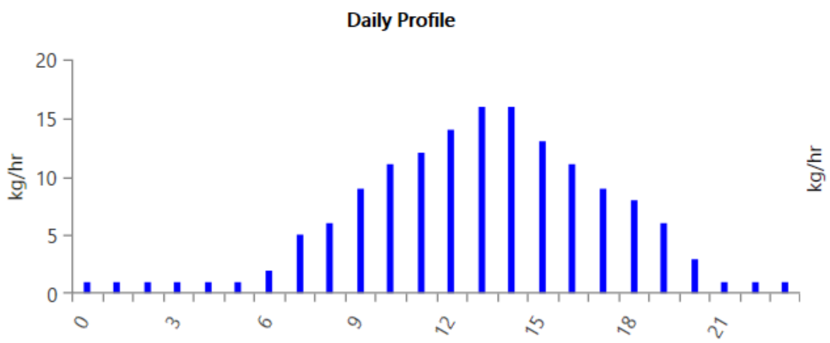

Figure 34 - Hydrogen daily profile. Graph taken by Homer.

The hydrogen production will be satisfied thanks to the electrolyzer; it works with the energy coming from the renewable sources which are highly variable, so the operation of the electrolyzer will also be quite intermittent. A PEM electrolyzer was chosen for its ability to function at high current densities. This feature is crucial when the system is connected to renewable energy sources such as solar or wind because they are highly dynamic, so unexpected rises in energy input may occur and the energy might be uncaptured [39].

4.2.2 Electric load

As was said in the previous paragraph, the electric load is proportional to the hydrogen load, and now we will examine the reasoning behind this fact using the formulas that were used to calculate it. The answers to a series of questions are provided to determine the single consumption of each component in order to calculate the electric load.

- The Electrolyzer does not count in the electric load because it is seen by HOMER as a component, so the electric consumption of it will be provided after the simulation. Once insert the hydrogen load in the software, it will return the electric energy needed to power the electrolyzer. We will see all the energy results in the paragraph 5.1.1.
- How much energy needs an H2 purification system?
  A purification system is not needed because modern PEM electrolyzer can reach 99.99% of hydrogen's purity we talked about this aspect in paragraph 2.2.
- How much energy a booster compressor needs to rise hydrogen pressure from that coming out to the medium-pressure storage tanks to that one into the high-pressure storage tanks?
  We can calculate the power needed to compress hydrogen in a compressor from 20 bar to 900 bar through the first law of thermodynamics for open systems with an isentropic transformation:

$$W_{compress} = c_p \frac{T_{IN}}{\eta_c}\left[\left(\frac{p_{OUT}}{p_{IN}}\right)^{\frac{k-1}{k}} - 1\right] m_c \qquad \textit{Eq. 2}$$

  Where:
  - c_p : specific heat of Hydrogen at constant pressure [14.304 kJ/ (kg K)].
  - T_{IN} : compressor inlet temperature [293 K].
  - η_c : efficiency of the compressor [70 %].
  - p_{OUT} : compressor outlet pressure. [900 bar]
  - p_{IN} : compressor inlet pressure. [20 bar]
  - k : isentropic exponent of hydrogen. [1.4]
  - m_c: flow rate through the compressor.

  To calculate the flow rate through the compressor we used the daily hydrogen load profile supposed before, converting the kg/h in kg/s, in this way, we can calculate the power required by the compressor hour per hour.

- How much energy does a cooling unit need to cool hydrogen from the temperature of the high-pressure storage tanks to -40°C?
  The heat withdrawn to chill hydrogen from the ambient temperature to -40 °C will be given from the first law of thermodynamics for ideal gas (hydrogen loosely approximates the behaviour of an ideal gas):

$$Q_{chiller} = m_c c_p (T_{in} - T_{out}) \qquad \textit{Eq. 3}$$

  Where:
  - c_p : specific heat of Hydrogen at constant pressure [14.304 kJ/ (kg K)].

- T_{IN} : chiller inlet temperature [308 K].
- T_{OUT} : chiller outlet temperature [233 K].
- m_c: flow rate through the chiller.

The flow rate through the chiller is the same as the compressor, so in the same way, we can obtain the power needed per hour.

Through the inverted formula of the definition of the coefficient of performance (COP), the electric power needed to power the chiller is found. Typical values of the COP for this kind of heat exchanger are between 0.8 – 1, in this analysis we assume a unit value [58].

$$W_{chiller} = \frac{Q_{chiller}}{COP} \qquad \text{Eq. 4}$$

- Electric load of Dispenser negligible.

The total electric load profile will be found by adding the two electric powers of the compressor and chiller.

All calculations are reported in below.

Table 7 - Electric load calculation.

Hour	Hydrogen Load [kg/hr]	Hydrogen flow rate [kg/s]	Wcompress [kW]	Qcooler [kW]	Wcooler [kW]	Total electric load [kW]
0	1	0.000277778	3.271692751	0.298	0.298	3.57
1	1	0.000277778	3.271692751	0.298	0.298	3.57
2	1	0.000277778	3.271692751	0.298	0.298	3.57
3	1	0.000277778	3.271692751	0.298	0.298	3.57
4	1	0.000277778	3.271692751	0.298	0.298	3.57
5	1	0.000277778	3.271692751	0.298	0.298	3.57
6	2	0.000555556	6.543385503	0.596	0.596	7.14
7	5	0.001388889	16.35846376	1.49	1.49	17.85
8	6	0.001666667	19.63015651	1.788	1.788	21.42
9	9	0.0025	29.44523476	2.682	2.682	32.13
10	11	0.003055556	35.98862027	3.278	3.278	39.27
11	12	0.003333333	39.26031302	3.576	3.576	42.84
12	14	0.003888889	45.80369852	4.172	4.172	49.98
13	16	0.004444444	52.34708402	4.768	4.768	57.12
14	16	0.004444444	52.34708402	4.768	4.768	57.12
15	13	0.003611111	42.53200577	3.874	3.874	46.41
16	11	0.003055556	35.98862027	3.278	3.278	39.27
17	9	0.0025	29.44523476	2.682	2.682	32.13
18	8	0.002222222	26.17354201	2.384	2.384	28.56
19	6	0.001666667	19.63015651	1.788	1.788	21.42
20	3	0.000833333	9.815078254	0.894	0.894	10.71
21	1	0.000277778	3.271692751	0.298	0.298	3.57
22	1	0.000277778	3.271692751	0.298	0.298	3.57
23	1	0.000277778	3.271692751	0.298	0.298	3.57
SUM	150	0.041666667	490.7539127	44.7	44.7	535.4539127

To prove the consistency of the results obtained, in Reference [59] was carried an analysis on the energy consumption derived by the compression of hydrogen. The results show how to compress hydrogen from 20 to 880 bar they need an energy consumption of 3.0 kWh/kgH2, so making a fast calculation with our data, multiplying this value for 150 kg/day of hydrogen requested by our HRS we obtain 450 kWh/day, which is similar to the 490 kWh/day obtain with our calculations.

Moreover, the same confirmation can be done with the chiller 's consumption, where in Reference [59] and [58] they obtained respectively a consumption of 0.2-0.3 kWh/kg and 0.3-0.4 kWh/kg, so, considering the same 150 kg/day of hydrogen processed, and dividing the electric consumption of 44.7 kWh/day by the kilogram of hydrogen, the specific consumption is 0.298 kWh/kgH2, which fall in the middle of the ranges seen.

4.2.3 Other components

Once calculated the total electric load (including the electrolyzer consumption which will be calculated by the software), the other components must be defined with their technical features and costs.

PV panels:

The PV panel chosen for the simulation is a generic flat plate PV with a lifetime of 25 years, which coincides with that of the entire project so we will not consider a replacement cost for this item. A derating factor of 80% is also considered. The derating factor is a reduction factor for the PV array power output that takes in consideration the real operating conditions of the panels compared with the nominal ones; indeed, many external factors can negatively affect the performance of the PV system like the dirt or high temperature. The PV system is linked to the DC bus, this is one of the reasons why is needed an inverter to convert electricity from DC to AC at which the electric load is served.

To run the simulation the HOMER Optimizer was used. This tool will automatically find the right size of the PV system through thousands of iterations.

Grid:

On-grid and off-grid systems are compared, so the possibility to use the grid during the night or during hours when there is no sun is also considered. This choice could be convenient in terms of costs, but not in environmental terms because in this case will also be taken into account the emissions derived from the production of electricity of the grid. Therefore, the analysis is also focused on reducing as much as possible the use of grid electricity.

Homer also calculates the emissions coming from the grid; in particular it considers three types of emissions, specifying the quantity in g per kWh of energy withdrawn from the grid. For every kWh of energy, the emissions will be: 632 g of Carbon Dioxide (CO_2), 2.74 g of Sulfur Dioxide and 1.34 of Nitrogen Oxides (g\kWh).

Converters:

The converters play a crucial role in converting electricity from AC to DC and vice versa. An inverter is required to convert the electricity from DC to AC because the electric load is in AC while the PV panels produce electricity in DC. Additionally, the electrolyzer operates in DC, thus if it is to be powered by the grid, the AC current must be converted to DC using a rectifier. The converters are designed with a 15-year lifetime and a 95% efficiency for the inverter and rectifier. The HOMER Optimizer is still used to select the converter's size.

Electrolyzer:

The electrolyzer selected has an efficiency of 85% (today reached by modern electrolyzers [39]). This time, the capacity optimization is set manually by assuming various electrolyzer sizes. At the end of the simulation, via various iterations, the software will provide the ideal electrolyzer size. The lifetime is set to 15 years.

Hydrogen tank:

The use of a unique hydrogen tank in Homer come from a simplification, since the real storage system usually used for HRS is the Cascade refueling system, which is composed of 3 tanks of different pressures linked with the compressor system (this kind of system is widely discussed in paragraph 2.4.1).

The parameters set for the hydrogen tank are a lifetime of 25 years and an initial tank level of 50%, useful to start the simulation without a small percentage of unmet load. Moreover, in this case the HOMER Optimizer tool is not available, so a series of possible sizes were supposed for the tank and the system will choose the correct size after several iterations.

4.2.4 Components cost and economic parameters.

Another input required by HOMER is the cost per unit of each component. Through this information the software can combine all components and iterate thousands of times until it finds the configuration with the lowest Net present cost.

However, Homer has several limits, it is used as a mean to size every component and obtain the best combination of them, but to have a complete analysis with the actual values of the performance indicators further information and inputs are needed. The first limit of the software is that it does not consider every cost item, especially that linked with the dispensing part. In Table 8 below the cost per unit of each component is indicated. The first five components were inserted in the software, but the compressor, the chiller and the dispensers were not included in the analysis, because, they are considered as an electric load, so the sizing of these components will be done later in paragraph 4.2.6. Moreover, other two cost of item that are not considered are the cost of the land (which is a considerable part of the capital cost) and the cost of the water system needed to feed the electrolyzer. These two will be calculated after the components sizing.

As it is shown in Table 8, the cost per unit of each component is divided in three cost items: The Capital Cost, The replacement cost and finally the operational and Maintenance cost.

- The Capital Cost (or Capital Expenditure, CAPEX) refers to the expenses incurred for acquiring, constructing, or upgrading physical assets or long-term investments. It represents the initial investment or outlay required to establish or expand the project. CAPEX includes costs related to purchasing land, buildings, machinery, equipment, technology infrastructure, and other fixed assets. These costs are typically incurred upfront and are considered as long-term investments with an expected useful life.
- Replacement Cost represents the cost incurred to replace existing assets or infrastructure to their original condition. It is the expense associated with replacing worn-out or obsolete equipment, machinery, or facilities. It is incurred when existing assets reach the end of their useful life or become inefficient or non-compliant with regulations.
- The Operational and Maintenance Costs (or Operational Expenditure, OPEX) refers to the ongoing costs incurred to operate and maintain the day-to-day activities and assets of a company or project. These costs are recurring and are necessary for the functioning, upkeep, and sustainability of the business.

Proper management of these three costs is essential for effective financial planning, budgeting, and decision-making within an organization.

Table 8 - Cost per unit of the components

	Cost per-unit							
Components	**Capital cost**	**[unit]**	**Replacement cost**	**[unit]**	**Yearly O & M costs**	**[unit]**	**Lifetime [years]**	**source**
PV panels	800	€/kWp	0	€/kWp	10	€/kWp	25	[60]
Inverters	500	€/kW	500	€/kW	1	€/kW	15	[50]
Batteries	450	€/kW	400	€/kW	10	€/kW	10	[61]
Electrolyzer	1000	€/kW	500	€/kW	20	€/kW	15	[62]
Hydogen tank	100	€/kg	0	€/kg	1	€/kg	25	[50]
Ionic Compressor IC90	10800	€/kW	0	€/kW	17.27	€/kW	25	[51]
Chiller	5374	€/kW	5374	€/kW	161.22	€/kW	15	[52]
Dispenser	65000	€/unit	65000	€/unit	156	€/unit	15	[51]

The replacement cost is set to zero when the lifetime of the component is equal to the lifetime of the project.

An important cost not shown in the table is the cost of the grid and any remuneration deriving from the sale of electricity. From Reference [63] the price of electricity purchased by the grid in Italy is 0.112 €/kWh, while the sellback price of electricity coming from PV panel is 0.08 €/kW (The prices are updated to June 2023).

The last input data before starting the simulation are the economic data, they are the project lifetime, which is set to 25 years, the nominal discount rate (or interest rate) and the infltaction rate, with which we will calculate the real discount rate.

- The Nominal discount rate is a financial concept that represents the rate at which future cash flows are discounted to their present value. It is also referred to as the nominal cost of capital or the nominal interest rate. The term "nominal" implies that the discount rate is expressed in current, or nominal, currency units without adjusting for inflation [64]. For this kind of investment, a nominal interest rate of 8% was considered [62].
- The expected inflation rate represents the anticipated increase in prices over time. In Italy it has undergone significant changes in the last 2 years (see Table 34 in appendix). The reason of this suddenly increase is due to the rise of the cost of energy especially after the conflict between Russia and Ukraine since Italy strongly depend on imported energy. As it is shown in Table 34 we reach a peak of 9.1% this year, but the future forecasts say that this percentage will return to normal values in 2024 thanks to governments supports measure to low the energy prices [65]. Given these fluctuating results, an average of the inflation rates over the previous ten years was adopted; the result of the calculation is 2.19%, but in a positive light, 2% was utilized for the simulation.
- Having the nominal interest rate and the inflaction rate the real interest rate can be calculated. It represents the compensation required for deferring consumption or investment in the present in favor of future benefits. It accounts for factors such as the opportunity cost of capital and the risk associated with the investment. The value is calculated through the following equation:

$$i = \frac{i' - f}{1 + f} = 5.88\% \qquad \textit{Eq. 5}$$

Where:

- i is the real discount rate.
- i' is the nominal discount rate.
- f is the inflaction rate.

4.2.5 First Simulation Results and components sizing

The first simulation was run inserting the cost per unit seen in Table 8. As shown in Table 9 Homer gives the capacity of each component, so multiplying this by the cost per unit the total cost of the component is easily gettable.

Table 9 - Capacity and total cost of the components of Scenario 1. HOMER results.

	Total cost					
Components	**Capital cost [€]**	**Replacement cost [€]**	**O&M cost [€/year]**	**Lifetime**	**Capacity**	**[unit]**
PV panels	2735200	0	34190	25 years	3419	kWp
Inverters	223500	223500	447	15 years	447	kWp
Electrolyzer	1300000	650000	26000	15 years	1300	kW
Hydogen tank	220000	0	2200	25 years	2200	kg

4.2.6 Sizing of compressor and chiller

Regarding the sizing of the compressor and of the chiller, they have been done through the electric load calculated in paragraph 4.2.2. The compressor and chiller power were extracted from Table 7 reported in Table 10 below.

Table 10 - Compressor and cooler power

Hour	Wcompress [kW]	Wcooler [kW]
0	3.271692751	0.298
1	3.271692751	0.298
2	3.271692751	0.298
3	3.271692751	0.298
4	3.271692751	0.298
5	3.271692751	0.298
6	6.543385503	0.596
7	16.35846376	1.49
8	19.63015651	1.788
9	29.44523476	2.682
10	35.98862027	3.278
11	39.26031302	3.576
12	45.80369852	4.172
13	52.34708402	4.768
14	52.34708402	4.768
15	42.53200577	3.874
16	35.98862027	3.278
17	29.44523476	2.682
18	26.17354201	2.384
19	19.63015651	1.788
20	9.815078254	0.894
21	3.271692751	0.298
22	3.271692751	0.298
23	3.271692751	0.298
PEAK POWER [Kw]	52.34708402	4.768
SECURITY COEFFICIENT [-]	1.1	1.1
INCREASED WITH SECURITY COEFF [Kw]	57.58179243	5.2448
CHOSEN POWER [Kw]	60	5.5

the peak power of each component has been identified; the latter has been increased by a safety factor supposed equal to 1.1, so approximating by excess and comparing with the powers available in the catalogues, a power of 60 kW was obtained for the compressor, while 5.5 kW for the heat exchanger.

4.2.7 Land and water system cost

<u>Water system cost</u>

To determine the water system cost the first thing to identify is the water needed for the production of 1 kg of hydrogen for a PEM electrolyzer, which commonly is 9 l/kgH2 [66]; hence for 150 kg/day of hydrogen the water needed daily will be 1350 l/day. The price established by the Italian company ABC consist of two rates [51]:

- The fixed annual cost equal to 18.12 €/year
- The variable cost equal to 1.006 €/m^3 of water consumed.

Finally, the total annual cost for the water system will be 513.83€.

The Table 3 below schematize the calculation just descripted.

Table 11 - Water system cost.

PRICE OF WATER	
WATER SPECIFIC COMSUMPTION [l/kg]	9
WATER YEARLY CONSUMPTION [l/day]	492750
WATER YEARLY CONSUMPTION [m^3/day]	492.75
VARIABLE COST OF WATER [€/m^3]	1.006
FIXED ANNUAL COST [€/year]	18.12
TOTAL VARIABLE COST PER YEAR [€/year]	495.7065
TOTAL COST OF WATER SYSTEM [€/year]	513.8265

Land cost

To determine the land cost, first we must determine the m^2 of land needed to fit the entire project. The first thing is identifying the critical component in term of space. This is the PV panel plant, which area can be found having the peak power of the plant and the efficiency of the single PV panel. The efficiency of a solar panel can be calculated with the following formula:

$$\eta_{PV} = \frac{P_{PV}}{I_{STC} * A_{PV}} \qquad \text{Eq. 6}$$

Where:

- η_{PV} is the efficiency of the PV panel.
- P_{PV} is the peak power of the solar plant found through HOMER equal to 3419 kW
- I_{STC} is the solar density irradiance in standard condition equal to 1 kW/m^2.
- A_{PV} is the area of the solar panel.

The type of panel chosen is a generic flat plate. The modern PV panels have an efficiency ranging from 15 to 20%, hence an average of 17% was chosen [67]. if higher efficiency are required, the concentrator PV modules which can reach an efficiency of 36%, but they are used only for big solar plantfor its high cost [68].

So, putting these values with the inverse formula we can find the area occupied by the solar plant.

$$A_{PV} = \frac{P_{PV}}{I_{STC} * \eta_{PV}} = 20112\ m^2$$

Then we have to add the space required for the dispensing part, plus the electrolyzer cabin. The footprint of the entire refueling station can reach an extension of 100 m^2 [69].

Taking in consideration the building of a rest stop and other possible infrastructure this value will be increased up to 21000 m^2.

The cost of a buildable land in that area has an average value of 60 €/m^2 [70], so the total cost of the land that will be added to the Capital cost of the investment will be:

$$Land\ cost = 21000\ m^2 * 60\ \frac{€}{m^2} = 1260000\ €$$

4.3 Scenario 2: Off grid HRS, PV panels, Electrolyzer, accumulation with lithium-ion battery, Turin.

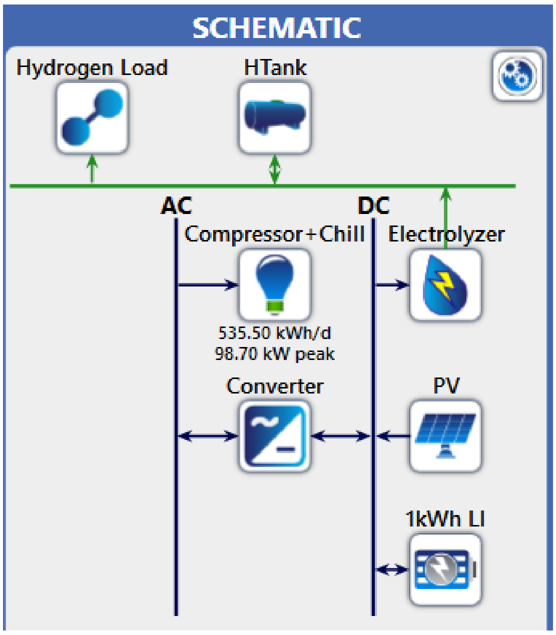

Figure 35 - Off grid HRS, PV panels, Electrolyzer, accumulation with lithium-ion battery, Turin.

The hydrogen and electric load will be the same of the first scenario. Same thing will be with the components. The only change made to the system is the add of a battery to store electricity and then use it during cloudy hours or during the night, while the grid will be removed. In this case we have a 100% free emission system. The battery specifications are made below.

Battery:

It is also considered the possibility to include a storage system through batteries, in this way excess electricity can be stored and used when energy is needed during the night or cloudy days. The main features of the battery are a nominal capacity of 1kWh, a nominal voltage of 6 V, efficiency of 90%, Maximum Charge current of 167 A and Maximum Discharge current of 500 A. The initial state of charge was set to 100% while the minimum one to 20%. The lifetime chosen for the battery is 15 years.

Regarding the cost per unit, it is reported in the table below.

Table 12 - Cost per unit of the battery.

	Cost per-unit							
Components	**Capital cost**	**[unit]**	**Replacement cost**	**[unit]**	**Yearly O & M costs**	**[unit]**	**Lifetime [years]**	**source**
Batteries	450	€/kW	400	€/kW	10	€/kW	10	[61]

In this case we don't consider the cost of the grid, or a possible profit come from the sold of electricity to the grid, because here we are considering an off-grid system.

Also the economic data are all the same.

4.3.1 First Simulation Results and components sizing

In Table 13 are reported the results of the software simulation in terms of capacity and total costs.

Table 13 - Capacity and total cost of the components of Scenario 2. HOMER results.

	Total cost					
Components	**Capital cost [€]**	**Replacement cost [€]**	**O&M cost [€/year]**	**Lifetime**	**Capacity**	**[unit]**
PV panels	2735200	0	34190	25 years	3419	kWp
Inverters	223500	223500	447	15 years	447	kWp
Electrolyzer	1300000	650000	26000	15 years	1300	kW
Hydogen tank	220000	0	2200	25 years	2200	kg
Battery	94050	83600	2090	10 years	209	kWh

It can be notice that the size of all components is all the same, but we have a battery system of 209 kWh.

The size of the compressor and of the chiller, the water system cost and the land cost are unchanged from scenario 1.

4.4 Scenario 3: Off grid HRS, PV panels, Electrolyzer, accumulation with fuel cell, Turin.

For the third scenario it has been done several changes due to the addition of an electric refueling station (ERS) and the fuel cell, which will also include a thermal load and the presence of a boiler.

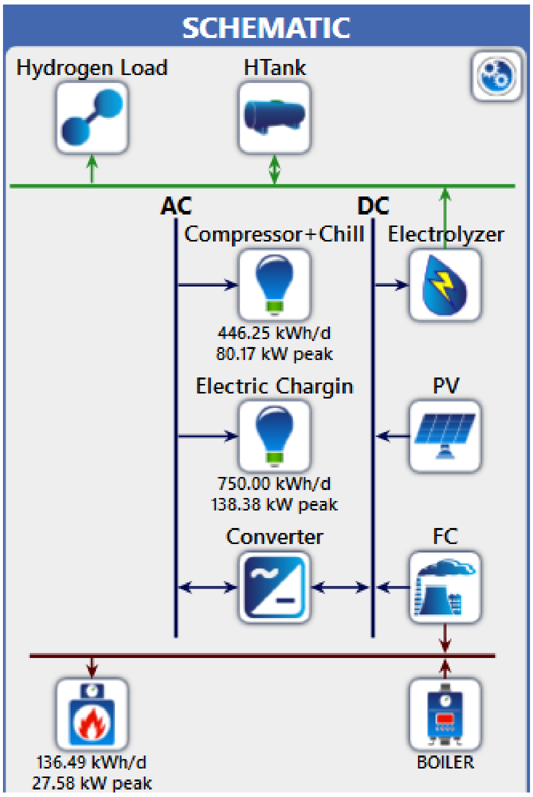

Figure 36 - Off grid HRS, PV panels, Electrolyzer, accumulation with fuel cell, Turin.

4.4.1 Hydrogen load

The hydrogen demand was modified for this layout where we consider 25 vehicles per day, so the daily hydrogen capacity has a decrease:

$$Daily\ Hydrogen\ Capacity = 25\frac{vehicles}{day} * 5\ kg = 125\frac{kg}{day} \qquad Eq.\ 7$$

So now the daily profile is that show in Figure 37.

