Politecnico di Torino

Ingegneria Energetica e Nucleare
A.a. 2021/2022
Sessione di Laurea Dicembre 2022

Green hydrogen production for high-temperature heat decarbonization

A case study from the ceramic sector

Relatore:
Ing. Gandiglio Marta

Correlatore:
Ing. De Pin Giuliano

Candidati:
Calzolari Andrea

Summary

List of figures

List of tables

Abstract

Nowadays the reduction of CO_2 emissions in many sectors is a primary need: the goal of the decarbonization of the industrial sector and the attempt to find sustainable alternatives to natural gas is leading to the implementation of the Renewable Energy Resources (RES). The production of hydrogen by means of water electrolysis is one of the most studied technologies