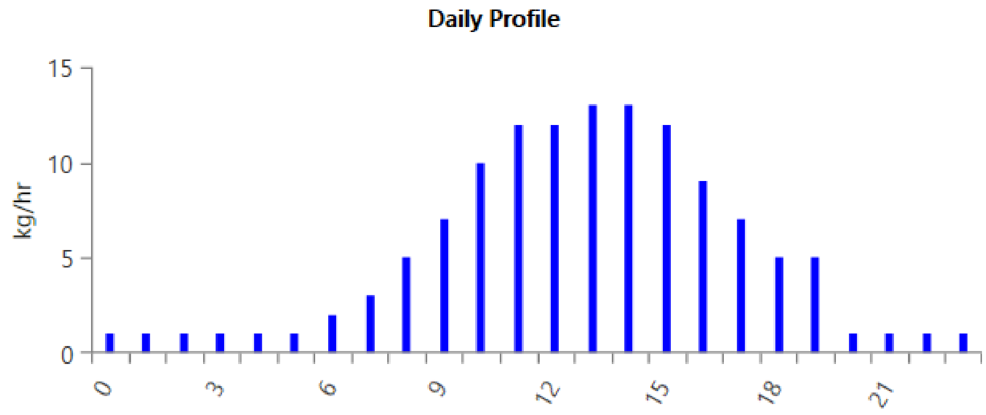

Figure 37 - Hydrogen daily profile. Graph taken by Homer.

4.4.2 Electric load

The procedure to calculate the compressor and chiller electric load is always the same, but in this case the energy needed to power these components is lower because we have a decrease in hydrogen demand. So in table below the new calculation are reported.

Table 14 - Electric load compressor+chiller.

PV-GRID-FUEL CELL						
	Hydrogen Load [kg/hr]	**Hydrogen flow rate [kg/s]**	**Wcompress [kW]**	**Qcooler [kW]**	**Wcooler [kW]**	**Electric load (Compressor+Chiller) [kW]**
SUM	125	0.034722222	408.9615939	37.25	37.25	446.2115939

However now it is considered also the electric load needed by the electric charging stations which are designed in the next paragraph.

4.4.3 Electric refueling station load.

The electric charging stations chosen for this scenario are fast charging station of 100 kW. To design them and find the electric load needed by the cars we assumed a demand of 15 electric vehicle/day; since a mean battery needs 50 kWh to a full charge from 10% to 80% (this is the typical range in which the charge should be to not be stressed too much [71]), the daily electric load needed by the electric station will be:

$$Daily\ Electric\ Capacity = 15\frac{vehicles}{day} * 50\ kg = 750\frac{kWh}{day} \qquad Eq.\ 8$$

4.4.4 Fuel cell.

Now, we can determine how much hydrogen is required for the fuel cell to generate this amount of energy.

The average consumption of a hydrogen fuel cell is about 0.8 Nm^3 of hydrogen per kWh produced [72], so considered the hydrogen density to be 0.089 kg/m^3 we can easily find the specific fuel consumption of the fuel cell and insert this value into the software HOMER.

$$Specific\ fuel\ consumption = 0.8 * 0.089 = 0.0712\ kg/kWh \qquad Eq.\ 9$$

In this way we obtain the fuel curve shown in the graph below. The hydrogen used to power the fuel cell is part of that one generated by the electrolyzer. The software HOMER allows to set this option by the setting “use stored hydrogen”.

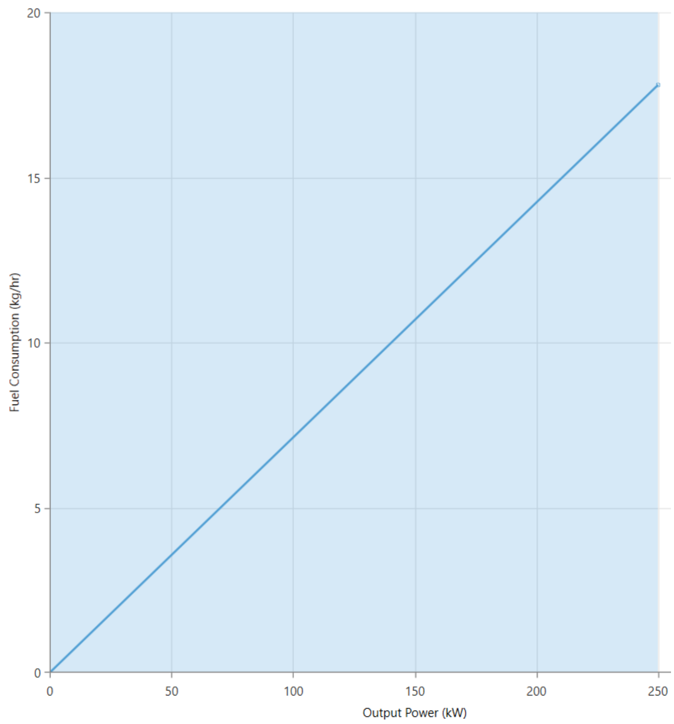

Figure 38 - Fuel consumption curve.

But running the analysis most of the electricity is picked by the PV panels, while just 5858 kg/year of H2 are needed by the fuel cell (that corresponds to 16 kg per day).

Regarding the cost of the fuel cell, it is highly variable, and it decrease year after year. Here is considered a cost of 500000 € for a 250 kW fuel cell [73].

All the costs per unit are shown in Table 15 below.

Table 15 - Cost per unit

	Cost per-unit							
Components	**Capital cost**	**[unit]**	**Replacement cost**	**[unit]**	**Yearly O & M costs**	**[unit]**	**Lifetime [h]**	**source**
Fuel cell	2000	€/kW	1600	€/kW	0.01	€/h	50000	[61]

4.4.5 Thermal load

As shown in paragraph 1.3.1 the outputs of fuel cells are electricity and heat that is a considerable part. So, a thermal load was inserted to not waste this heat. It was assumed that we have a rest stop considered as a commercial store, so the following thermal load was assumed:

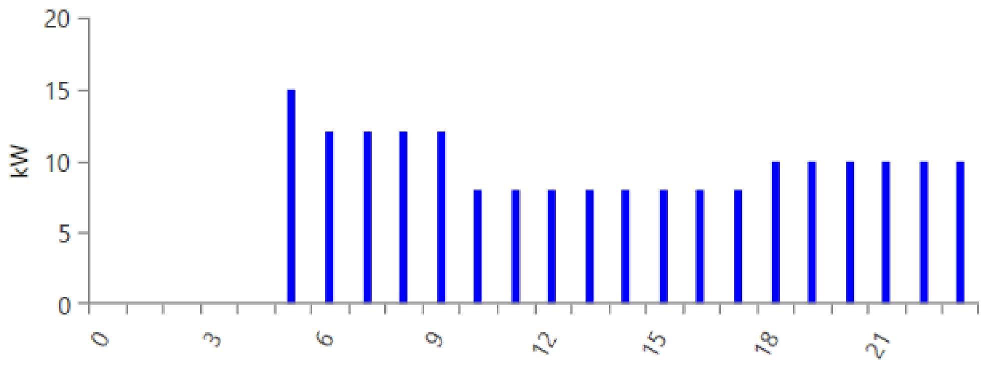

Figure 39 - Thermal load.

It has an average of 5.69 kW per day and of 136.49 kWh/day that represent a yearly average of about 50000 kWh. This value is coherent with the average thermal consumption of a building in Italy.

The thermal load is normally provided by the boiler, but using the thermal output of the fuel cell we will see that we can save on this electricity expense.

4.4.6 Total cost

Running the simulation we obtain the first results shown in the following table:

Table 16 - Capacity and total cost of the components of Scenario 3. HOMER results.

	Total cost					
Components	**Capital cost [€]**	**Replacement cost [€]**	**O&M cost [€/year]**	**Lifetime**	**Capacity**	**[unit]**
PV panels	2735200	0	34190	25 years	3518	kWp
Inverters	223500	223500	447	15 years	162	kWp
Electrolyzer	1300000	650000	26000	15 years	1500	kW
Hydogen tank	220000	0	2200	25 years	2200	kg
Fuel cell	500000	400000	6464	10 years	250	kWh

The Compressor and Chiller demand will be slightly lower than that of the previous scenarios, but we designed them always with the same power.

Since the PV panels power is slightly different also the water system and land cost will be different and these are the new values:

- Water system cost: 431.2 €/year
- Land cost: 1320000 €

The following three scenarios will be exactly the same of the previous three seen before, but they are located in Palermo. So, we just report the results of the HOMER simulation with the capacity, total costs and possible changes due to the change in location.

4.5 Scenario 4: On grid HRS, PV panels, Electrolyzer in Palermo.

Table 17 - Capacity and total cost of the components of Scenario 4. HOMER results.

	Total cost					
Components	**Capital cost [€]**	**Replacement cost [€]**	**O&M cost [€/year]**	**Lifetime**	**Capacity**	**[unit]**
PV panels	2141600	0	26770	25 years	2677	kWp
Inverters	223500	223500	447	15 years	447	kWp
Electrolyzer	1000000	500000	20000	15 years	1000	kW
Hydogen tank	220000	0	2200	25 years	2200	kg

We can immediately notice the difference between the same layout in Turin and in Palermo. Here the component's size is smaller but producing the same amount of hydrogen. This is due to the higher solar irradiance present in the south of Italy compared to that one in the north side.

This show a clear difference also in terms of costs that will be definitely lower in the layouts designed in Palermo.

We will see the same advantage also for the following layouts.

This difference will bring to split the decision process for each city, so we will choose the best scenario in Turin and then the best in Palermo, but the overall best scenario will be in Palermo due to the higher potential in terms of natural resources.

4.6 Scenario 5: Off grid HRS, PV panels, Electrolyzer, accumulation with lithium-ion battery, Palermo.

Table 18 - Capacity and total cost of the components of Scenario 5. HOMER results.

	Total cost					
Components	**Capital cost [€]**	**Replacement cost [€]**	**O&M cost [€/year]**	**Lifetime**	**Capacity**	**[unit]**
PV panels	1782400	0	22280	25 years	2228	kWp
Inverters	60500	60500	121	15 years	121	kWp
Electrolyzer	1250000	625000	25000	15 years	1250	kW
Hydogen tank	220000	0	2200	25 years	2200	kg
Battery	8460	75200	25000	10 years	188	kWh

4.7 Scenario 6: Off grid HRS, PV panels, Electrolyzer, accumulation with fuel cell, Palermo.

Table 19 - Capacity and total cost of the components of Scenario 6. HOMER results.

	Total cost					
Components	**Capital cost [€]**	**Replacement cost [€]**	**O&M cost [€/year]**	**Lifetime**	**Capacity**	**[unit]**
PV panels	1998400	0	24980	25 years	2498	kWp
Inverters	82500	82500	165	15 years	165	kWp
Electrolyzer	1200000	600000	24000	15 years	1200	kW
Hydogen tank	220000	0	2200	25 years	2200	kg
Fuel cell	500000	400000	6464	10 years	250	kWh

5 Techno-economic analysis

5.1 1st scenario HRS Turin – On grid, PV, Electrolyzer

5.1.1 Energy analysis

After running the simulation in Homer, all the energy results are extracted from the software and reported here.

In the graph below is shown the plot of the solar Irradiance power in one year, compared with the solar panel output. It is clear how the latter is just a small part of the entire power avaliable. This is a normal result due to the relatively low efficiency of flat PV panels; in our case the solar panels efficiency is 17%.

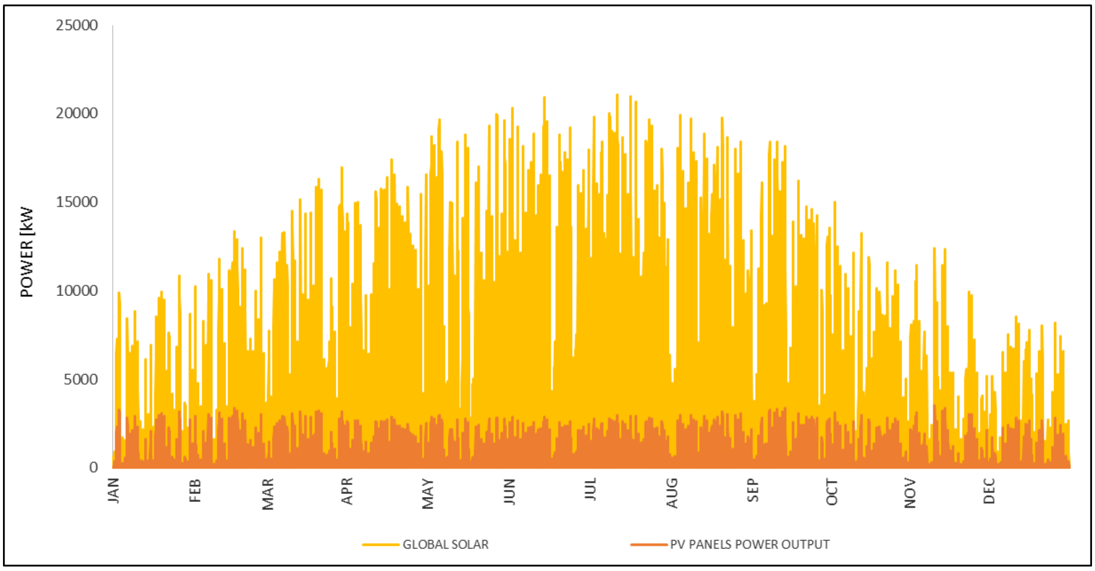

Figure 40 - Global solar irradiance compared with PV panels power output; Scenario 1.

However, not all the PV panels power output will be transferred in electric load, but a considerable part will be lost due to the presence of the converter that transform electricity from DC to AC; this is a considerable fraction: 22.3% of the total energy produced by the PV panels and purchased by the grid.

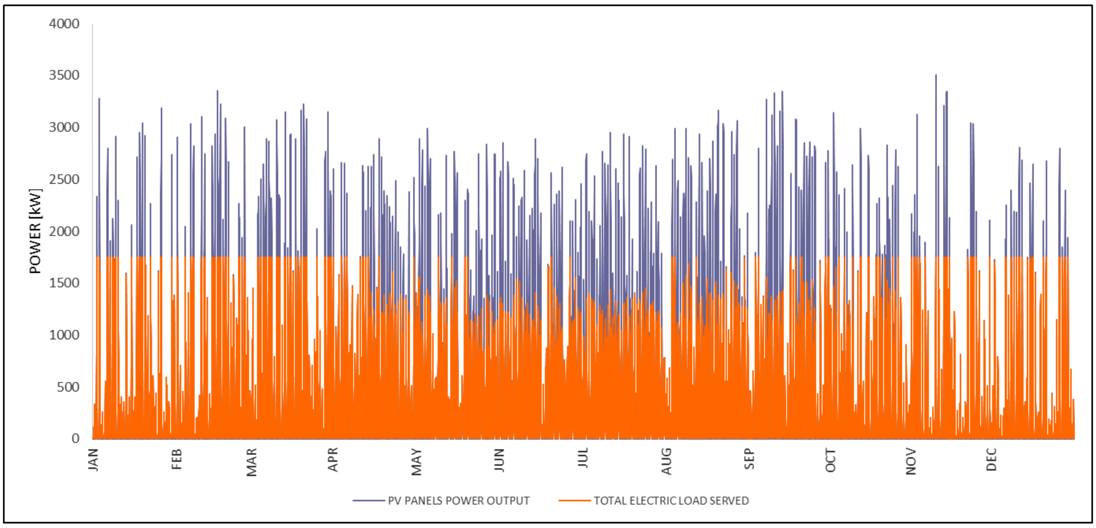

Figure 41 - PV panels power output confronted with total electric load served; Scenario 1.

The total electric load served is then divided into three rates:

- Electrolyzer Input
- Compressor and chiller (identified as AC load)
- Grid Sales

The yearly consumption of these three rates is shown in the graph below.

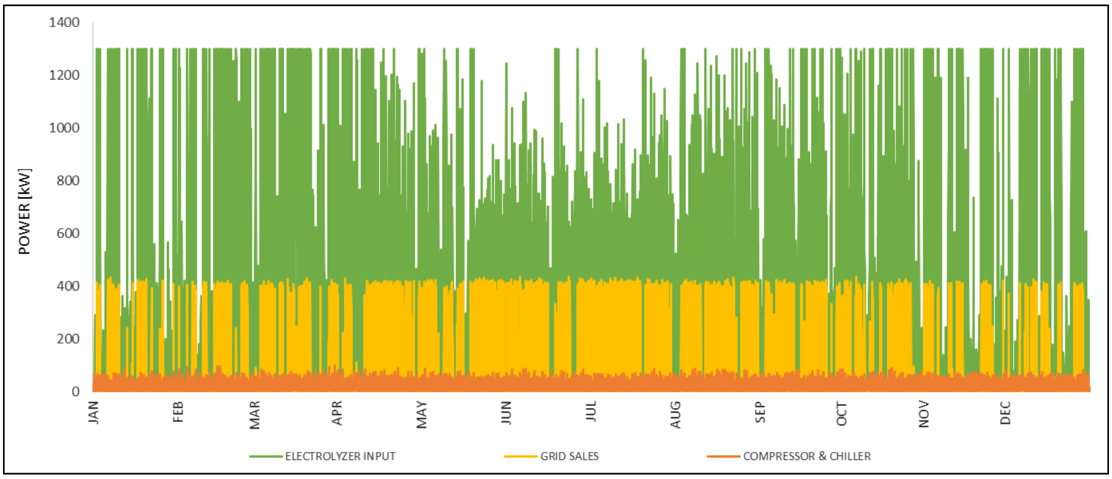

Figure 42 - Three rates of energy yearly consumption; Scenario 1.

It is noted as the main consumption come from the electrolyzer, which has a specific consumption of 46.4 kWh/kg.

A summary of the total electricity production and consumption is presented in the two pie charts below. Note that the chart shown on the left is the total electricity production output, so it represents how the electricity produced will be distributed; to see where the electricity produced came from, we should see the chart in Figure 45.

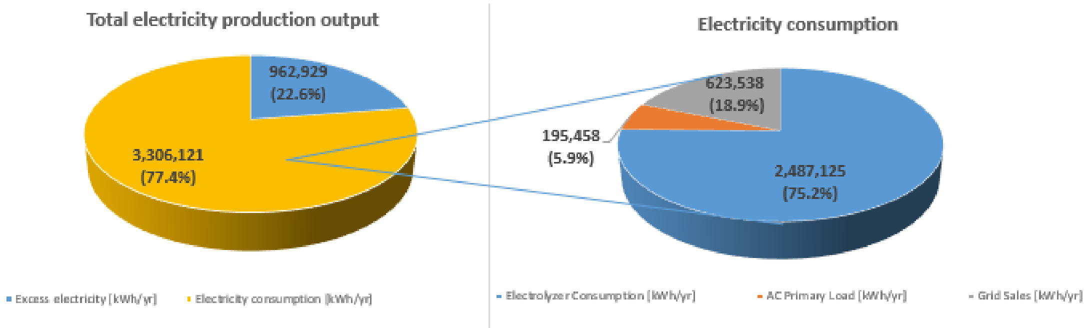

Figure 43 - Electricity summary Scenario 1.

Finally, the hydrogen load served is shown in Figure 44. The hydrogen consumed coincide with the produced hydrogen, since the unmet hydrogen load was set to 0%.

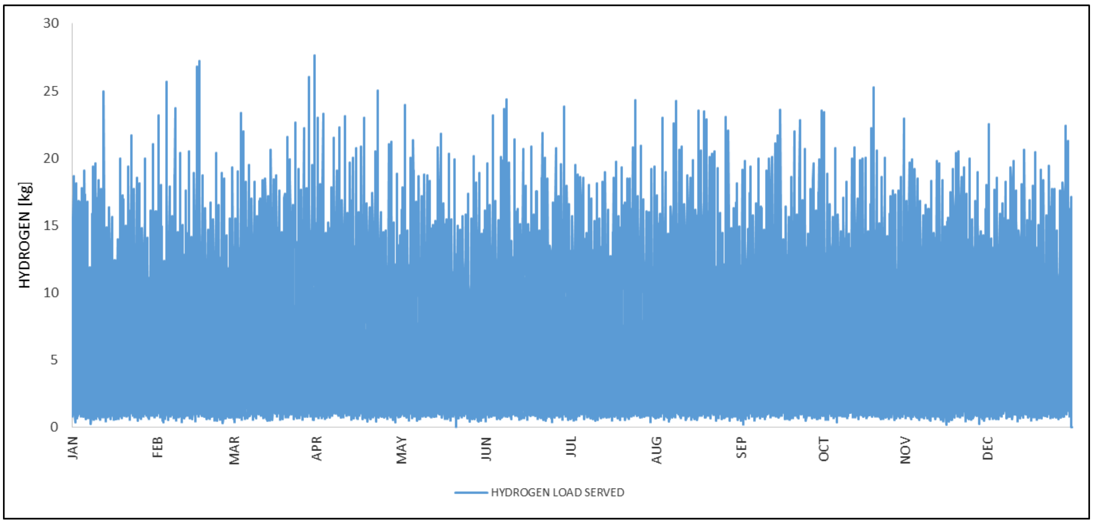

Figure 44 - Yearly hydrogen served; Scenario 1.

Emissions

The system's emissions will be influenced by the electricity generated by the grid. In this scenario, the grid will purchase 33712 kWh/year of electricity, which is only 1% of the total energy generated. This outcome was also made possible by the large hydrogen tanks used in the analysis, which were 2200 kg for each scenario. By doing this, we can store large amounts of hydrogen and use it as needed without having to purchase electricity from the grid.

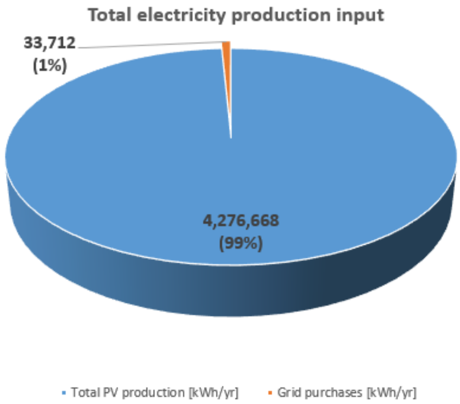

Figure 45 - Electricity summary input; Scenario 1.

The software Homer also calculates the quantity of emissions generated from the production of electricity by the grid. It assumed:

- 632 g/kWh of Carbon Dioxide emissions.
- 2.74 g/kWh Sulfur Dioxide g/kWh.
- 1.34 g/kWh Nitrogen Oxides.

The global yearly emissions are shown in Table 20.

Table 20 – Emissions; Scenario 1.

Emissions	Carbon Dioxide	Sulfur Dioxide	Nitrogen Oxides
Units	kg/yr	kg/yr	kg/yr
Quantity	21306	92.4	45.2

So, neglecting the Sulfur Dioxide and the Nitrogen Oxides emissions that represent 0.4% and 0.2% respectively of the Carbon Dioxide emissions, the yearly CO2 emissions are 21306 kg. It is a small value considering that the typical emissions of a gasoline passenger vehicle in the U.S are about 4600 kg/year of CO2 [74]. So, the emissions of a station that refuels thousands of cars every year are about the emission of just 5 vehicles with a combustion engine in a year.

5.1.2 Economic analysis

Several indicators that aid in better understanding the investment's viability, and in comparing the various scenarios are used to guide the economic analysis.

<u>NPC</u>

Net Present Cost (NPC) is a financial evaluation method used to assess the total cost of a project or investment over its entire lifespan. It takes into account the time value of money by discounting future cash flows to their present value. It is commonly employed in capital budgeting decisions to determine the profitability and feasibility of a project.

To calculate the NPC, the future cash inflows and outflows are discounted to their present value using the chosen discount rate. The present value of each cash flow is then subtracted from the initial investment. If the NPC is positive, it indicates that the project is expected to generate a net positive value, meaning the potential benefits outweigh the costs. Conversely, a negative NPC suggests that the project is likely to result in a net loss (in the first part of the analysis we just analyze the costs of the investment, so the costs are reported with a positive value). It is calculated with the following formula:

$$NPC = \sum_{n=1}^{n} \frac{TC_n}{(1+i)^n} \qquad \text{Eq. 10}$$

Where:

- i: annual real interest rate
- n: project life
- TC_n: total costs at the year n

The NPC provides decision-makers with a quantitative measure to compare different projects or investment options. It helps assess the economic viability of projects by considering the time value of money and providing a comprehensive view of the costs and benefits involved. By utilizing NPC analysis, organizations can make informed decisions about resource allocation, prioritize investments, and maximize the value generated from their projects.

<u>LCOE</u>

LCOE stands for Levelized Cost of Electricity. It is a financial metric used to assess the cost competitiveness of generating electricity from different sources or technologies over the lifetime of a project. The LCOE considers both the upfront capital costs and the ongoing operational expenses to provide a standardized measure of the average cost of electricity production.

The calculation of LCOE involves several key components:

1. Capital Costs: These are the initial investment expenses required to build the power plant, install equipment, and develop the necessary infrastructure for electricity generation. Capital costs include costs such as construction, equipment, land, and permits.
2. Operational Costs: These are the ongoing expenses incurred during the operation and maintenance of the power plant. Operational costs encompass factors such as fuel costs, maintenance and repair, labour, insurance, and other operational expenditures.
3. Lifetime Electricity Generation: This refers to the total amount of electricity expected to be generated by the power plant over its operational lifetime. It takes into account factors such as capacity factor (the ratio of actual electricity generation to maximum potential generation) and availability.
4. Discount Rate: The discount rate is the rate used to convert future cash flows to their present value, considering the time value of money. It reflects the opportunity cost of capital or the required rate of return on investment.

To calculate the LCOE, the present value of all costs (capital and operational) over the lifetime of the project is determined by discounting future cash flows using the chosen discount rate. The present value costs are then divided by the total lifetime electricity generation to obtain the levelized cost of electricity per unit (typically expressed in euro per kilowatt-hour, €/kWh). The formula to calculate the LCOE is reported below:

$$LCOE = \frac{\sum_{n=1}^{n}\left(\frac{TC_n}{(1+i)^n}\right)}{\sum_{n=1}^{n}\left(\frac{E_n}{(1+i)^n}\right)} \qquad \text{Eq. 11}$$

- E_n: Electricity produced at year n.

A lower LCOE indicates a more cost-effective source of electricity generation. It allows for comparisons between different technologies or energy sources and assists in decision-making regarding the selection and planning of power generation projects. LCOE analysis helps policymakers, investors, and energy planners evaluate the economic feasibility and competitiveness of various electricity generation options, considering both the upfront and operational costs involved.

<u>LCOH</u>

Levelized Cost of Hydrogen (LCOH): The LCOH is a similar metric to LCOE but specifically applies to the production and delivery of hydrogen. It represents the average cost of producing and delivering a unit of hydrogen (typically in dollars per kilogram, $/kg) over the project's lifetime. The factors considered in LCOH calculation include:

- Capital Costs: The upfront investment required for building hydrogen production facilities, storage infrastructure, and associated equipment.
- Operational Costs: Ongoing expenses such as feedstock costs, energy inputs, maintenance, and distribution.
- Lifetime Hydrogen Production: The total amount of hydrogen expected to be produced over the project's lifetime, accounting for capacity utilization and availability.
- Discount Rate: The discount rate used to convert future cash flows to their present value.

The formula to calculate the Levelized cost of hydrogen is reported below:

$$LCOH = \frac{\sum_{n=1}^{n}\left(\frac{TC_n}{(1+i)^n}\right)}{\sum_{n=1}^{n}\left(\frac{H_n}{(1+i)^n}\right)} \quad \text{Eq. 12}$$

- H_n: Hydrogen produced at year n.

Similar to LCOE, a lower LCOH indicates a more cost-effective hydrogen production process.

Both LCOE and LCOH are useful tools for decision-making in the energy sector, allowing for comparisons between different technologies or energy sources. These metrics consider the full cost profile, including both upfront investment and ongoing operational expenses, providing insights into the long-term economic viability and competitiveness of energy projects.

Once established all the cost items like the capital, replacement, and operational and management costs we also considered the sources of profit coming from the grid sellback and the salvage value estimated at the end of the investment for each component. To calculate the salvage value, we assumed a depreciation percentage of 6.67% every year for each component, so we subtract 6.67% of its original value and the remaining value at the end of the 25 years will be the salvage value of the component.

In this way we have all the means to calculate the cumulative cash flow of each scenario (discounted and nominal as well). It is shown in Figure 46.

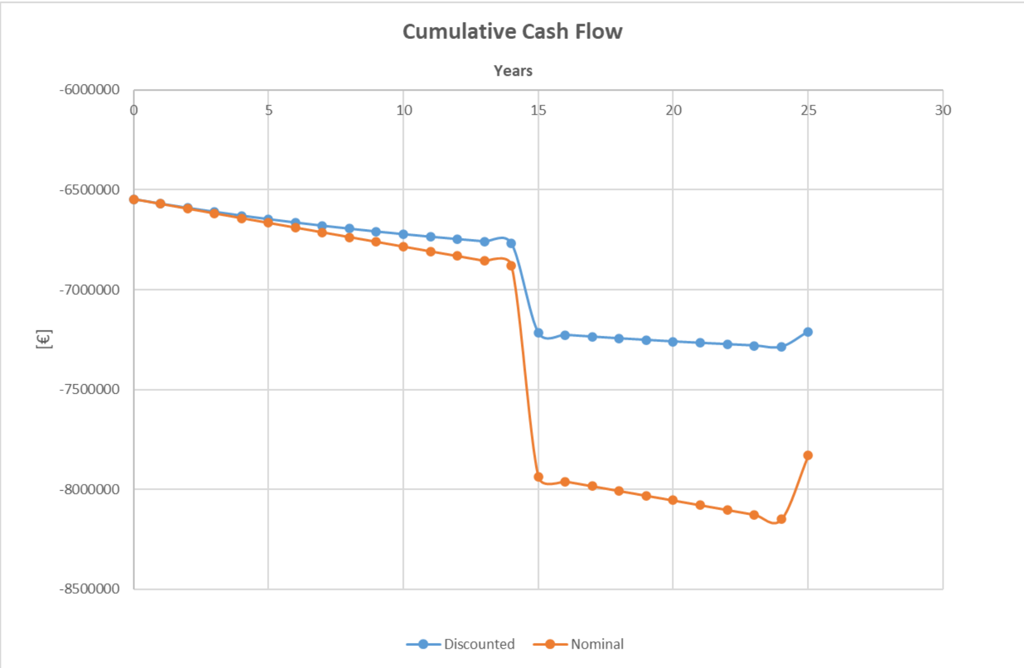

Figure 46 - Cumulative cash flow Scenario 1.

The Net Present Cost was also calculated for each component and divided for each cost item. In Figure 47 is clear how the most expensive component is the PV plant, followed by the electrolyzer.

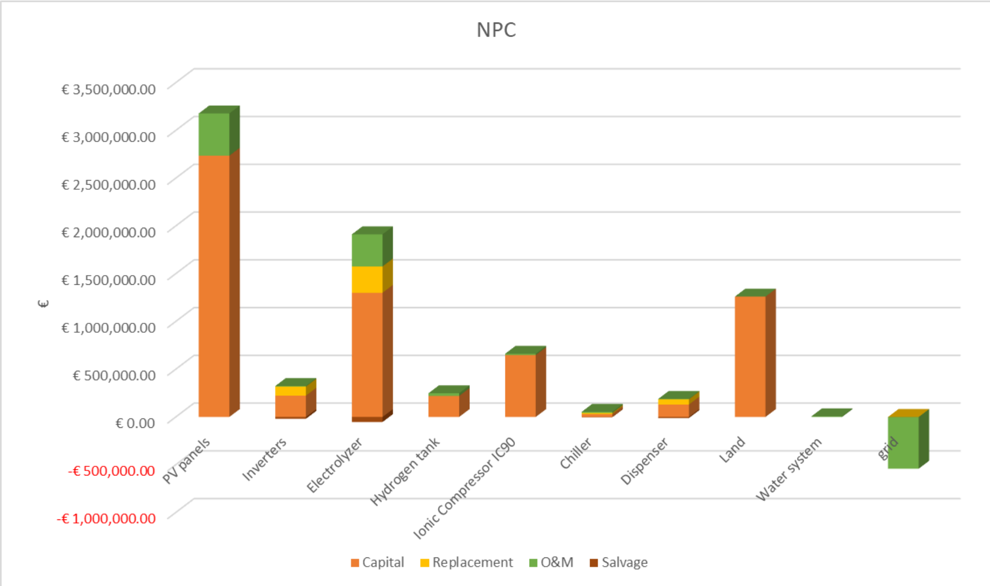

Figure 47 - NPC per component and cost item; Scenario 1.

For this scenario we found an NPC= 7209536.4 €, a LCOE = 0.17€/kWh and a LCOH = 10.38 €/kg.

5.1.3 Source of income and other economic indexes

To evaluate a complete economic analysis a source of income is considered to obtain a possible Net Present Value arising from the sale of the hydrogen. We considered the price of hydrogen to the Bolzano hydrogen station that is 13.7 €/kg, so considering the best case where all the daily demand is satisfied the yearly income will be 750075 €. Having a source of income, we can calculate other economic indexes that could be crucial in the decision process to choose the best scenario for each city.

The main economic indexes calculated are:

- The Net present Value (NPV) that is dual of the NPC.
- Payback Period (PBP): It is a financial metric used to evaluate the time it takes for an investment to generate enough cash flows to recover the initial investment cost. It is expressed in years and a shorter payback period indicates that the investment is recovering its initial cost more quickly, which is often seen as favorable. Therefore, it's generally considered a basic tool for initial screening of investment options, but more sophisticated metrics like net present value (NPV) or internal rate of return (IRR) are often used for more comprehensive investment analysis.
- Internal rate of return (IRR): It is a financial metric used to evaluate the potential profitability and attractiveness of an investment or project. The IRR represents the discount rate that equates the present value of expected cash inflows with the present value of cash outflows over the project's lifespan. In other words, it is the rate at which the net present value (NPV) of an investment becomes zero.
  The IRR calculation involves the following steps:

1. Identify Cash Flows: Determine the expected cash inflows and outflows associated with the investment or project. These cash flows typically occur over multiple periods and can include initial investment, operational cash flows, salvage value, and any other relevant financial flows.

2. Discount Cash Flows: Apply different discount rates to the cash flows and calculate their present values. The present value of each cash flow is determined by dividing it by (1 + discount rate) raised to the power of the period in which the cash flow occurs.

3. Find the IRR: Adjust the discount rate until the sum of the present values of the cash flows equals zero. This rate, at which the NPV becomes zero, is the Internal Rate of Return.

   The IRR is typically expressed as a percentage and can be interpreted in the following ways:

- If the IRR is greater than the required rate of return or the cost of capital, the investment is considered attractive because it generates returns higher than the expected minimum return.
- If the IRR is equal to the required rate of return or the cost of capital, the investment is expected to break even, with no net gain or loss.
- If the IRR is less than the required rate of return or the cost of capital, the investment is considered unattractive as it fails to meet the expected minimum return.

   The IRR is widely used in financial analysis and investment decision-making. It provides a single rate of return that summarizes the profitability of an investment, allowing for comparison with other investment opportunities. However, it is important to consider other factors such as risk, cash flow patterns, and the magnitude and timing of cash flows when making investment decisions, as the IRR has some limitations.

- Return on investment (ROI): It is a financial metric used to assess the profitability and efficiency of an investment or project. ROI measures the return or gain generated from an investment relative to its cost. It is typically expressed as a percentage or a ratio. The calculation of ROI involves the following formula:

$$ROI = \frac{Net\ Profit}{Cost\ of\ Investment} * 100 \qquad \textit{Eq. 13}$$

   Here are the key components used in the formula:

1. Net Profit: It refers to the total profit or gain generated from the investment. Net profit is calculated by subtracting the total cost of the investment (including expenses, taxes, and other associated costs) from the total revenue or returns generated.
2. Cost of Investment: This represents the total cost or initial outlay required for the investment. It includes the purchase cost, installation costs, fees, and any other expenses directly associated with the investment.

   By dividing the net profit by the cost of investment and multiplying by 100, the ROI is expressed as a percentage.
   The ROI metric helps assess the efficiency and profitability of an investment by comparing the gains or returns to the initial investment. A positive ROI indicates that the investment generated a profit, while a negative ROI suggests a loss. A higher ROI indicates a more profitable investment.

The economic indexes were calculated, and the results are reported in the table below:

Table 21 - Economic results; Scenario 1.

	NPV [€]	PBP [years]	IRR	ROI
Scenario 1	2487070.617	14	9.66%	34%

Also, the graph of the cumulative NPV was built and it is shown in Figure 48.

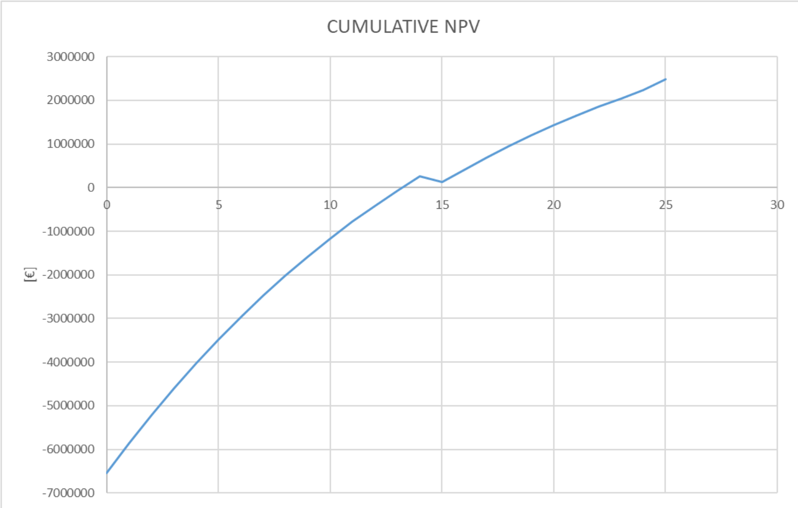

Figure 48 - Cumulative NPV Scenario 1.

From this graph we can also identify the payback period where the curve crosses the abscissa axis. While the NPV value at the final year is the overall NPV of the scenario.

5.1.4 Risk analysis

For this form of investment, it is crucial to assess a risk analysis that takes into consideration the potential for a financial loss. In this case we did a strong assumption: That the actual demand of the HRS hovers around 85 % of the demand, while for the last scenario the ERS demand is around 95%. This assumption is quite risky since it can be considered realistic in a country where fuel cell vehicles are well established or in fast growing like in Germany, Japan, Korea, or California, however, there are hardly any fuel cell vehicles in Italy, and there are only two active refuelling stations: one in Bolzano and the other in Mestre; moreover in 2022 have been sold just 11 hydrogen car that are just the 0,0008% compare to 1,33 million of cars sold the same year in Italy [15]. However, we know that the Italian government financed the construction of 36 HRS in all Italian territory, so the analysis is tenable for a future period when fuel cell vehicles will be more spread in our area.

Risk analysis: Monte Carlo Method

The Monte Carlo method is a numerical technique used to approximate the Value at Risk (VaR) of a financial portfolio. VaR is a measure of the potential loss an investment portfolio may experience over a given time horizon at a specified confidence level.

The first step of the Monte Carlo method is to define the composition of the investment portfolio, including the assets, their quantities, and their historical price or return data.

PROBLEM: lack of historical data

- The price of hydrogen is considered fixed because it depends on the production cost, influenced by the technology used. 13.7 €/kg is the price of hydrogen assumed that is the same at the HRS in Bolzano.
- The variables considered in the risk analysis are all the cost items, and the daily hydrogen demand. We assume an average of 85% HRS's capacity (127.5 kg/day).
- Regarding the costs' volatility, an average value and a standard deviation were assumed. We chose a small standard deviation (of 3%) for that cost or income sources considered with a low volatility like the capital costs or the grid sales; on the contrary the replacement cost, the O&M costs, the salvage value and the income proceeds from the hydrogen's sale is considered with a high standard deviation (around 15%)

- So, the next step is the simulation of future scenarios.

We simulated 500 scenarios where the values follow a normal distribution. With the function NORM.INV we can generate the inverse of a normal distribution given the mean and the standard deviation. A random probability is assumed for each scenario since we cannot know the future demand. To obtain the first simulation values we use the standard deviation mentioned before and as mean value the average value of each cost/income.

- With the values obtained we can calculate the new mean value and the new standard deviation.
- Value at Risk quantifies the statistical probability that an investment will lose money given a particular probability. It estimates the potential loss at various confidence levels.
- We calculated the Value at risk with the PERCENTILE function in Excel, where given a specific level of confidence (i.e. 95%) and the value obtained is the maximum percentage of losses.

In the graph below the frequency of the simulation's results is shown:

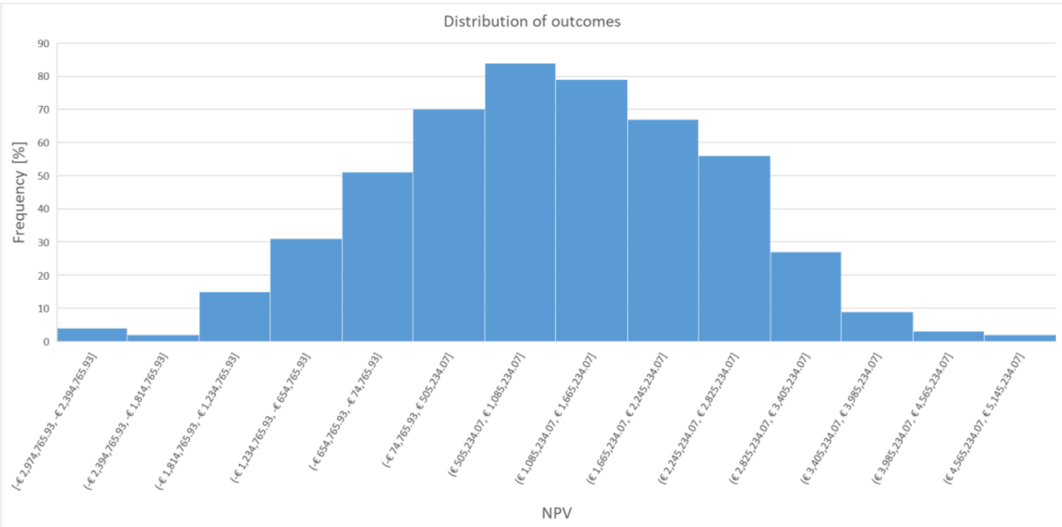

Figure 49 – Frequency distribution, Scenario 1.

We found a 5% VaR of -888341.8955 €. So, it means that we have a 5% of probability to lose this amount of money.

While the risk of loss was calculated considering the probability that the NPV is a negative value. For this scenario we found a risk of loss of 21%.

We also calculated the probability that the NPV reach a determined value and we plotted these results obtaining the following graph.

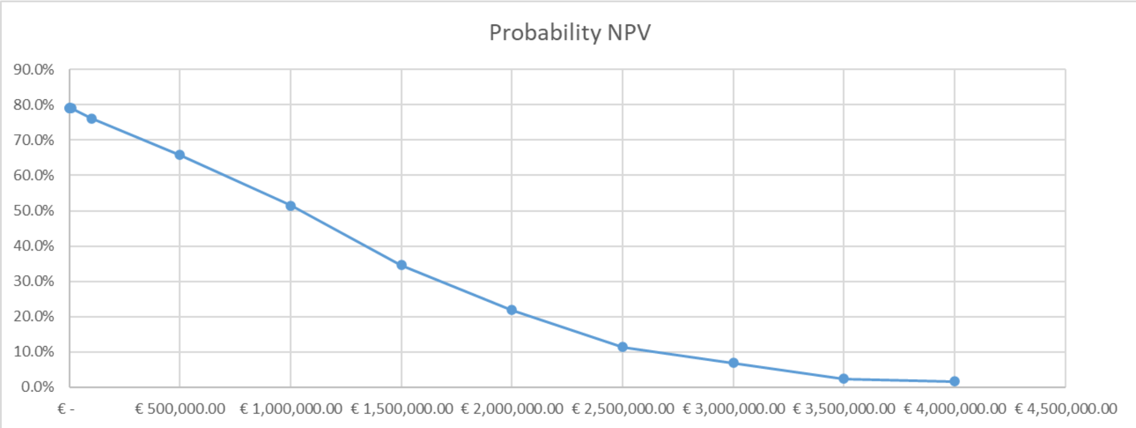

Figure 50 - NPV probability Scenario 1.

5.2 2nd scenario HRS Turin- Off grid, PV, Battery, Electrolyzer

5.2.1 Energy analysis

The results here are similar to those of the first scenario, so we just report all the graphs resulted by the simulation.

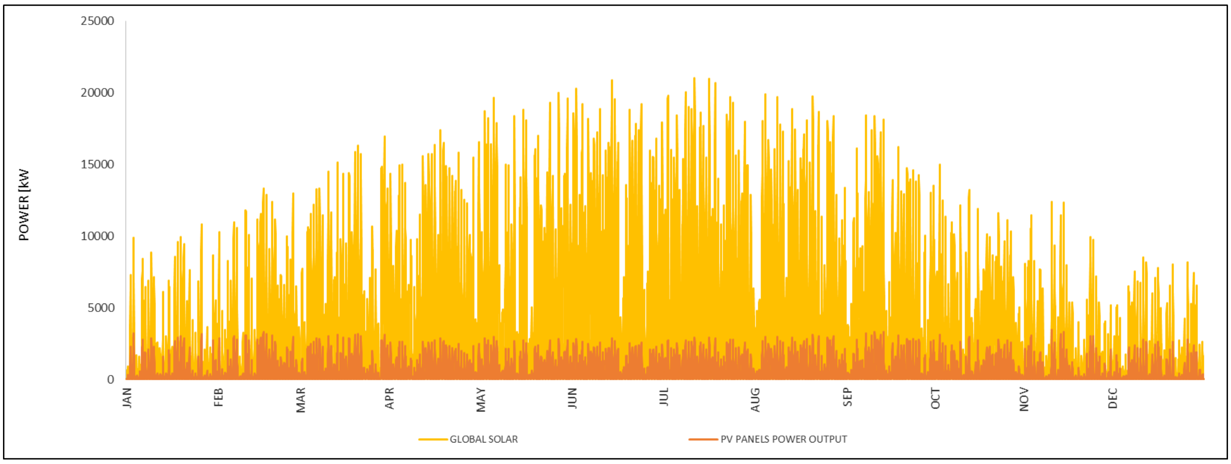

Figure 51 - Global solar irradiance compared with PV panels power output; Scenario 2.

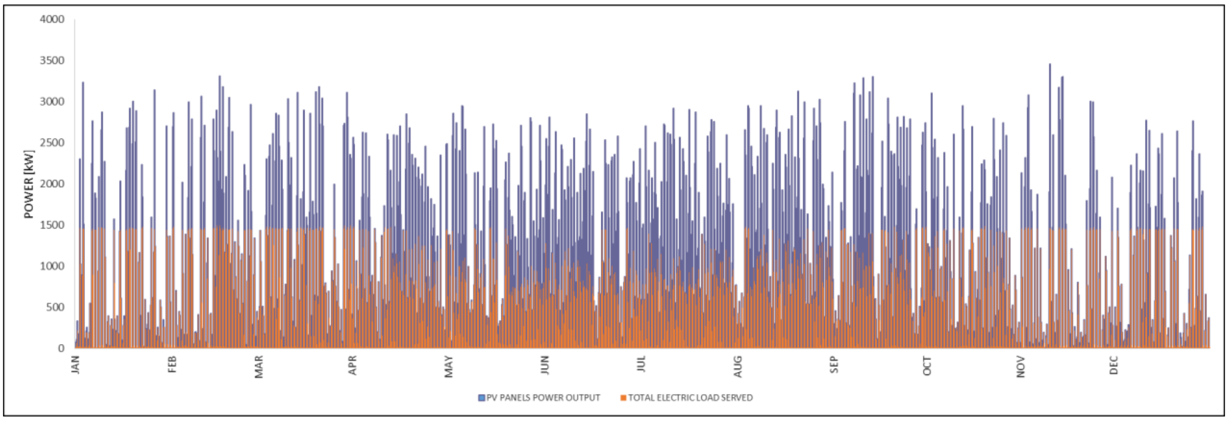

Figure 52 - PV panels power output confronted with total electric load served; Scenario 2.

The first difference that we can notice is the lack of the grid sales, which in the previous scenario is a considerable percentage of the electricity produced.

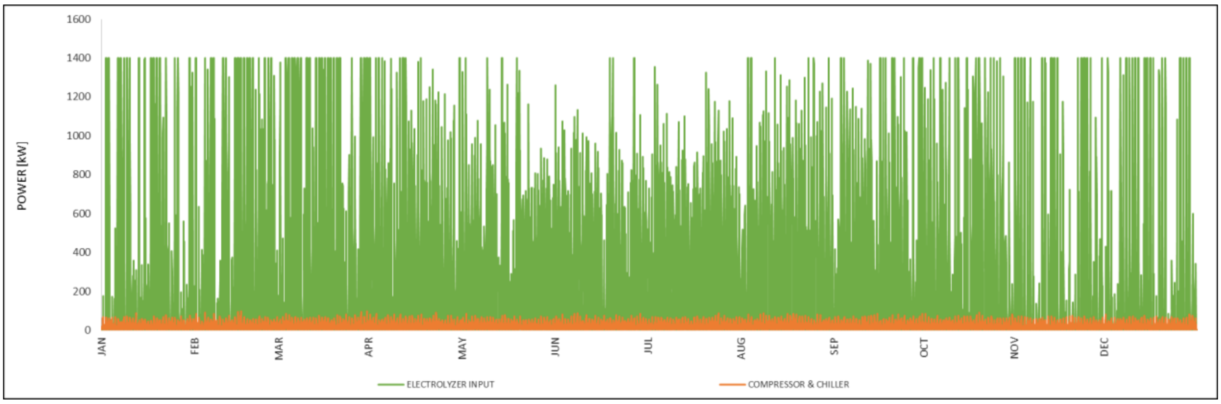

Figure 53 - Two rates of energy yearly consumption; Scenario 2.

The hydrogen produced is the same of the previous scenario.

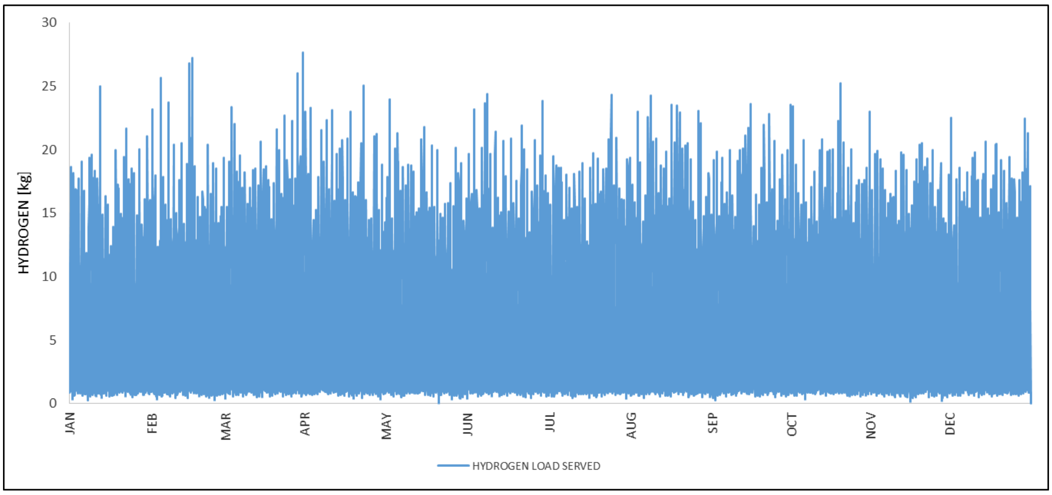

Figure 54 - Yearly hydrogen served; Scenario 2.

Regarding the electricity consumption in the pie-chart below we can see that in this scenario the excess electricity that we lose for the conversion is higher also for the presence of the battery, which involve another conversion of electricity from DC to AC. Moreover, here we cannot sell the electricity to the grid.

If we look at the chart on the right, the electrolyzer consumption is the same of the scenario 1, but the percentage is difference because of the lack of the grid sales that were 18.9% in the previous scenario.

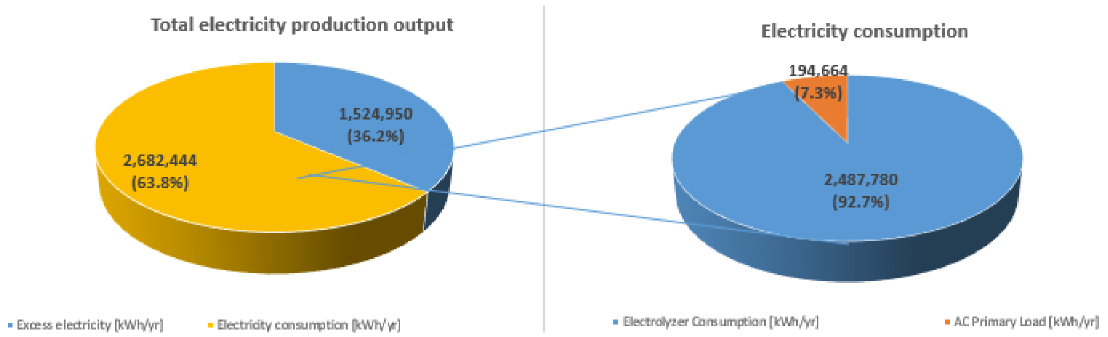

Figure 55 - Electricity summary Scenario 2.

5.2.2 Economic analysis

We can clearly see the disadvantage in economic terms of the scenario 2 compared with the scenario 1 observing the cumulative cash flow graph below. The curve has a higher negative slope, and it starts from a lower point; this is due to the presence of the battery, which add new costs to the system, and also we lose the profit coming from the sale of the electricity to the grid.

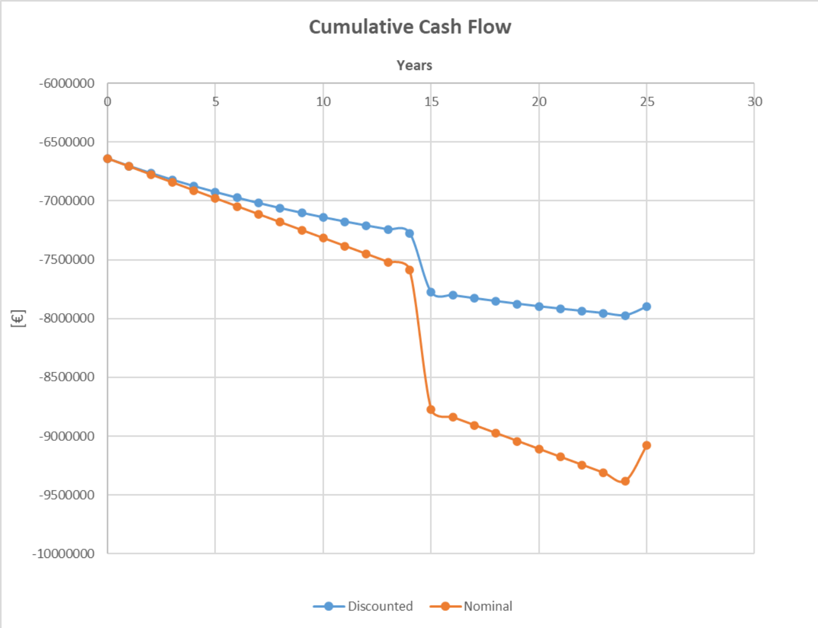

Figure 56 - Cumulative Cash Flow; Scenario 2.

Here in Figure 57 the NPC per component and cost item is shown. The last component is the battery which involve a small percentage of the entire NPC, but it also misses the profit coming from the electricity sale, so observing this graph we can predict that the NPC of this scenario will be higher than the previous one.

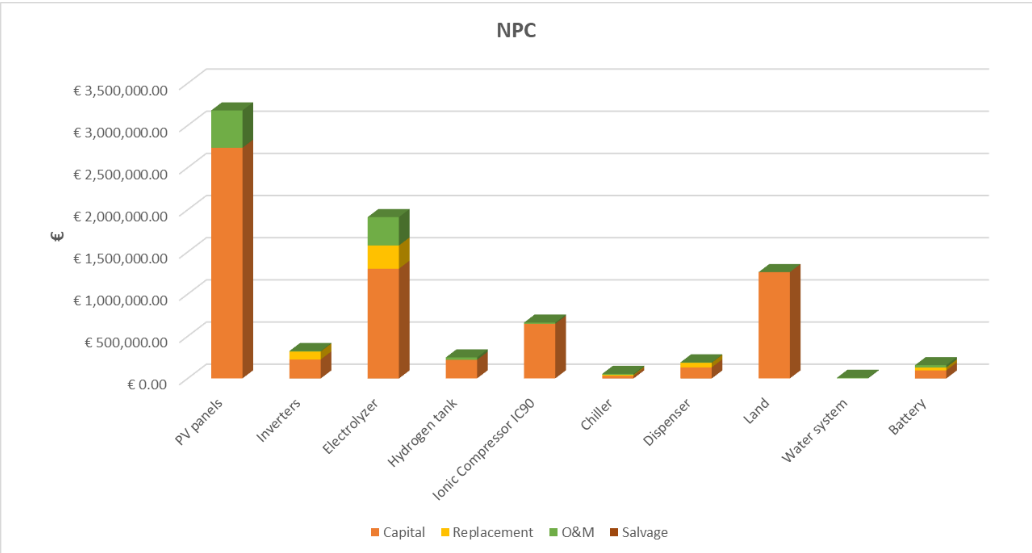

Figure 57 - NPC per component and cost item; Scenario 2.

The NPC of this scenario is 7899873 € so it is almost 700000 € higher than the previous one. Since the electricity and hydrogen produced are almost the same, but costs have increased, the LCOE and the LCOH will results higher. Their values are respectively: LCOE=0.23 €/kWh and LCOH=11.17 €/kg.

The other economic indexes are reported in the table below:

Table 22 - Economic results; Scenario 2.

	NPV [€]	PBP [years]	IRR	ROI
Scenario 2	1796733.831	17	8.62%	23%

Making a comparison with the Scenario 1 we can immediately see that all the economic indexes got worse. The NPV is lower, as well as the ROI and the IRR. Only the PBP is higher, but it means that we need more time to make the investment profitable. Comparing the graph in Figure 58 with the trend of the NPV of the previous scenario you can clearly see how the growth of this scenario is slower than the other in Figure 48.

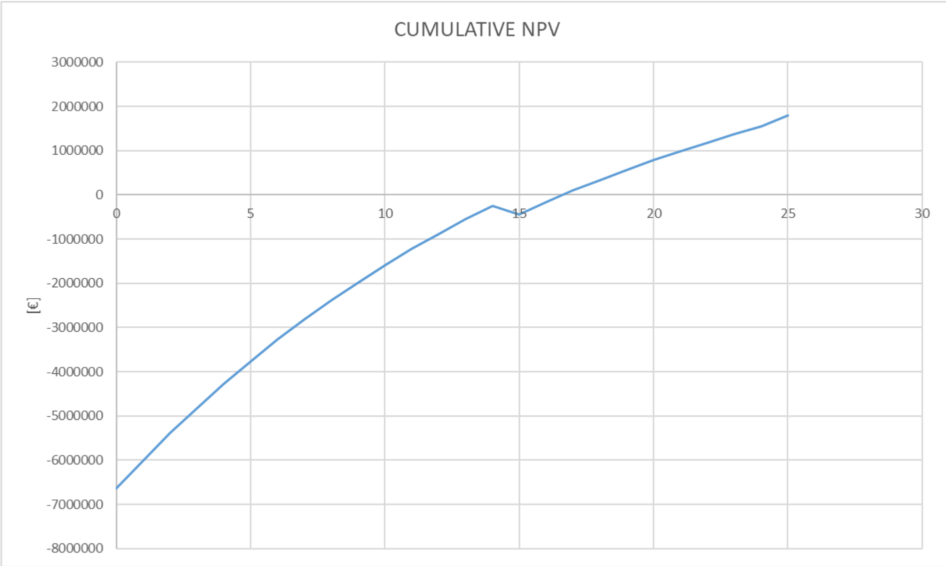

Figure 58 - Cumulative NPV; Scenario 2.

5.2.3 Risk analysis

The procedure and the hypotesis of the risk analysis are the same seen for the Scenario 1 so, in this paragraph we just report the results obtained. First, the distribution of the frequency of the NPV with which we get a 5 % VaR of -1618577.391 €.

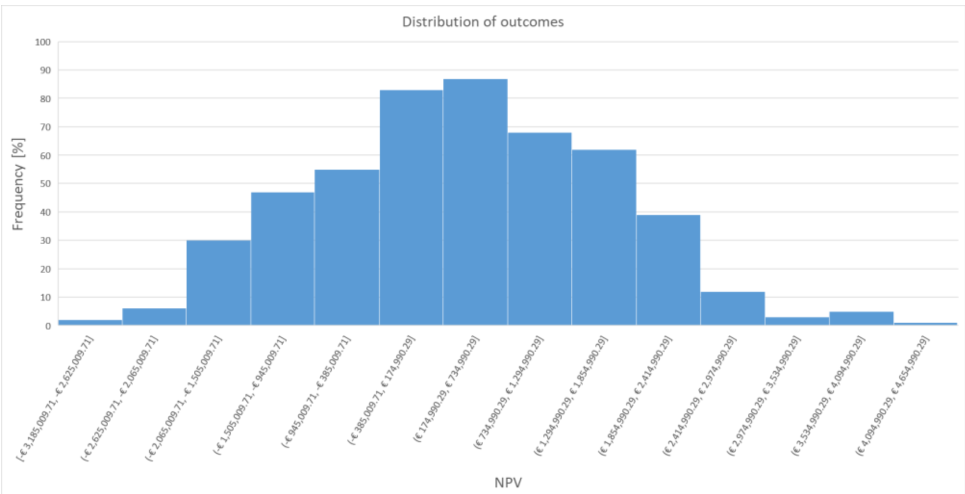

Figure 59 – Frequency distribution, Scenario 2.

In this case the risk of loss is 35% and the following graph summarizes the NPV probability of several values.

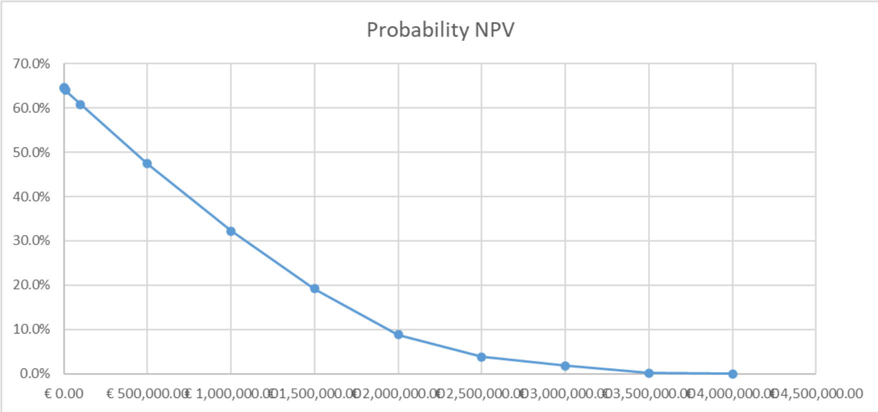

Figure 60 - NPV probability; Scenario 2.

5.3 3rd scenario HRS+ERS Turin- Off grid, PV, Fuel Cell, Electrolyzer and Thermal load

The third scenario has several changes both for the energy and the economic analysis. These changes will be described analyzing each graph resulting from the simulation.

5.3.1 Energy analysis

Since the location is the same the graph of the global solar will be the same, while the PV power output has undergone a slight change in power since the capacity of the PV system has increased.

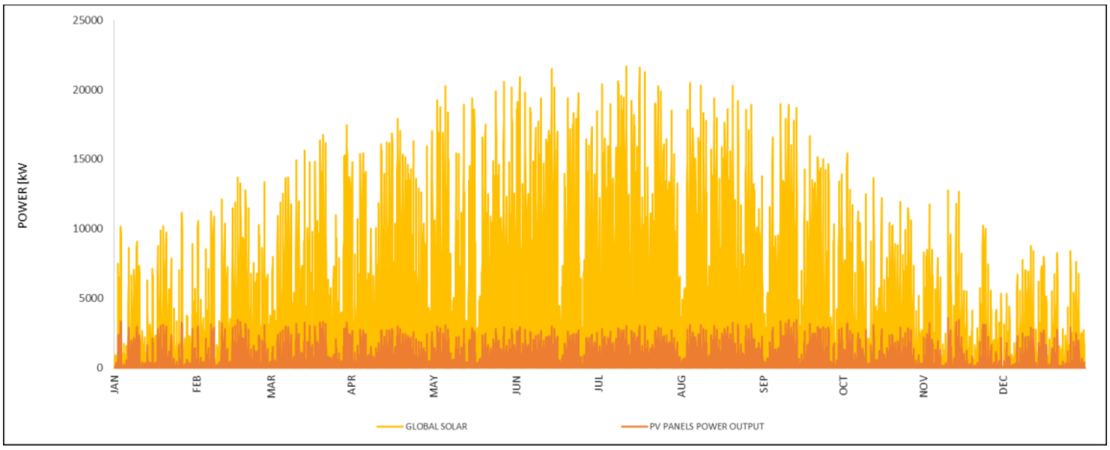

Figure 61 - Global solar irradiance compared with PV panels power output; Scenario 3.

Here we can see the total electric load compared with the PV panels power output that always keep the same trend.

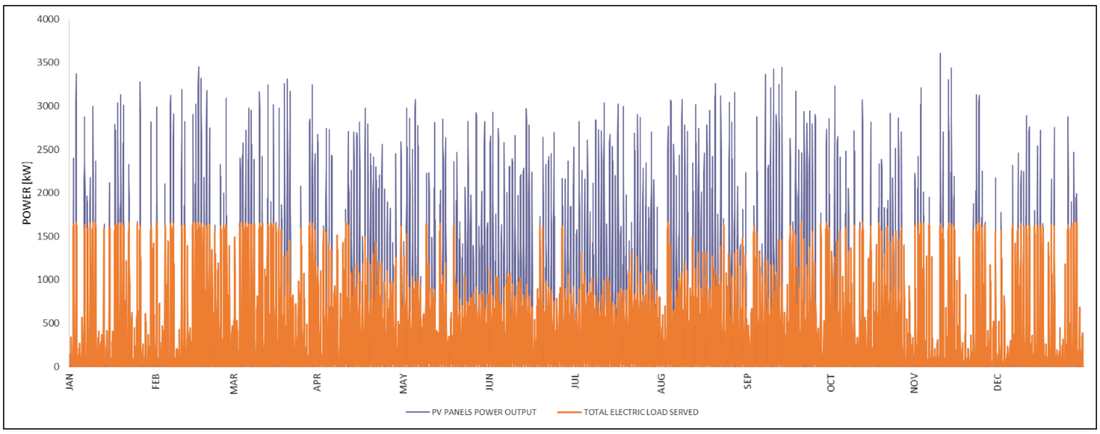

Figure 62 - PV panels power output confronted with total electric load served; Scenario 3.

Like in the Scenario 2, here we do not have the grid sales.

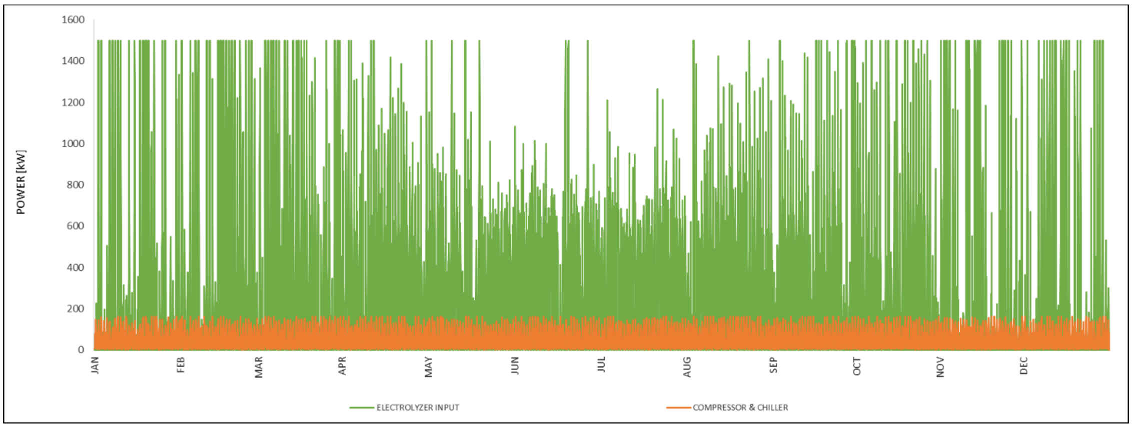

Figure 63 – Two rates of energy yearly consumption; Scenario 3.

Figure 64, which relates to the hydrogen load, illustrates how the electrolyzer's hydrogen output is split into two rates: the hydrogen demand is depicted in green, and the fuel cell input is depicted in blue. About 11.4% of the total hydrogen produced yearly is consumed by the fuel cell. The blue graph's trend shows that the fuel cell uses less hydrogen in the summer than it does in the winter. This is due to the fuel cell's need to meet the thermal demand, which is certainly higher in the winter.

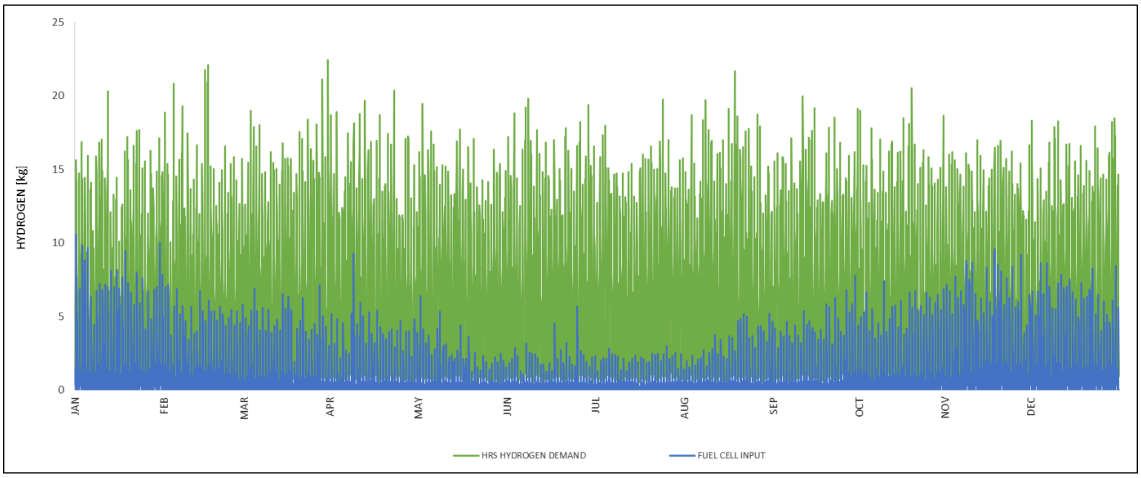

Figure 64 - Hydrogen load; Scenario 3.

Regarding the total production of electricity, this is the scenario with the higher kWh, it reaches 4459825 of kWh/year, however it is also that one with the higher excess electricity. In the pie chart below we see that the excess electricity reach 37.8% of the entire production. So just the 62.2% of electricity is divided between the electrolyzer consumption and the electric load.

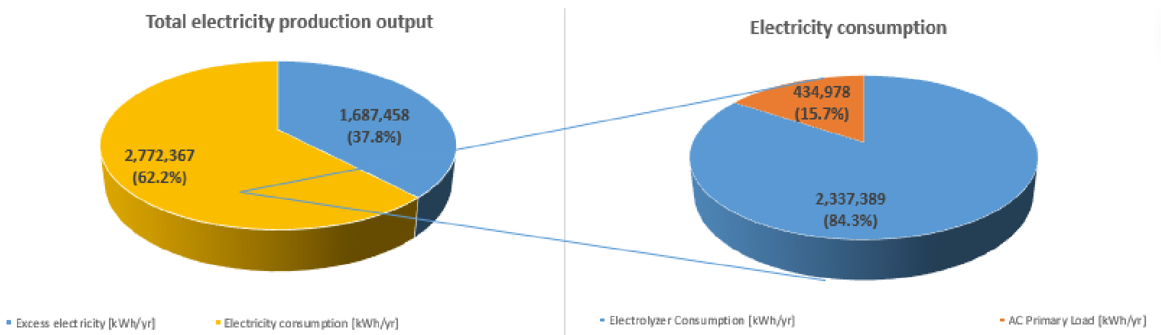

Figure 65 - Electricity summary Scenario 3.

98% of the yearly electricity comes from the PV panels, while just 2% of it is produced by the fuel cell that can be seen as an alternative to the battery, but it stores hydrogen transforming it in electricity.

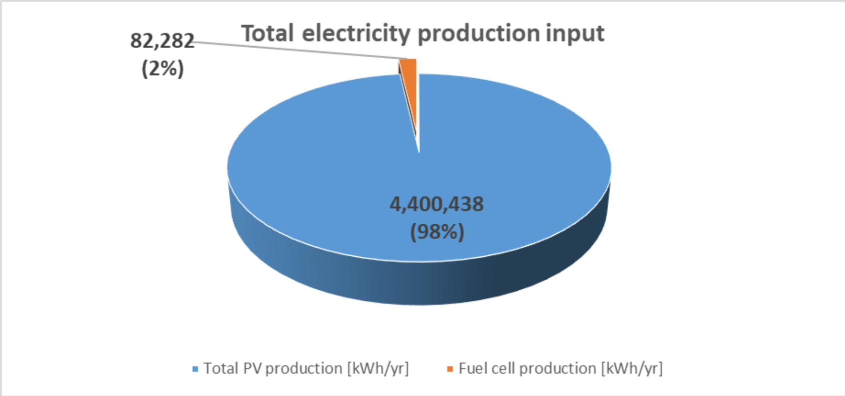

Figure 66 - Electricity summary input; Scenario 3.

Here we added a graph showing the thermal analysis. We have 3 different rates:

1) The fuel cell thermal output (that is about 73450 kWh/yr)
2) The boiler thermal output (30296 kWh/yr)
3) The thermal load of the building

If we observe the fuel cell thermal output, it is disconnected from the thermal load, the reason is because the fuel cell works when we have a hydrogen demand, so the thermal load is not our first goal, but just a energy output that we do not want to waste.

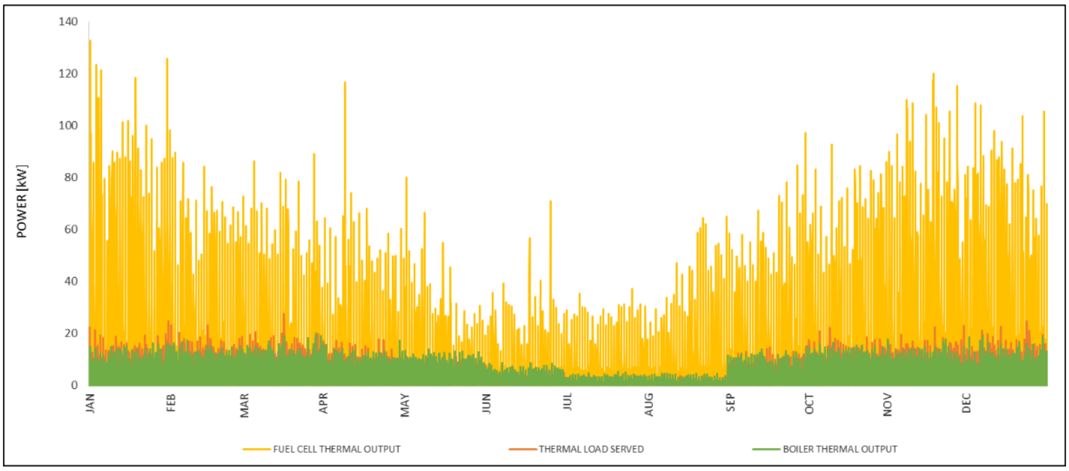

Figure 67 - Thermal rates; Scenario 3.

In Figure 68 is shown how only a small percentage of the thermal load comes from the boiler, while the rest is satisfied by the fuel cell's thermal output. Moreover, we can see again how the thermal load is higher in winter than in summer.

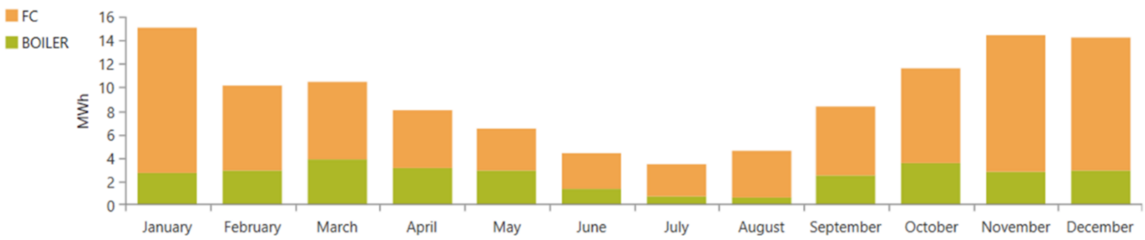

Figure 68 - Thermal inputs; Scenario 3.

5.3.2 Economic analysis

This is the scenario with the higher costs, indeed comparing the cumulative cash flow of the other two scenarios with this in Figure 69, we can immediately see how the curves are lower than the previous cases and it is due to an additional drop in costs around the 8th year because of the replacement of the fuel cell which has a considerable cost.

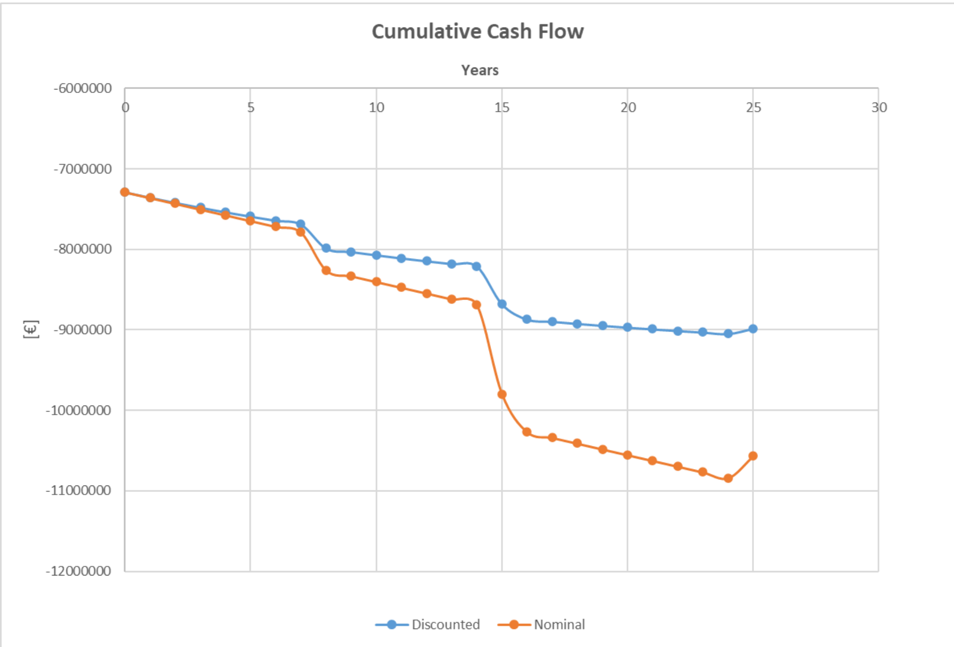

Figure 69 - Cumulative Cash Flow; Scenario 3.

The detail of this cost is stressed in the figure below, where half of the total NPC of the fuel cell is represented by the replacement cost. Beside the fuel cell cost we also have another new cost item that is the electric charging station cost.

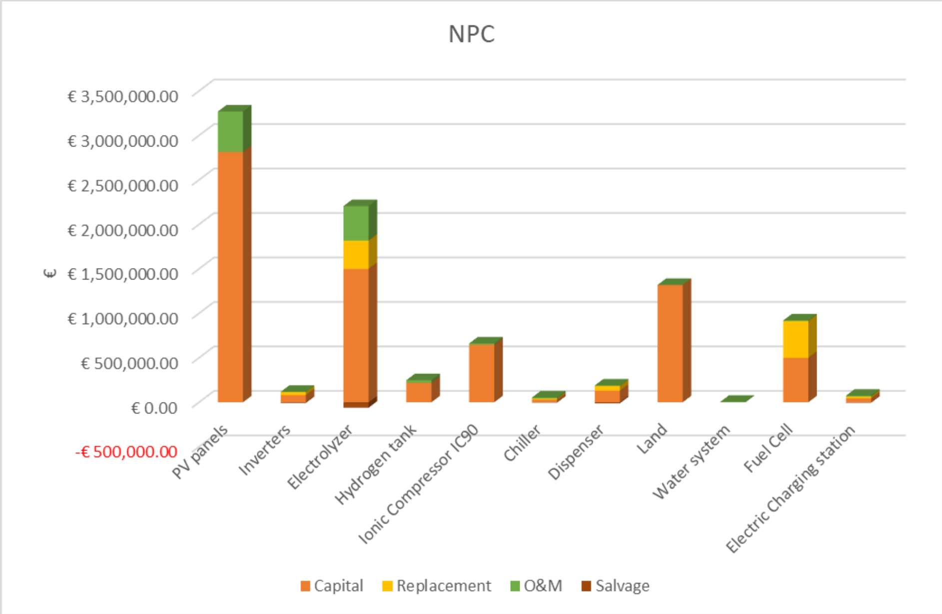

Figure 70 - NPC per component and cost item; Scenario 3.

Regarding the LCOE a change has been made in this scenario due to the presence of the thermal load. Indeed, the software HOMER calculates the LCOE with the following equation:

$$LCOE = \frac{C_{ann,tot} - c_{boiler} H_{served}}{E_{served}} \quad \text{Eq. 14}$$

Where:

- $C_{ann,tot}$ = total annualized cost of the system [€/year]
- c_{boiler} = boiler marginal cost [€/kWh]
- H_{served} = total thermal load served [kWh/yr]
- E_{served} =total electrical load served [kWh/yr]

In the other two scenarios the systems don't serve a thermal load, so H_{served} was null and the formula becomes equal to that described in paragraph 5.1.2.

The boiler marginal cost is the marginal cost of thermal energy from the boiler. It was calculated with the following equation:

$$c_{boiler} = \frac{3.6 * (c_{fuel} + c_{boiler,emissions})}{\eta_{boiler} * LHV_{fuel}} \quad \text{Eq. 15}$$

Where:

- c_{fuel} =cost of fuel [€/kg] (1.85 €/L then converted in €/kg through the fuel density that is 820 kg/m^3)
- $c_{boiler,emissions}$ =cost penalty associated with emissions from the boiler [€/kg of fuel] (supposed equal to zero)
- η_{boiler} = boiler efficiency [-] (85%)
- LHV_{fuel} = the lower heating value of the boiler fuel [MJ/kg] (43.2 MJ/kg)

After the calculations we obtained the following values: NPC= 8982707 €/kg, LCOE=0.24 €/kWh and LCOH=13.35 €/kg.

In terms of costs this is the more expensive investemnt because all the indexes are higher than those of the previous scenario.

The other economic indexes are reported in Table 23 below.

Table 23 – Economic results; Scenario 3

	NPV [€]	PBP [years]	IRR	ROI
Scenario 3	2105870.427	17	9.33%	23%

The graph of the cumulative NPV is shown below.

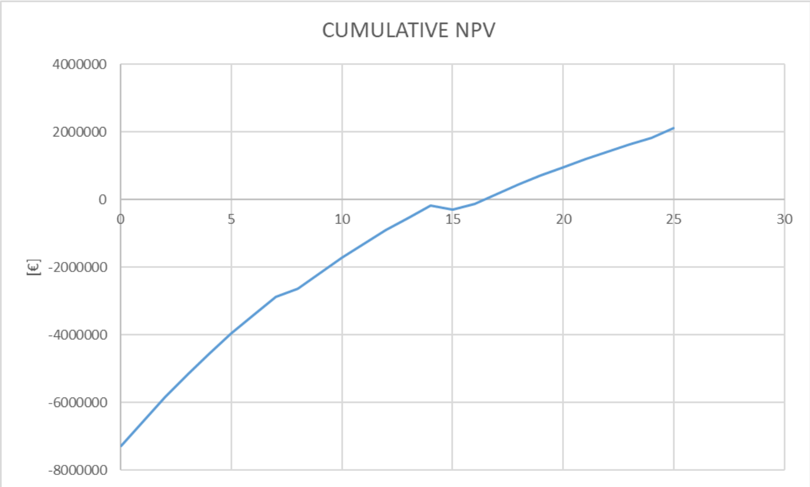

Figure 71 - Cumulative NPV; Scenario 3.

5.3.3 Risk analysis

For the risk analysis in the 3rd scenario the initial assumptions are always the same, so, the average hydrogen demand is considered 85% of the total capacity of the system, but since we have a reduction of the capacity for this scenario the amount of hydrogen will be 106.25 kg, it means an yerly demand of 38781.25 kg.

But this is an hybrid system so we also have an electric refueling station where the demand was considered 95% of the total capacity of the electric station. The reason why this value is higher than the HRS average demand is that the electric vehicles market is wellestabilished also in Italy, so the probability to satisfy almost the entire electric demand is higher than that one to satisfy the hydrogen demand. So considering the 95% of the electric demand the average electric demand will be 712.5 kWh/day.

It means that for this scenario we have a double source of income, one coming from the HRS and the other one from the ERS

But the procedure to find the VaR and the risk of loss is the exact same thing done for the other scenarios. So, we found a 5% VaR of -995408.2381 € with the following frequency distribution:

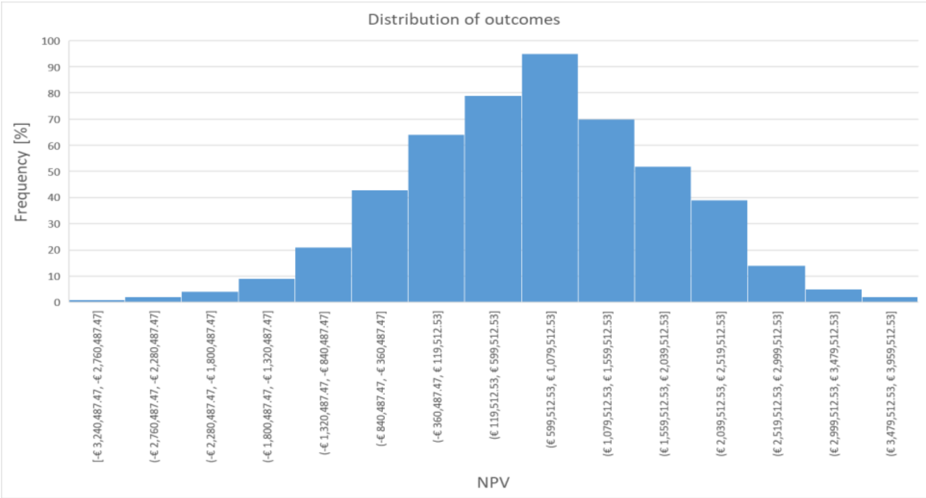

Figure 72 – Frequency distribution, Scenario 3.

Moreover, the risk of loss is 25% and the NPV probability distribution is shown in Figure 73.

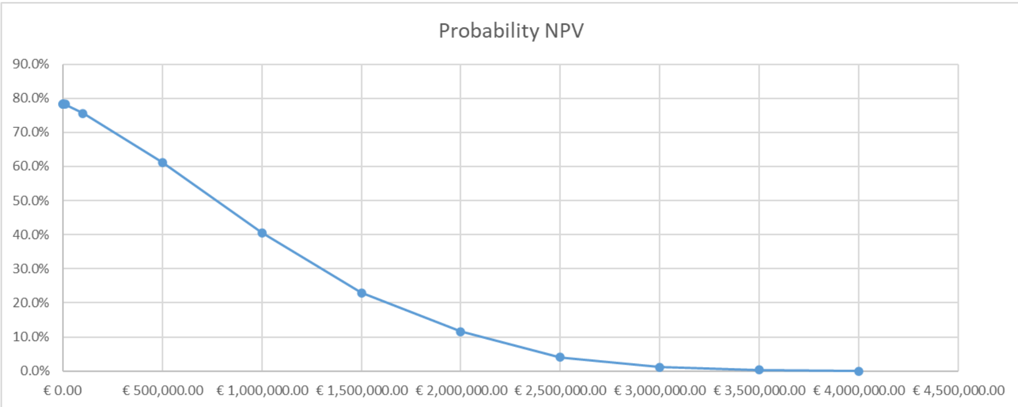

Figure 73 - NPV probability; Scenario 3.

From the risk analysis it’s clear how this scenario has a low level of risk despite it has the higher costs. This is due to the integration of the electric station which guarantee higher security for his well-established market.

5.4 4th scenario HRS Palermo – On grid, PV, Electrolyzer

As we previously saw, scenario numbers 4, 5, and 6 are identical to the first three scenarios but they are located in Palermo. As a result, all assumptions and calculations are identical, and the results will follow the same trend of the scenario with the same layouts. Accordingly, scenario number 1 is connected to scenario number 4, scenario number 2 is connected to scenario number 5, and scenario number 3 is connected to scenario number 6. However, the outcomes will be different and better in terms of both energy and economics. As we previously stated, this is because of the higher levels of solar radiation present in southern Italy, which enables smaller components to produce the same quantity of hydrogen.

So, we just show the graphs of the results below and we will talk about the comparison between the scenarios in the Decision Process paragraph.

5.4.1 Energy analysis

The efficiency of the solar panels does not change, so the PV panels power output will represent always about 17% of the global solar.

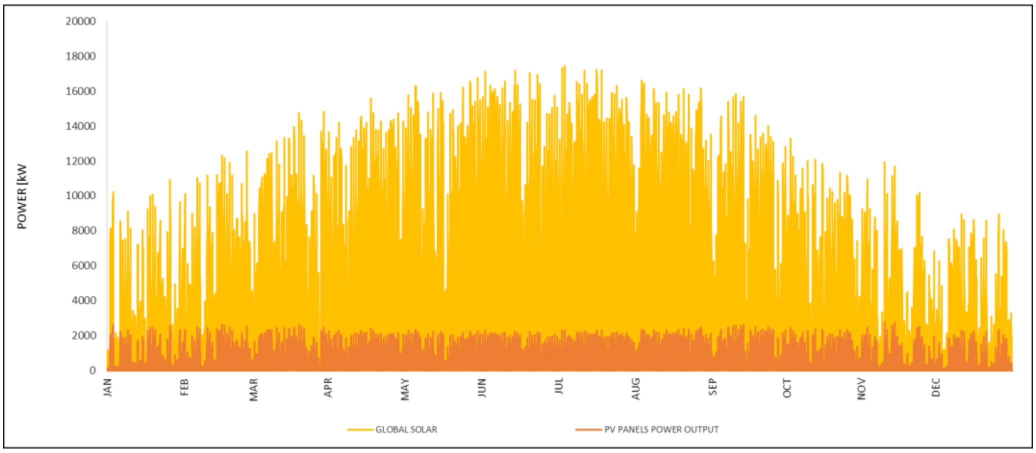

Figure 74 - Global solar irradiance compared with PV panels power output; Scenario 4.

The first difference that we can notice linked with the change in location is that the total electric load power served is a considerable part of the PV panels power output, so we will see that the excess electricity will be lower than the previous scenarios.

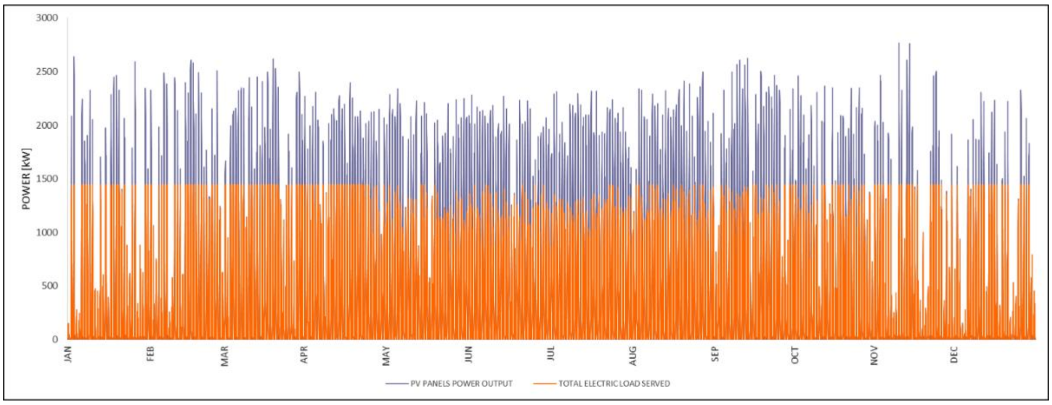

Figure 75 - PV panels power output confronted with total electric load served; Scenario 4.

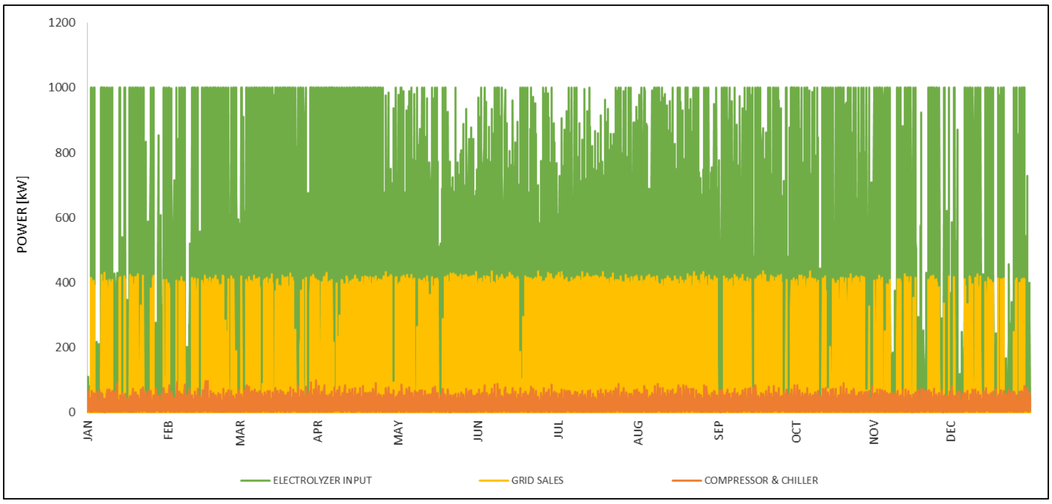

Figure 76 - Three rates of energy yearly consumption; Scenario 4.

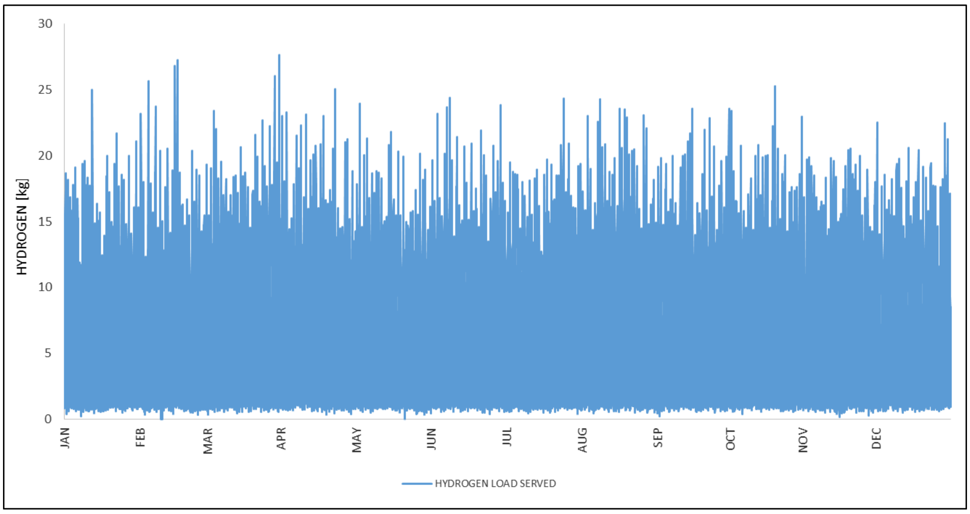

Figure 77 - Hydrogen load; Scenario 4.

The total energy production is always around 4300000 kWh/year but looking the total electricity production output in the pie chart below, the excess electricity is 2% lower than its dual scenario 1.

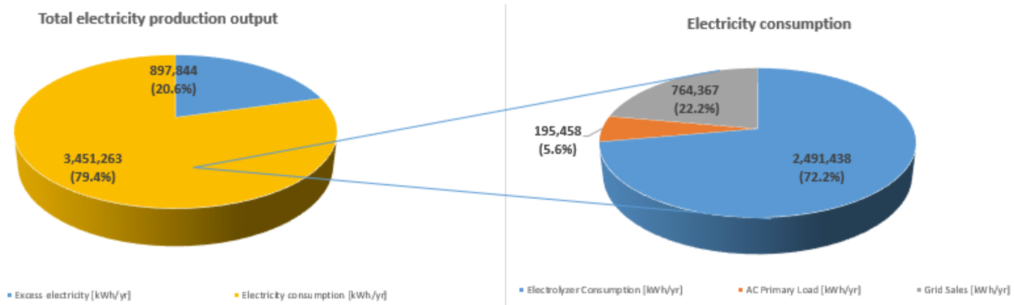

Figure 78 - Electricity summary Scenario 4.

Emissions

The electricity produced by the grid is always the 1% of the total electricity production, so the hydrogen produced is always considered green.

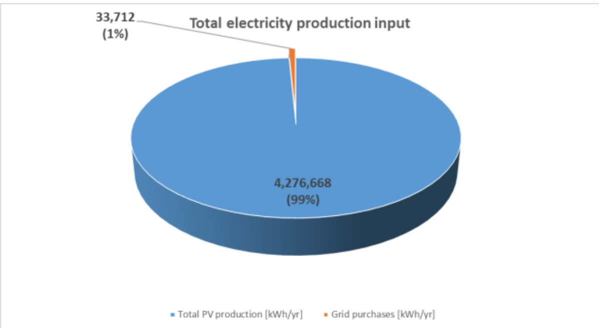

Figure 79 - Electricity summary input; Scenario 4.

Since the total electricity produced is greater than scenario 1, also the emissions will be higher, but the extra amount is negligible.

Table 24 - Emissions; Scenario 4.

Emissions	Carbon Dioxide	Sulfur Dioxide	Nitrogen Oxides
Units	kg/yr	kg/yr	kg/yr
Quantity	22391	97.1	47.5
	99.36%	0.43%	0.21%

5.4.2 Economic analysis

Here in Figure 80 we can notice the first big advantage in terms of costs for the new location, the curve is clearly more flat with a final NPC of 6190773.926 €.

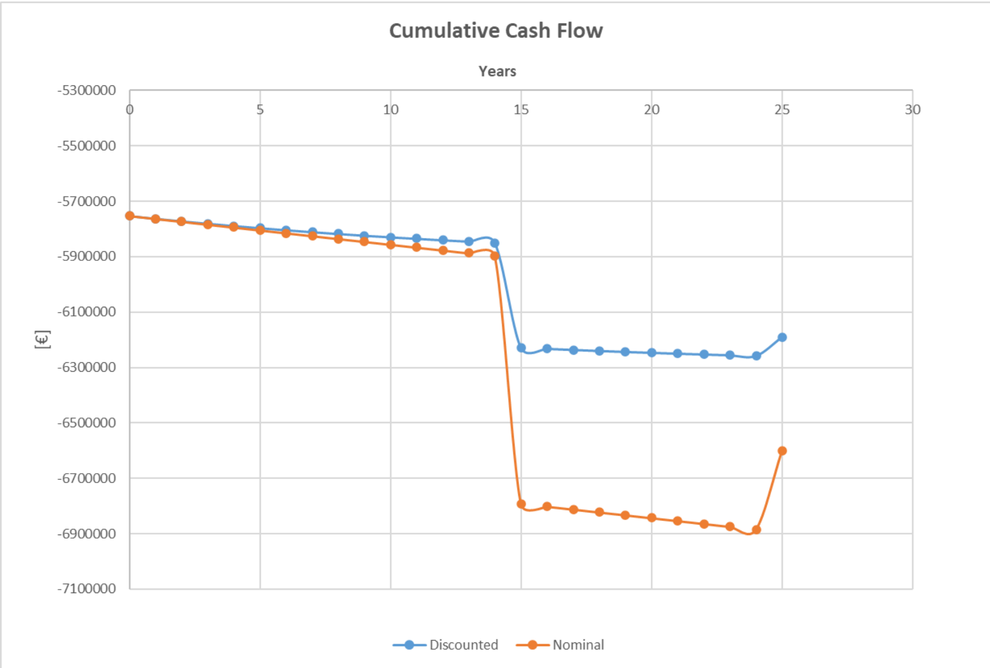

Figure 80 - Cumulative Cash Flow; Scenario 4.

Below is shown the usual graph of the NPC per component.

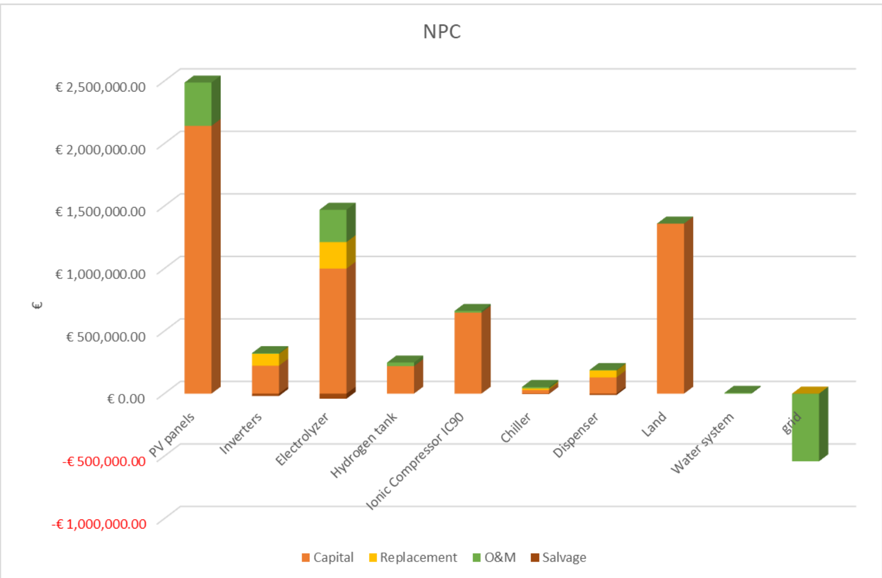

Figure 81 - NPC per component and cost item; Scenario 4.

The first economic results are: NPC= 6190774 €, LCOE=0.14 €/kWh, LCOH=8.91 €/kg.

After established the source of income we obtained the other economic results, summarised in the table below, followed by the cumulative NPV.

Table 25 - Economic results; Scenario 4.

	NPV [€]	PBP [years]	IRR	ROI
Scenario 4	3505833.049	11	11.76%	57%

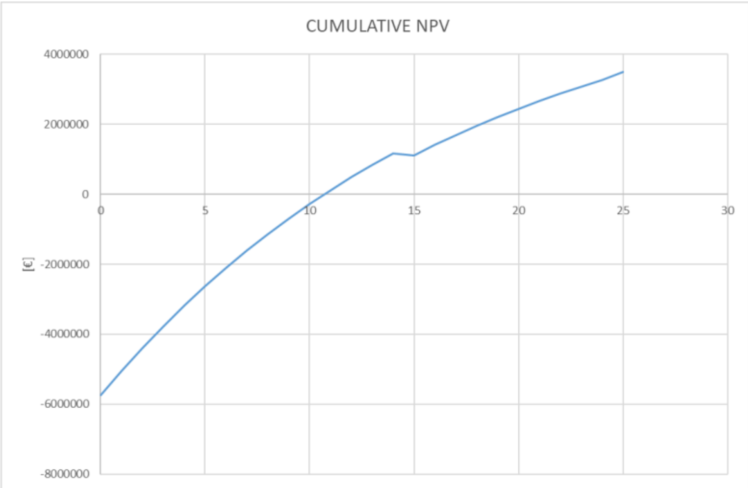

Figure 82 - Cumulative NPV; Scenario 4.

5.4.3 Risk analysis

The risk analysis conducted shows as the risk of the investments located in Palermo is lower than the scenarios located in Turin. This is due to the lower costs faced, so the probability to get a greater profit from the investment is higher.

After the 500 simulations we obtained a 5% var of -59560.38936 €. Compared to the large numbers seen so far this is a small loss.

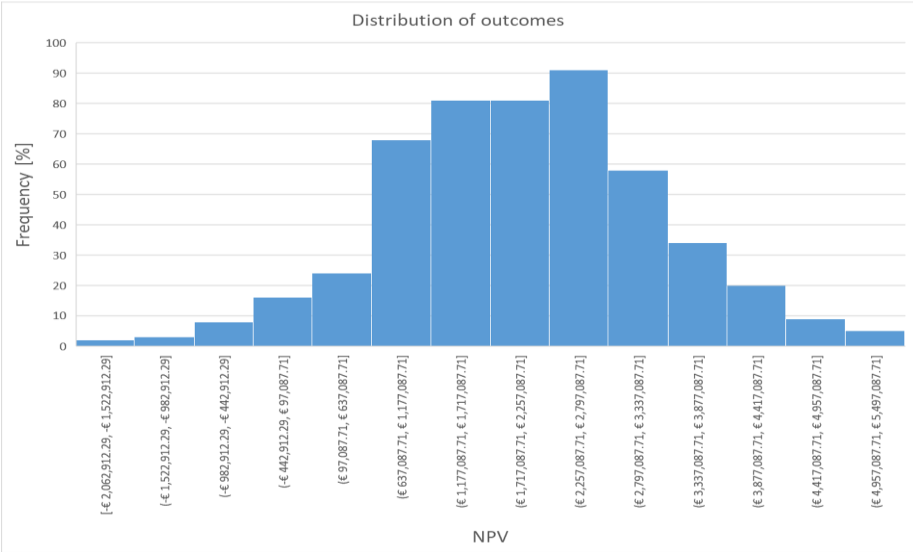

Figure 83 – Frequency distribution, Scenario 4.

Also, the risk of loss is lower than the previous cases. Here it reaches the value of 6%, and from Figure 84 below we can see how the probability to obtain a certain NPV is getting bigger and bigger.

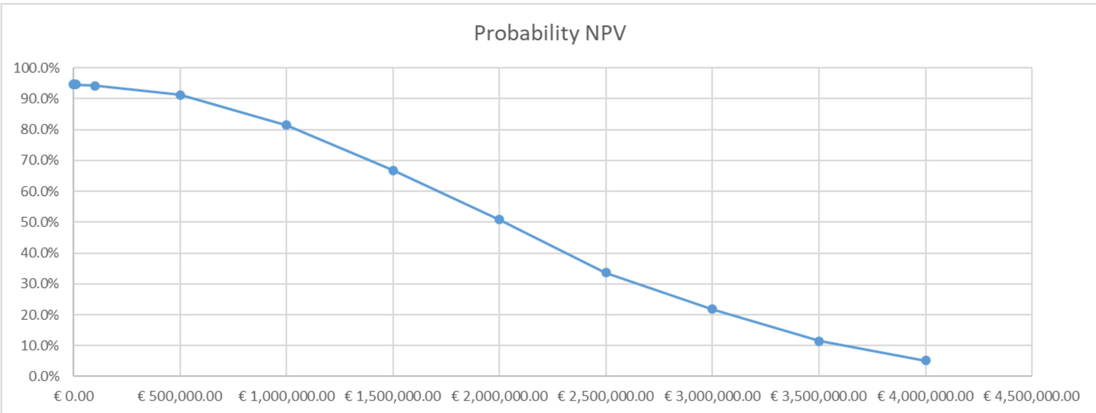

Figure 84 - NPV probability; Scenario 4.

5.5 5th scenario HRS Palermo- Off grid, PV, Battery, Electrolyzer

5.5.1 Energy analysis

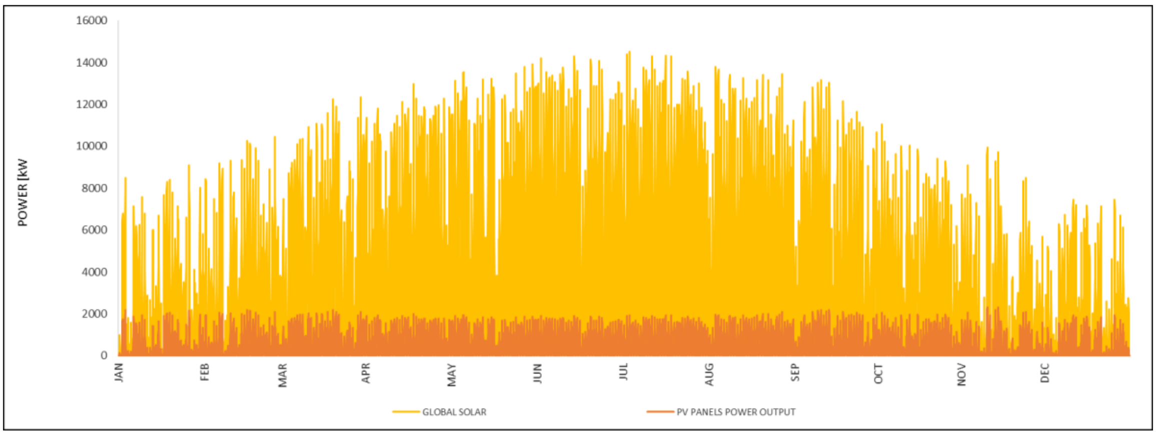

Figure 85 - Global solar irradiance compared with PV panels power output; Scenario 5.

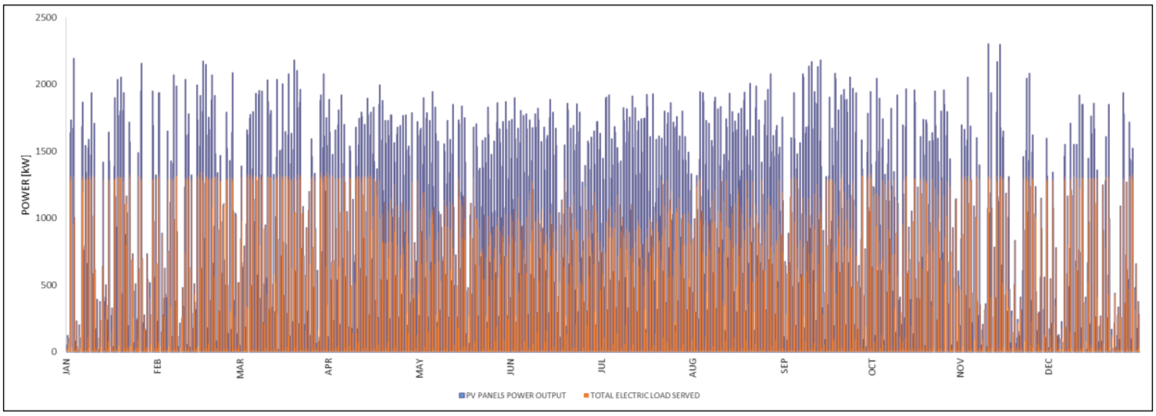

Figure 86 - PV panels power output confronted with total electric load served; Scenario 5.

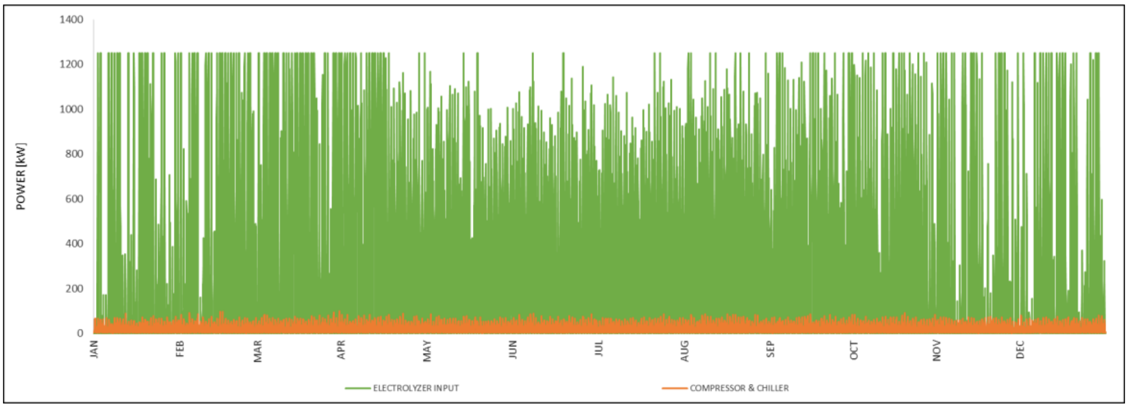

Figure 87 - Two rates of energy yearly consumption; Scenario 5.

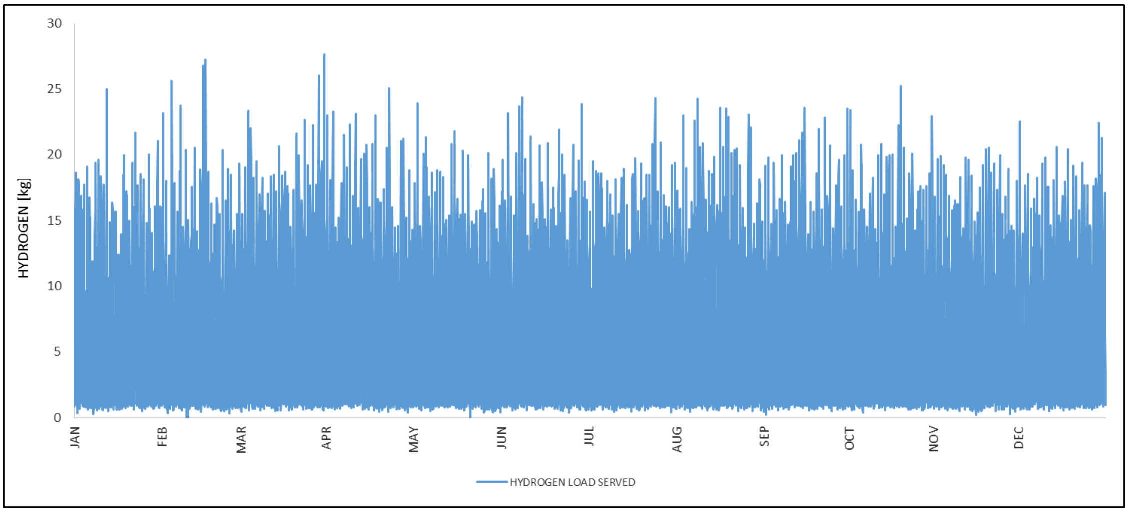

Figure 88 - Hydrogen load; Scenario 5.

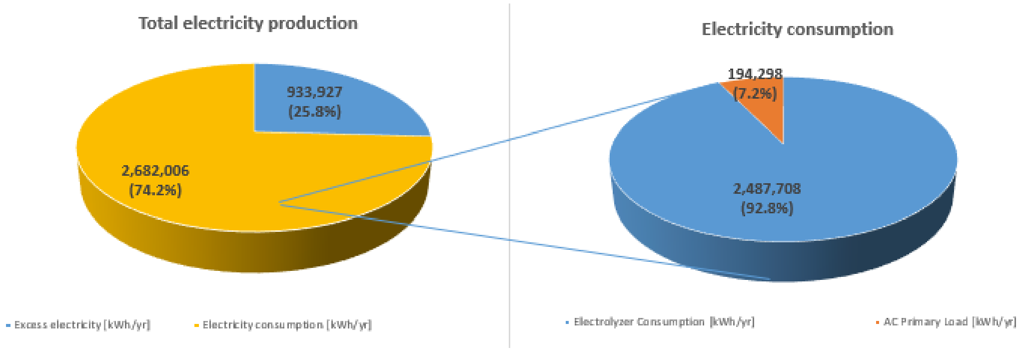

Figure 89 - Electricity summary Scenario 5.

5.5.2 Economic analysis

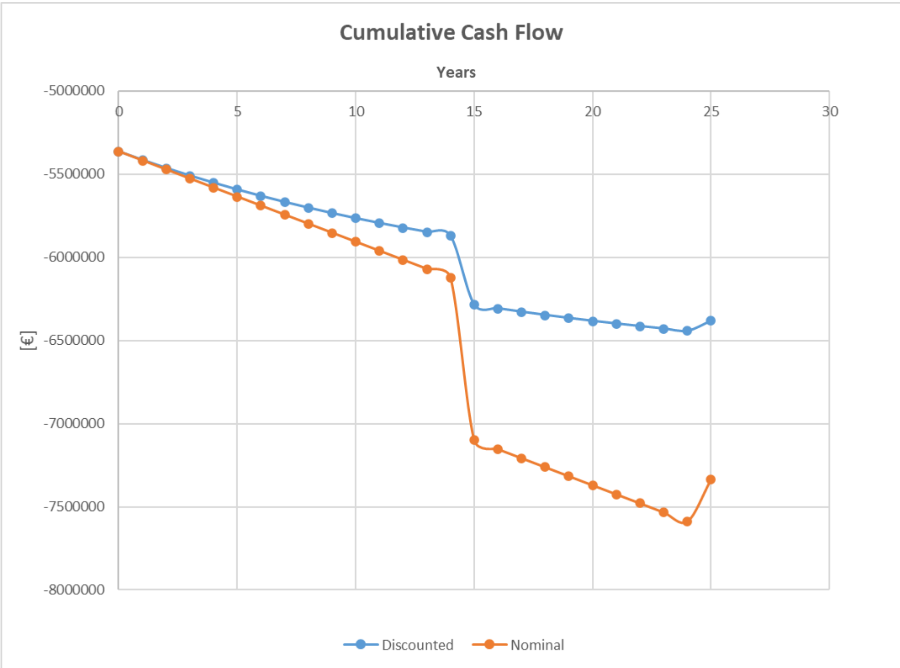

Figure 90 -Cumulative Cash Flow; Scenario 5.

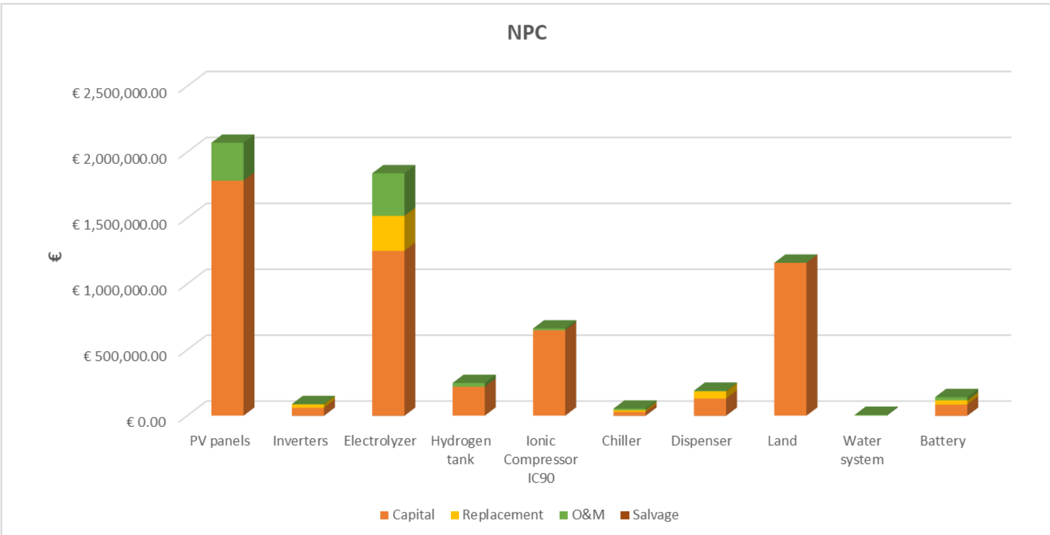

Figure 91 - NPC per component and per cost item; Scenario 5.

NPC= 6383139.7, LCOE=0.18, LCOH= 9.03

Table 26 - Economic results; Scenario 5.

	NPV [€]	PBP [years]	IRR	ROI
Scenario 5	3313467.227	11	11.84%	52%

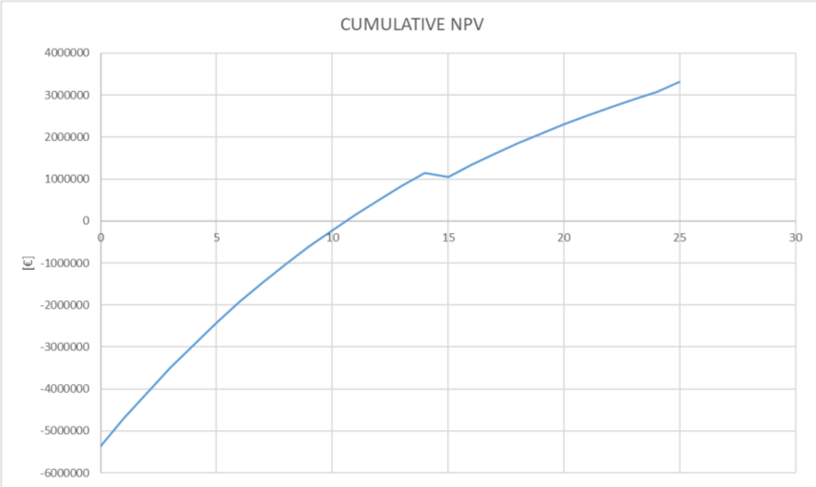

Figure 92 - Cumulative NPV; Scenario 5.

5.5.3 Risk analysis

5% VaR of -195218.9976 €

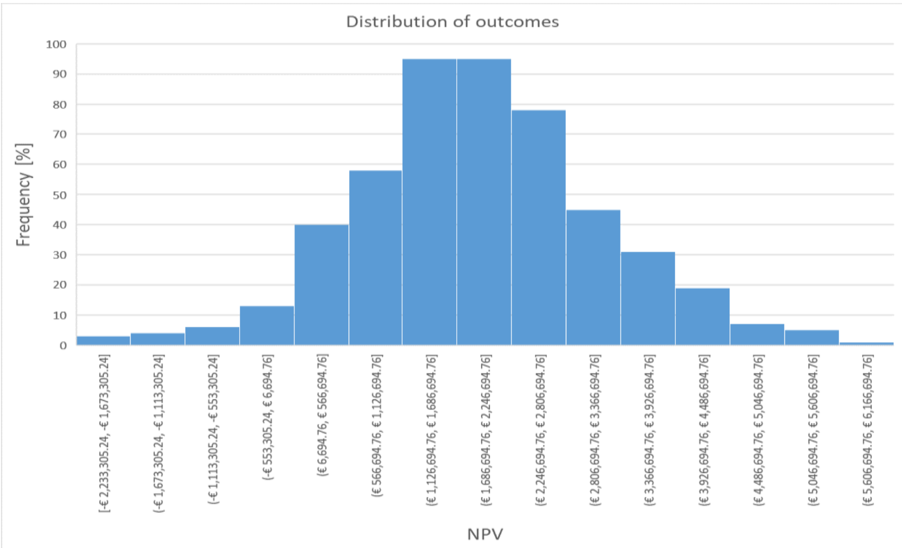

Figure 93 – Frequency distribution, Scenario 5.

Risk of loss= 7%

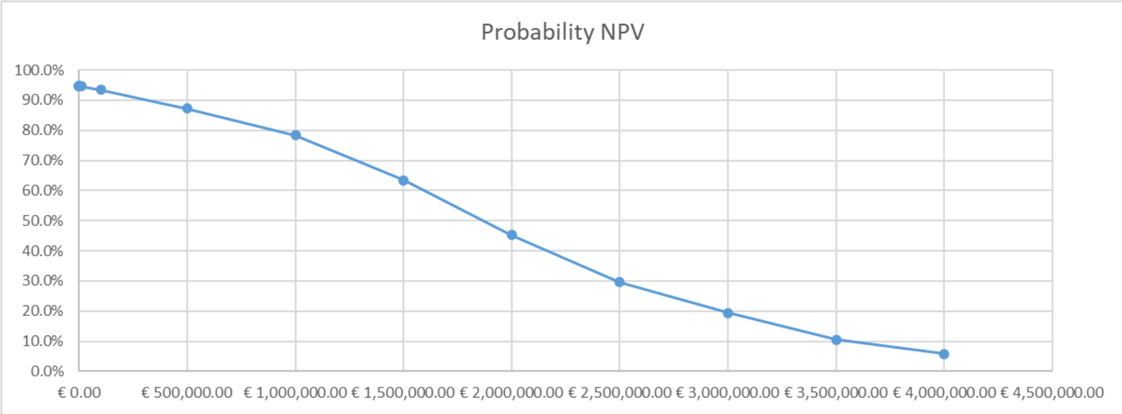

Figure 94 - NPV probability; Scenario 5.

5.6 6th scenario HRS+ERS Palermo- Off grid, PV, Fuel Cell, Electrolyzer and Thermal load

Energy analysis

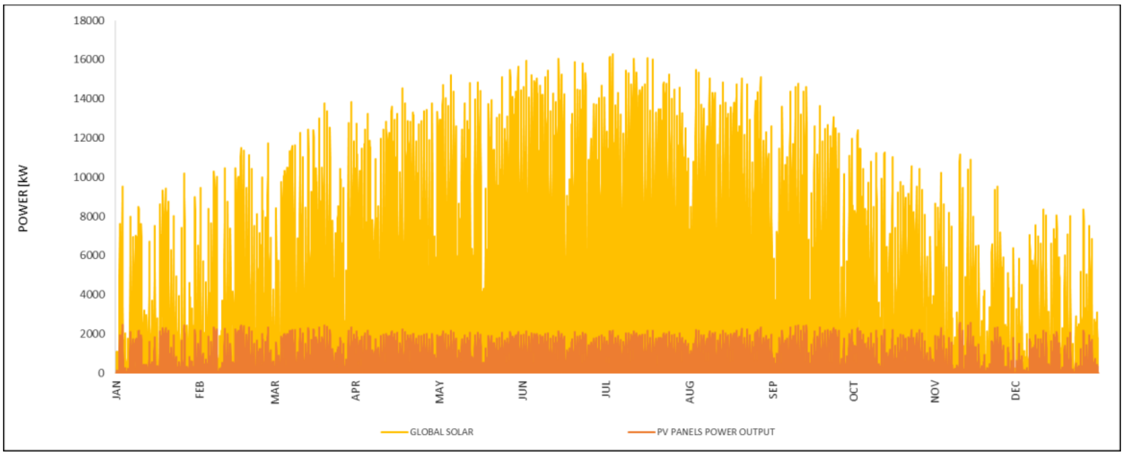

Figure 95 - Global solar irradiance compared with PV panels power output; Scenario 6.

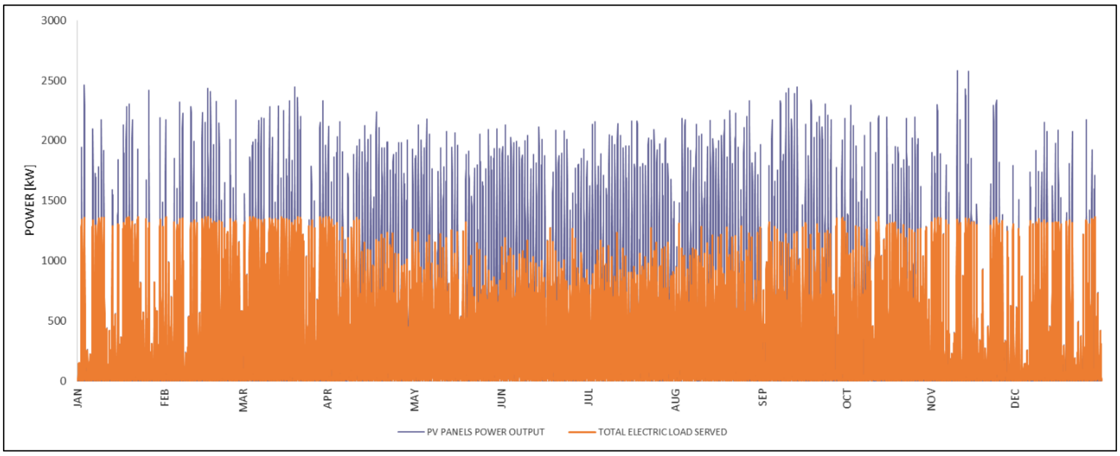

Figure 96 - PV panels power output confronted with total electric load served; Scenario 6.

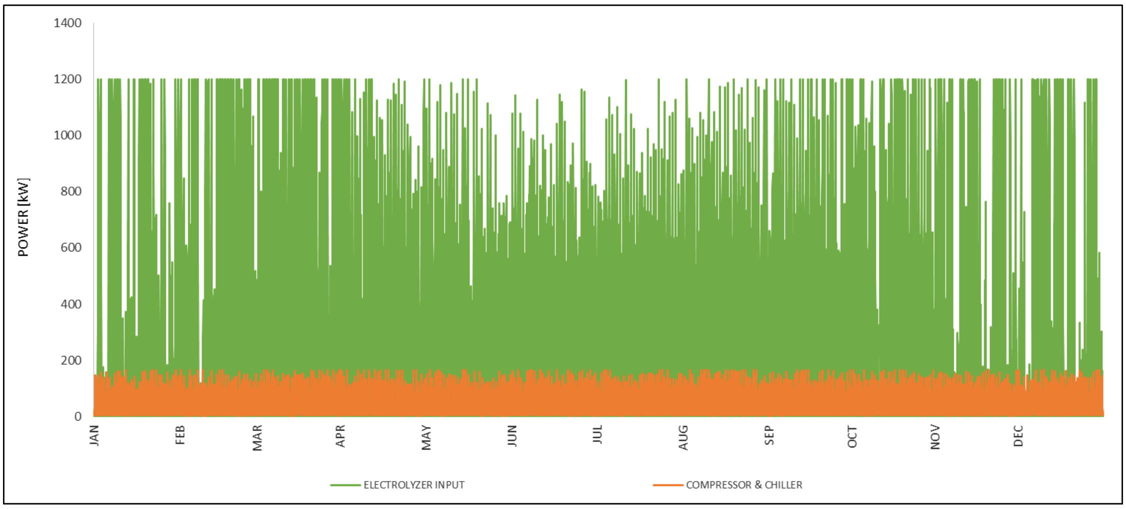

Figure 97 Figure 83 - Two rates of energy yearly consumption; Scenario 6.

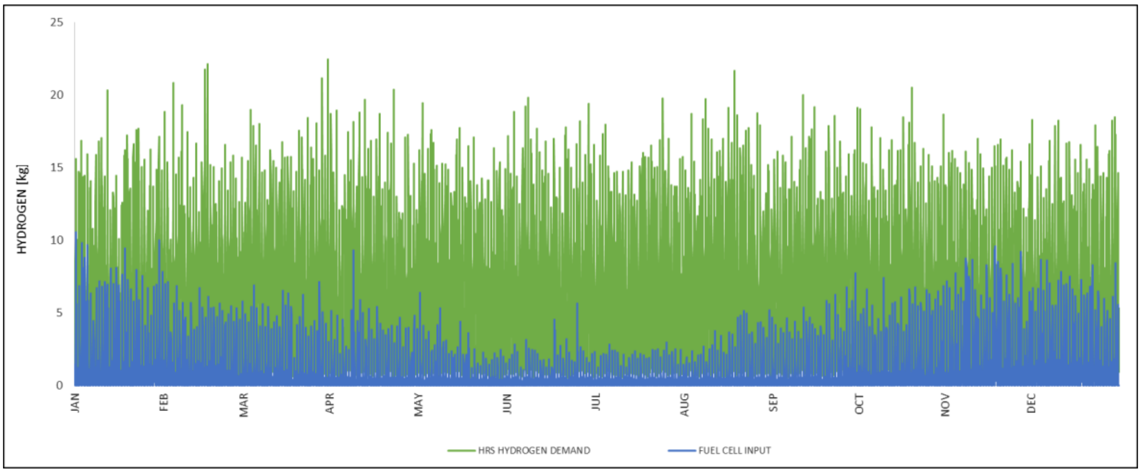

Figure 98 - Hydeogen load; Scenario 6.

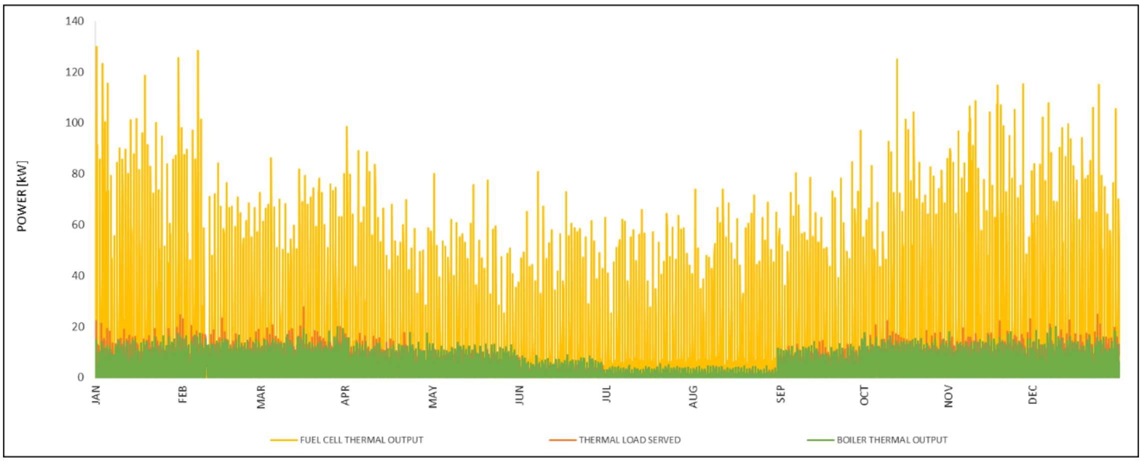

Figure 99 - Thermal rates; Scenario 6.

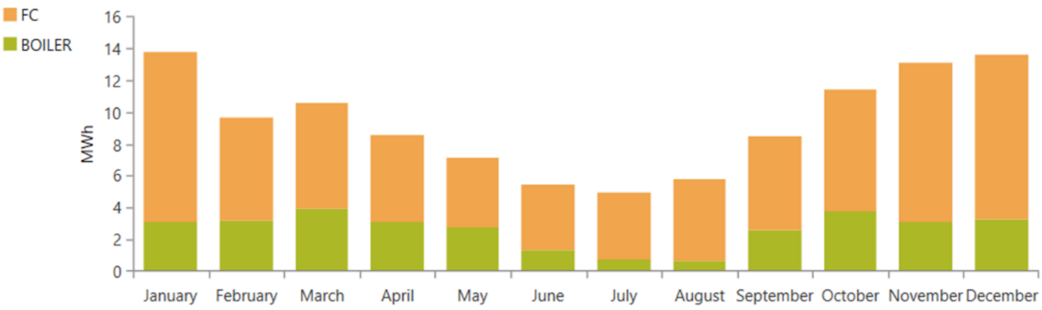

Figure 100 - Thermal inputs; Scenario 6.

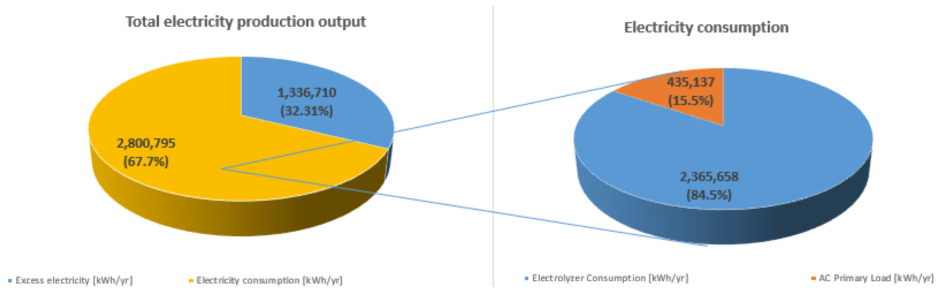

Figure 101 - Electricity summary Scenario 6.

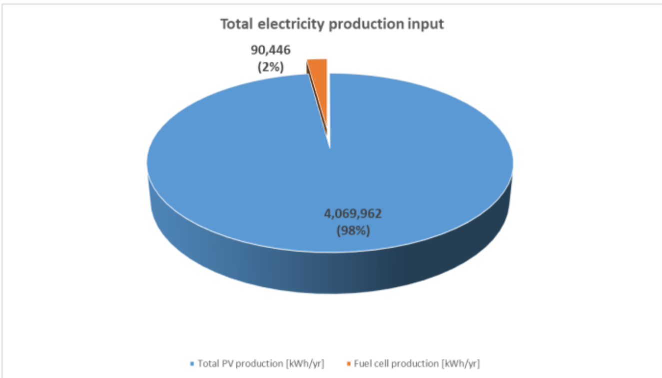

Figure 102 - Electricity summary input; Scenario 6.

5.6.1 Economic analysis

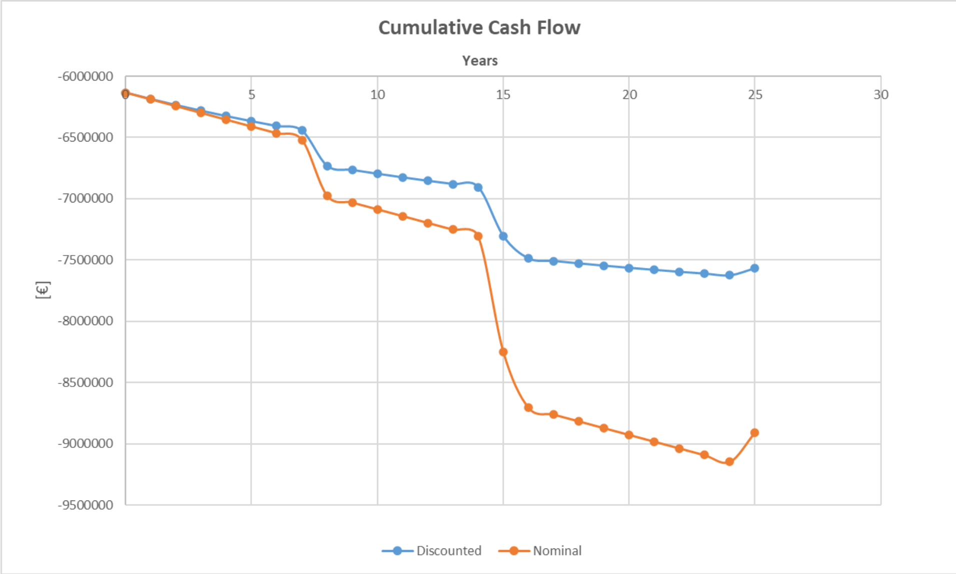

Figure 103 -Cumulative Cash Flow; Scenario 6.

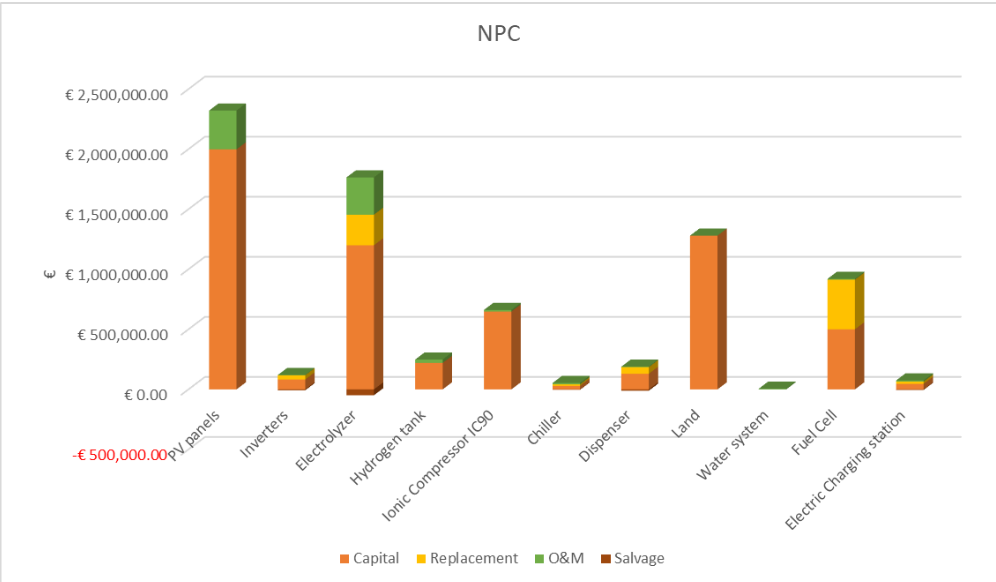

Figure 104 - NPC per component and per cost item; Scenario 6

NPC= 7567661, LCOE=0.20, LCOH=11.25

Table 27 - Economic results; Scenario 6.

	NPV [€]	PBP [years]	IRR	ROI
Scenario 6	3520915.821	11	11.84%	52%

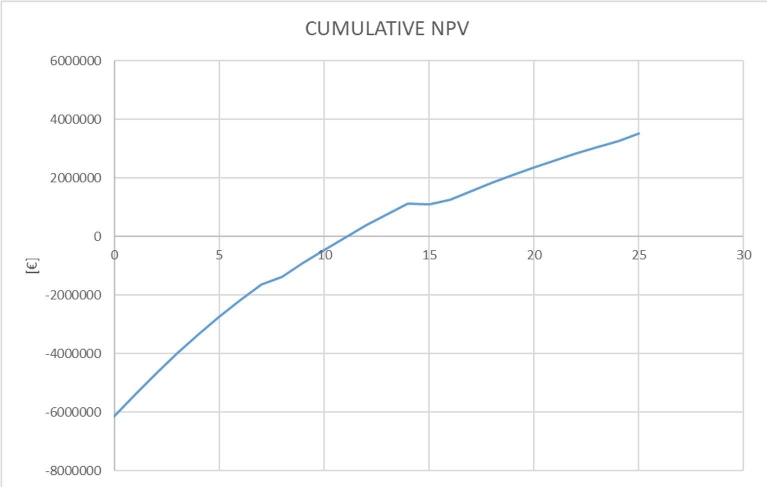

Figure 105 - Cumulative NPV; Scenario 6.

5.6.2 Risk analysis

Here we have a 5% VaR of 426159.706 €. So this is the only case where the VaR is positive; it means that we have the 5% of probability to earn that value.

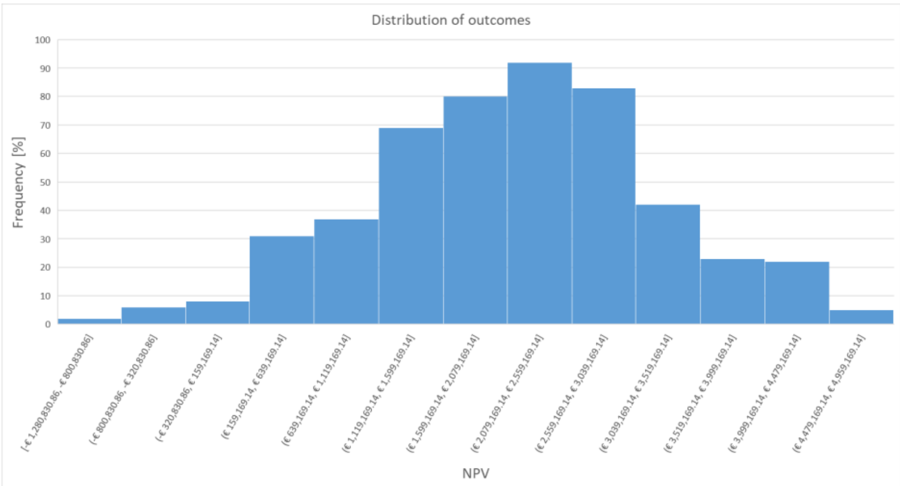

Figure 106 – Frequency distribution, Scenario 6.

So, this is the best scenario in terms of risk and it is clear also from the risk of loss that reach only the 2% of probability.

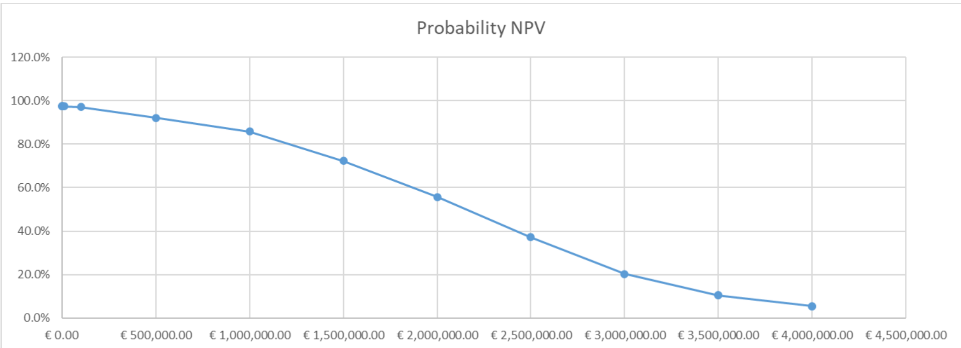

Figure 107 NPV probability; Scenario 6.

6 Decision process

In this chapter the best scenario for each city is identified. But we should consider a lot of criteria of different nature to choose the best one. Hence, to overcome this problem the Analytic Hierarchy Process was used. The Analytic Hierarchy Process (AHP) is a decision-making framework designed to help people make complex decisions involving multiple criteria and alternatives. AHP provides a structured and systematic approach for evaluating and prioritizing different options in a way that considers both qualitative and quantitative factors.

The primary purpose of AHP is to support decision-makers in situations where they need to make choices among various alternatives while considering multiple criteria that might have differing levels of importance.

Here are listed some steps of how AHP works:

1. **Identify the Decision or Goal:** In our case is choosing the best scenario in which to invest.
2. **Identify Criteria:** Determine the criteria that are important for evaluating the alternatives. In our analysis 8 criteria are identified, they are: LCOH, NPV, PBP, IRR, VaR, Risk of loss, Emissions. Our Criteria are summarized in Table 28 below with their values.

Table 28 - Criteria.

CRITERIA	LCOH [€/kg]	NPV [€]	PBP [years]	IRR	ROI	5% VaR of	Risk of loss (NPV<0)	EMISSIONS [kg/year]
scenario 1	10.37870249	2487070.617	14	10%	34%	-888341.8955	21%	21443.6
scenario 2	11.16961748	1796733.831	17	9%	23%	-1618577.391	35%	0
scenario 3	13.35328817	2105870.427	17	9%	23%	-995408.2381	25%	0
scenario 4	8.912112733	3505833.049	11	12%	57%	-59560.38936	5%	22535.6
scenario 5	9.025110657	3313467.227	11	12%	52%	-195218.9976	7%	0
scenario 6	11.24974531	3520915.821	12	12%	47%	426159.706	2%	0

3. **Create a Hierarchy:** Organize the decision problem in a hierarchical structure. At the top is the main objective, followed by intermediate-level criteria, and at the bottom, the specific alternatives. This hierarchy helps break down the problem into manageable parts. This structure is illustrated in Figure 108.

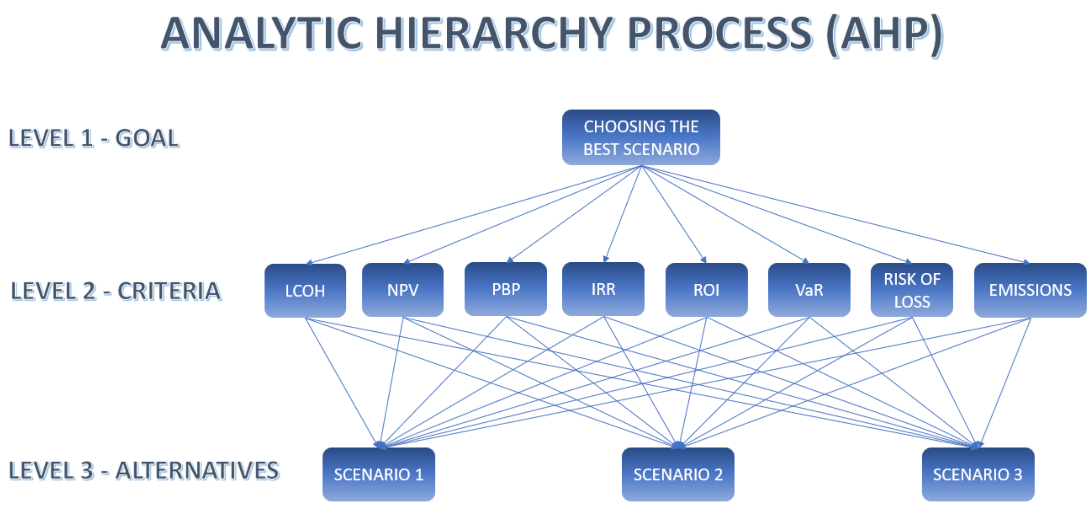

Figure 108 - Hierarchical structure AHP.

4. **Pairwise Comparisons:** The core of AHP involves making pairwise comparisons between elements at each level of the hierarchy. Decision-makers compare each element against every other element in terms of its relative importance with respect to the level above. This is done using a scale that usually ranges from 1 (equal importance) to 9 (extremely more important). All the comparison are reported in the pair-wise comparison matrix below.

Table 29 - Pair-wise comparison matrix.

	LCOH [€/kg]	NPV [€]	PBP [years]	IRR	ROI	5% VaR of	Risk of loss (NPV<0)	EMISSIONS [kg/year]
LCOH [€/kg]	1	1	3	5	4	3	2	1
NPV [€]	1	1	3	5	3	2	2	1
PBP [years]	0.333333333	0.333333333	1	3	2	1	1	0.333333333
IRR	0.2	0.2	0.333333333	1	0.5	0.333333333	0.25	0.2
ROI	0.25	0.25	0.5	2	1	1	0.5	0.25
5% VaR of	0.333333333	0.5	1	3	1	1	0.5	0.333333333
Risk of loss (NPV<0)	0.5	0.5	1	4	0.5	2	1	0.5
EMISSIONS [kg/year]	1	1	3	5	4	3	2	1
SUM	4.616666667	4.783333333	12.83333333	28	16	13.33333333	9.25	4.616666667

5. **Derive Priorities:** With the pairwise comparison data, AHP calculates numerical weights or priorities for each element in the hierarchy. These priorities reflect the relative importance of each element within its respective level. To calculate the criteria weights, we normalized the pair-wise comparison matrix for the sum of each column, and making the average of each row of this new matrix we obtain the criteria weights.

Table 30 - Criteria weights.

	LCOH [€/kg]	NPV [€]	PBP [years]	IRR	ROI	5% VaR of	Risk of loss (NPV<0)	EMISSIONS [kg/year]	CRITERIA WEIGHT
LCOH [€/kg]	0.216606498	0.209059233	0.233766234	0.17857	0.25	0.225	0.216216216	0.216606498	22%
NPV [€]	0.216606498	0.209059233	0.233766234	0.17857	0.1875	0.15	0.216216216	0.216606498	20%
PBP [years]	0.072202166	0.069686411	0.077922078	0.10714	0.125	0.075	0.108108108	0.072202166	9%
IRR	0.0433213	0.041811847	0.025974026	0.03571	0.0313	0.025	0.027027027	0.0433213	3%
ROI	0.054151625	0.052264808	0.038961039	0.07143	0.0625	0.075	0.054054054	0.054151625	6%
5% VaR of	0.072202166	0.104529617	0.077922078	0.10714	0.0625	0.075	0.054054054	0.072202166	8%
Risk of loss (NPV<0)	0.108303249	0.104529617	0.077922078	0.14286	0.0313	0.15	0.108108108	0.108303249	10%
EMISSIONS [kg/year]	0.216606498	0.209059233	0.233766234	0.17857	0.25	0.225	0.216216216	0.216606498	22%

6. **Consistency Check:** AHP checks the consistency of the pairwise comparisons to ensure that the judgments provided by the decision-maker are coherent and not contradictory. If inconsistencies are found, the decision-maker might need to revise their comparisons. To calculate the consistency of the criteria weight we followed several steps to find the consistency ratio and finally compare this value with a standard value consistency ratio, if the calculated value is minor of the standard value, the results are consistent.

    a. First of all, we obtain a new matrix multiplying each value of the pair-wise comparison matrix for the criteria weight for each column. Summing each row of this matrix we obtain the weighted sum value.

Table 31 - Weighted sum value.

	LCOH [€/kg]	NPV [€]	PBP [years]	IRR	ROI	5% VaR of	Risk of loss (NPV<0)	EMISSIONS [kg/year]	WEIGHTED SUM VALUE
LCOH [€/kg]	0.218228264	0.201040764	0.26522392	0.17089	0.2313	0.234582352	0.207818361	0.218228264	1.74726515
NPV [€]	0.218228264	0.201040764	0.26522392	0.17089	0.1734	0.156388234	0.207818361	0.218228264	1.611257067
PBP [years]	0.072742755	0.067013588	0.088407973	0.10253	0.1156	0.078194117	0.10390918	0.072742755	0.701170718
IRR	0.043645653	0.040208153	0.029469324	0.03418	0.0289	0.026064706	0.025977295	0.043645653	0.272095239
ROI	0.054557066	0.050260191	0.044203987	0.06835	0.0578	0.078194117	0.05195459	0.054557066	0.459895928
5% VaR of	0.072742755	0.100520382	0.088407973	0.10253	0.0578	0.078194117	0.05195459	0.072742755	0.624908956
Risk of loss (NPV<0)	0.109114132	0.100520382	0.088407973	0.13671	0.0289	0.156388234	0.10390918	0.109114132	0.833070909
EMISSIONS [kg/year]	0.218228264	0.201040764	0.26522392	0.17089	0.2313	0.234582352	0.207818361	0.218228264	1.74726515

b. Making the average of the weighted sum value we obtain the parameter lambda max that we use to calculate the consistency index (CI) with the following formula:

$$CI = \left|\frac{\lambda_{MAX} - n}{n-1}\right| = 0.00207$$

Where n is the number of criteria that in our analysis are 8, While the λ_{MAX} is equal to 7.985.

c. Finally, we can calculate the consistency ratio dividing the consistency index by the random index. The random index is the consistency index of a randomly generated pairwise matrix and for 8 criteria the random index is 1.41. So, we got a consistency ratio of 0.00147.

d. Comparing the consistency ratio with his standard value of 0.1 it is minor. So, the method is consistent, and we can use the criteria weights found before.

After the criteria weights, we need to aggregate all the criteria with them respective weight for each alternative or scenario; in this way the priority value of each criterion can be found, and summing all of them for each scenario the overall priority value for each scenario is obtained, establishing a clear ranking of the best investments for each city. These processes are faced in the Analytic Network Process (ANP). ANP is designed to address decision situations that involve multiple criteria and interdependencies among these criteria and alternatives. ANP is particularly useful when decisions are made in a network or hierarchical structure, where the relationships between elements are important to consider. All the steps of the ANP are shown in the scheme below.

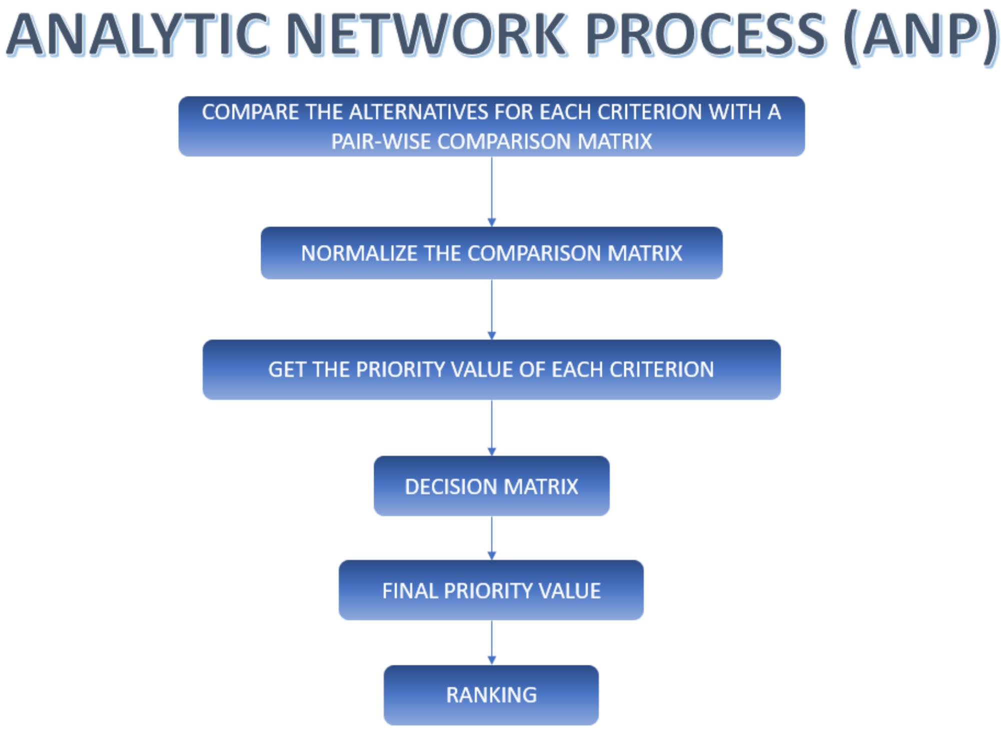

Figure 109 - Analytic Network Process.

7. **Aggregation:** The calculated priorities are aggregated to determine the overall priorities of the alternatives. This involves multiplying the priorities along the paths from the alternatives to the top-level objective. Hence, we compare the alternatives for each criterion finding the priority value of each criterion. Then we can aggregate all the values in the decision matrix.

Table 32 - Decision Matrix; Torino.

	LCOH	NPV	PBP	IRR	ROI	5% VaR of	Risk of loss (NPV<	EMISSIONS [kg/year]	PRIORITY VALUE
Scenario 1	0.117616532	0.13	0.053	0.018366076	0.034688379	0.025040735	0.037795537	0.024247585	44%
Scenario 2	0.064870162	0.03	0.0177	0.006651374	0.011562793	0.009588088	0.038353779	0.096990339	27%
Scenario 3	0.03574157	0.05	0.0177	0.009160023	0.011562793	0.043565294	0.027759864	0.096990339	29%

Table 33 - Decision Matrix; Palermo.

	LCOH	NPV	PBP	IRR	ROI	5% VaR of	Risk of loss (NPV<	EMISSIONS [kg/year]	PRIORITY VALUE
Scenario 4	0.117616532	0.06	0.0354	0.008544368	0.036031093	0.025040735	0.032123557	0.024247585	34%
Scenario 5	0.064870162	0.02	0.0354	0.008544368	0.013845728	0.009588088	0.011386997	0.096990339	27%
Scenario 6	0.03574157	0.11	0.0177	0.017088737	0.007937144	0.043565294	0.060398626	0.096990339	39%

8. **Decision and Interpretation:** The alternative with the highest overall priority is considered the preferred choice. We can see that:

   In Torino the best scenario is the on-grid station with PV panels with a priority value of 44%. Even though this scenario implies yearly emissions, the hydrogen produced is always considered "green" since the electricity requested by the grid is less than 1% and the emissions are extremely low.

   In Palermo the best scenario is the off-grid station with PV panels and a fuel cell storage system; here the priority value is 39%. In this case, we have a zero-emissions system.

7 Conclusions

The culmination of the research and analysis has revealed a rich tapestry of insights into the complexities of hydrogen infrastructure development in urban environments. The research endeavors, consisting of the design and analysis of six diverse scenarios across two distinct locations, Torino and Palermo, have yielded several significant conclusions:

1. Regional Influence on Hydrogen Cost:

One of the key takeaways from this study is the pronounced impact of geographical location on the cost of hydrogen production in PV-powered hydrogen refueling stations. Regions characterized by higher solar irradiance are more conducive to cost-effective hydrogen generation. This is because these regions require smaller and less expensive components to produce the same quantity of hydrogen, contributing to overall system cost reduction.

2. Cost-Effectiveness of On-Grid Layout:

The techno-economic analysis conducted in this study consistently identified the on-grid hydrogen refueling station layout as the most cost-effective option, both in Torino and Palermo. In Torino, this layout exhibited a Levelized Cost of Hydrogen (LCOH) of 10.38 €/kg, while in Palermo, it demonstrated an even lower LCOH of 8.91 €/kg. These findings underscore the importance of leveraging existing grid infrastructure to optimize hydrogen production costs.

3. Risk-Informed Decision-Making:

Complementing the economic analysis, a comprehensive risk assessment, utilizing the Analytic Hierarchy Process (AHP), played a pivotal role in evaluating the resilience of each scenario. Remarkably, the risk analysis consistently favored the on-grid scenario for Torino, aligning with the economic assessments. However, in Palermo, the hybrid refueling station with a fuel cell emerged as the optimal choice, illustrating the contextual importance of risk considerations.

4. Promising Potential of Fuel Cell Vehicles:

The research conducted in this thesis underscores the promising potential of fuel cell vehicles (FCVs) as a viable alternative to traditional combustion engine vehicles. FCVs, when considered alongside battery electric vehicles (BEVs), offer a compelling solution for achieving a more sustainable, cleaner, and environmentally friendly future in the transportation sector. Their ability to generate electricity through hydrogen and emit only water vapor as a byproduct positions them as a critical player in reducing greenhouse gas emissions and mitigating the environmental impacts associated with conventional gasoline and diesel vehicles.

In summary, this thesis advances our understanding of hydrogen infrastructure design and economic viability within the dynamic urban landscapes of Torino and Palermo. The research underscores the pivotal role of regional characteristics, particularly solar irradiance, in influencing the cost-effectiveness of hydrogen production. Moreover, it highlights the potential for on-grid layouts to be a cost-efficient choice, especially in regions with favourable solar resources.

Additionally, the incorporation of risk analysis serves as a valuable reminder of the multifaceted nature of infrastructure projects, emphasizing the need for comprehensive assessments that go beyond economic considerations.

As the world continues to navigate the transition toward cleaner and more sustainable energy sources, the findings presented in this thesis provide a robust foundation for policymakers, industry stakeholders, and researchers to make informed decisions regarding the design and deployment of hydrogen refueling stations, ultimately contributing to the advancement of sustainable energy solutions. The interplay of location, technology, and risk assessment highlighted in this study points the way toward a more resilient and cost-effective hydrogen infrastructure future.

Appendix

Table 34 - Historical inflation rates for Italy last 10 years [75].

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2023	10.7%	9.8%	8.1%	8.7%	8.0%								9.1%
2022	5.1%	6.2%	6.8%	6.3%	7.3%	8.5%	8.4%	9.1%	9.4%	12.6%	12.6%	12.3%	8.7%
2021	0.7%	1.0%	0.6%	1.0%	1.2%	1.3%	1.0%	2.5%	2.9%	3.2%	3.9%	4.2%	1.9%
2020	0.4%	0.2%	0.1%	0.1%	-0.3%	-0.4%	0.8%	-0.5%	-1.0%	-0.6%	-0.3%	-0.3%	-0.1%
2019	0.9%	1.1%	1.1%	1.1%	0.9%	0.8%	0.3%	0.5%	0.2%	0.2%	0.2%	0.5%	0.6%
2018	1.2%	0.5%	0.9%	0.6%	1.0%	1.4%	1.9%	1.6%	1.5%	1.7%	1.6%	1.2%	1.2%
2017	1.0%	1.6%	1.4%	2.0%	1.6%	1.2%	1.2%	1.4%	1.3%	1.1%	1.1%	1.0%	1.3%
2016	0.4%	-0.2%	-0.2%	-0.4%	-0.3%	-0.2%	-0.2%	-0.1%	0.1%	-0.1%	0.1%	0.5%	-0.1%
2015	-0.5%	0.1%	0.0%	-0.1%	0.2%	0.2%	0.4%	0.3%	0.2%	0.3%	0.1%	0.1%	0.1%
2014	0.6%	0.4%	0.3%	0.5%	0.4%	0.3%	0.0%	-0.1%	-0.1%	0.2%	0.3%	0.0%	0.2%
2013	2.4%	2.0%	1.8%	1.2%	1.2%	1.2%	1.2%	1.1%	0.9%	0.7%	0.6%	0.6%	1.2%

References

[1] R. Hannah and R. Max, "Our World in Data," 2023. [Online]. Available: https://ourworldindata.org/co2-emissions.

[2] "United Nation Climate Change," [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement.

[3] L. William F., M. Grubb, D. Francesca and M. Jan C., "Country with sustained greenhouse gas emissions reductions: an analysis of trends and progress by sector," *Climate Policy,* vol. 22, 2021.

[4] R. Hannah and R. Max, "Our World in Data," [Online]. Available: https://ourworldindata.org/greenhouse-gas-emissions.

[5] H. Ritchie, "Our World in Data," 18 September 2020. [Online]. Available: https://ourworldindata.org/ghg-emissions-by-sector.

[6] "EPA," [Online]. Available: https://www.epa.gov/greenvehicles/hydrogen-transportation#:~:text=Most%20fuel%20cell%20electric%20vehicles,engine%20to%20power%20the%20wheels..

[7] A. J.O., P. A.P.I., A. E. and P. O.M., "Hydrogen energy, economy and storage: Review and recommendation," *International Journal of Hydrogen Energy.,* vol. 44, no. 29, pp. 15072-15086, 2019.

[8] A. A. and H. R., "Prospects and impediments for hydrogen and fuel cell vehicles in the transport sector.," *International Journal of Hydrogen Energy,* vol. 46, no. 16, pp. 10049-10058, 2021.

[9] G. David L., O. Joan M. and L. Zhenhong, "Challenges in the designing, planning and deployment of hydrogen refueling infrastructure for fuel cell electric vehicles," *eTrasportation,* vol. 6, p. 100086, 2020.

[10] R. Krish, E. Amgad, R. Neha and G. Erika, "Impact of Hydrogen Refueling Configurations and Market Parameters on the Refueling Cost of Hydrogen," *International Journal of Hydrogen Energy,* vol. 42, no. 34, pp. 21855-21865, 2017.

[11] [Online]. Available: https://www.google.com/imgres?imgurl=https%3A%2F%2Fwww.fuelcellbuses.eu%2Fsites%2Fdefault%2Ffiles%2Ffuel-cell.png&tbnid=EykFpapnBbq4UM&vet=12ahUKEwiO7Z7-yt6BAxX_8bsIHeR1BPAQMygDegQIARBW..i&imgrefurl=https%3A%2F%2Fwww.fuelcellbuses.eu%2Fwiki%2Ffuel-cells-h.

[12] "DriveClean," [Online]. Available: https://driveclean.ca.gov/hydrogen-fuel-cell#:~:text=Fuel%20cell%20cars%20are%20powered,powers%20the%20car's%20electric%20motors..

[13] "H2Stations.org," 1 February 2023. [Online]. Available: https://www.h2stations.org/press-release-2023-another-record-addition-of-european-hydrogen-refuelling-stations-in-2022/.

[14] Y. Rajan, "Verified Market Research," May 2023. [Online]. Available: https://www.verifiedmarketresearch.com/blog/top-hydrogen-fuel-companies/.

[15] "Autoscout24," 15 March 2023. [Online]. Available: https://www.autoscout24.it/informare/consigli/scelta-e-acquisto/auto-idrogeno-2023-i-modelli-in-vendita-e-prezzi/.

[16] Z. Caizhi and C. e. a. Xiujuan, "Review on the safety analysis and protection strategies of fast filling hydrogen storage system for fuel cell vehicle application," *Journal of Energy Storage,* vol. 45, p. 103451, 2022.

[17] "Hydrogen Fuel News," 22 May 2023. [Online]. Available: https://www.hydrogenfuelnews.com/how-safe-are-hydrogen-fuel-cell-vehicles-in-a-crash/8539783/?expand_article=1.

[18] K. Nejic and I. G. e. al, "A review on metal hydride materials for hydrogen storage," *Journal of Energy Storage,* vol. 72, p. 108456, 2023.

[19] A. Elham and S. Fatemeh, "Review of hydrogen safety during storage, transmission, and applications processes," *Journal of Loss Prevention in the Process Industries,* vol. 72, p. 104569, 2021.

[20] K. Adrian, N. Lorenzo and e. al, "An Overview of Parameter and Cost for Battery Electric Vehicles.," *World Electric Vehicles Journal,* 2021.

[21] H. Ahmed t. and O. Mehmet F., "An overview of regenerative braking systems," *Journal of Energy Storage,* vol. 52, p. 105033, 2022.

[22] R. Jiageng, W. Paul and Z. Nong, "A comparative study energy consumption and costs of battery electric vehicle trasmissions," *Applied Energy,* vol. 165, pp. 119-134, 2016.

[23] "ev-database," [Online]. Available: https://ev-database.org/cheatsheet/range-electric-car.

[24] S. Tyler J., W. Justin A. and e. al, "Comparative analysis of battery electric vehicle thermal managment systems under long-range drive cycles," *Applied Thermal Engineering,* vol. 198, p. 117506, 2021.

[25] Global EV Outlook 2023, "iea.org," 2023. [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2023/trends-in-electric-light-duty-vehicles.

[26] "Toyota," 2023. [Online]. Available: https://www.toyota.com/bz4x/2023/.

[27] "tate," 31 May 2022. [Online]. Available: https://tate.it/elettrica/mobilita/come-fare/potenza-kw-colonnine-tempi-ricarica.

[28] "Lyfe Heroes," 21 April 2023. [Online]. Available: https://www.lhyfe-heroes.com/about-hydrogen/hydrogen-cars-vs-electric-cars-which-is-the-better-choice.

[29] "leaseplan," 14 May 2021. [Online]. Available: https://www.leaseplan.com/it-it/news-auto/futuro-della-mobilita/auto-a-idrogeno-come-funzionano-costi-e-modelli/#:~:text=Il%20costo%20dell'idrogeno%20si,tratta%20di%20un%20rifornimento%20green..

[30] "Il sole 24 ore," August 2023. [Online]. Available: https://lab24.ilsole24ore.com/prezzo-benzina/.

[31] "AutoScout24," 03 January 2022. [Online]. Available: https://www.autoscout24.it/informare/consigli/prima-dell-acquisto/auto-che-consumano-meno-classifica/#:~:text=Ma%20quanto%20consuma%20un'auto,16%20chilometri%20con%20un%20litro.

[32] R. Ciriaco, "INSIDEEVs," 30 June 2023. [Online]. Available: https://insideevs.it/news/603071/prezzi-ricarica-auto-elettrica-confronto/.

[33] "AutoScout24," 03 March 2023. [Online]. Available: https://www.autoscout24.it/informare/consigli/migliori-auto/auto-elettrica-economica-queste-auto-elettriche-sono-efficienti-e-economiche/.

[34] B. David, F. Michael, M. Caio and G. Alessandro, "The Future of the EU Automotive Sector," October 2021. [Online]. Available: https://www.europarl.europa.eu/RegData/etudes/STUD/2021/695457/IPOL_STU(2021)695457_EN.pdf.

[35] "Chemistry Learner," [Online]. Available: https://www.chemistrylearner.com/electrolysis-of-water.html.

[36] K. S. Shiva and V. Himabindu, "Hydrogen production by PEM water electrolysis," *Materials Science for Energy Technologies,* pp. 442-454, 2019.

[37] G. e. a. Yujing, "Comparison between hydrogen production by alkaline water electrolysis and hydrogen production by PEM electrolysis," in *IOP Conference Series: Earth and Enviromental Science*, 2019.

[38] "Wikipedia," [Online]. Available: https://en.wikipedia.org/wiki/Solid_oxide_electrolyzer_cell.

[39] "Wikipedia," [Online]. Available: https://en.wikipedia.org/wiki/Proton_exchange_membrane_electrolysis.

[40] "Wikipedia," [Online]. Available: https://en.wikipedia.org/wiki/Proton-exchange_membrane.

[41] L. Li, H. Manier and M.-A. Manier, "Hydrogen supply chain network design: An optimization-oriented review," *Renewable and Sustainable Energy Reviews,* vol. 103, pp. 342-360, April 2019.

[42] D. Apostolou and G. Xydis, "A literature review on hydrogen refueling stations and infrastructure. Current status and future prospects," *Renewable and Sustainable Energy Reviews,* vol. 113, 2019.

[43] M. Genovese and P. Fragiacomo, "Hydrogen refueling station: Overview of the technological status and research enhancement," *Journal of Energy Storage,* vol. 61, p. 22, 2023.

[44] A. Bauer, T. Mayer, M. Semmel, M. A. G. Morales and J. Wind, "Energetic evaluation of hydrogen refueling stations with liquid or gaseous stored hydrogen," *International Journal of Hydrogen Energy,* vol. 44, no. 13, pp. 6795-6812, 2019.

[45] "Office of Energy efficiency & renewable energy," [Online]. Available: https://www.energy.gov/eere/fuelcells/gaseous-hydrogen-compression#:~:text=Hydrogen%20is%20typically%20produced%20at,can%20be%20reciprocating%20or%20rotary..

[46] E. Rothuizen and R. M., "Optimization of the overall energy consumption in cascade fueling stations for hydrogen vehicles," *International Journal of Hydrogen Energy,* vol. 39, pp. 582-592, 2014.

[47] E. Talpacci, M. Reub, T. Grube, R. G. M. R. P. Cilibrizzi and D. Stolten, "Effect of cascade storage system topology on the cooling energy consumption in fueling stations for hydrogen vehicles,"

International Journal of Hydrogen Energy, vol. 43, pp. 6256-6265, 2018.

[48] C. Blazquez-Diaz, "Techno-economic modelling and analysis of hydrogen fuelling stations," *International Journal of Hydrogen Energy,* vol. 44, pp. 495-510, 2019.

[49] C. P. e. al., "Model predictive control of an on-site green hydrogen production and refuelling station," *International Journal of Hydrogen Energy,* 2023.

[50] E. M. B. e. al., "Optimal sizing of photovoltaic systems based green hydrogen refueling stations case study Oman," *International Journal of Hydrogen Energy,* vol. 47, pp. 31964-31973, 2022.

[51] S. D. M. e. al., "On-site solar powered refueling stations for green hydrogen production and distribution: performances and costs," *Web of Conferences,* vol. 334, 2022.

[52] M. Minutillo and a. et, "Analyzing the levelized cost of hydrogen in refueling stations with on-site hydrogen production via water electrolysis in the Italian scenario," *International Journal of Hydrogen Energy,* vol. 46, pp. 3667-3677, 2021.

[53] M. G. e. al., "Optimal design of a Hydrogen Refuelling Station (HRFS) powered by Hybrid Power System," *Energy Conversion and Management,* vol. 161, pp. 215-224, 2018.

[54] X. X. e. al., "Optimal operational strategy for an offgrid hybrid hydrogen/electricity refueling station powered by solar photovoltaics," *Journal of Power Sources,* vol. 451, 2020.

[55] "ANAS," [Online]. Available: https://www.stradeanas.it/it/le-strade/osservatorio-del-traffico/dati-traffico-medio-giornaliero-annuale.

[56] A. Karakilic, A. Karafil and N. Genc, "Effects of temperature and solar irradiation on performance of monocrystalline, polycrystalline and thin-film PV panels," *Intrnational Journal on "Technical and Physical Problems of Engineering",* vol. 14, no. 51, pp. 254-260, 2022.

[57] "Hyfindr," [Online]. Available: https://hyfindr.com/hydrogen-refueling-station/.

[58] E. Amgad and K. Reddi, "Hydrogen Fueling Station Pre-Cooling Analysis," *DOE Hydrogen and Fuel Cells Program,* 2016.

[59] M. Gardiner, "Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs," *DOE Hydrogen and Fuel Cells Program Record,* 2009.

[60] F. Spertino, "RIENERGIA," 20 July 2021. [Online]. Available: https://rienergia.staffettaonline.com/articolo/34808/Fotovoltaico:+%C3%A8+vero+che+sul+tetto+abbiamo+un+tesoro+nascosto/Spertino#:~:text=Infine%2C%20per%20gli%20usi%20industriali,i%2010.000%20%E2%82%AC%20all'anno..

[61] L. Schirru, "mr.kilowatt," 27 April 2023. [Online]. Available: https://www.mrkilowatt.it/sistemi-di-accumulo/costo-batterie-per-fotovoltaico/.

[62] C. Alessandro and F. Samuele, "l'Astrolabio," 26 June 2023. [Online]. Available: https://astrolabio.amicidellaterra.it/node/2350.

[63] "Segugio.it," 27 June 2023. [Online]. Available: https://tariffe.segugio.it/guide-e-strumenti/domande-frequenti/quanto-costa-un-kwh-di-energia-elettrica.aspx.

[64] S. Nickolas, "Investopedia," 25 January 2023. [Online]. Available: https://www.investopedia.com/ask/answers/032515/what-difference-between-real-and-nominal-interest-rates.asp.

[65] "Economy and Finance," Spring, 2023. [Online]. Available: https://economy-finance.ec.europa.eu/economic-surveillance-eu-economies/italy/economic-forecast-italy_en.

[66] S. Rain, M. Keith and S. Kim, "Water for the Hydrogen Economy," 2020.

[67] "Center for sustainable systems," [Online]. Available: https://css.umich.edu/publications/factsheets/energy/photovoltaic-energy-factsheet#:~:text=PV%20conversion%20efficiency%20is%20the,that%20is%20converted%20to%20electricity.&text=Though%20most%20commercial%20panels%20have,cells%20with%20efficiencies%20appr.

[68] "Wikipedia," [Online]. Available: https://en.wikipedia.org/wiki/Concentrator_photovoltaics#:~:text=In%20a%20concentrating%20system%2C%20the,range%20of%2075%E2%80%9390%25..

[69] "Hyfindr," [Online]. Available: https://hyfindr.com/dual-pressure-hydrogen-refueling-station/.

[70] "Idealista," [Online]. Available: https://www.idealista.it/aree/vendita-terreni/lista-mappa?shape=%28%28%7BiwrGy%60rm%40gDclFyEszIxaJ%7CLhArhPaxIdP%29%29.

[71] "tate," 2022. [Online]. Available: https://tate.it/elettrica/mobilita/come-fare/potenza-kw-colonnine-tempi-ricarica.

[72] "Air Liquide," [Online]. Available: https://energies.airliquide.com/resources-planet-hydrogen/fuel-cell#:~:text=PEM%20fuel%20cells%20consume%20about,for%20every%20100%20miles%20covered.

[73] B. M. Institute, "Manufacturing Cost Analysis of 100 and 250 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications," U.S. Department of Energy, Columbus, 2016.

[74] "United States Enviromental Protection Agency," [Online]. Available: https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle#:~:text=typical%20passenger%20vehicle%3F-,A%20typical%20passenger%20vehicle%20emits%20about%204.6%20metric%20tons%20of,8%2C887%20grams%20of%20CO2..

[75] "Rate Inflation," 16 June 2023. [Online]. Available: https://www.rateinflation.com/inflation-rate/italy-historical-inflation-rate/.

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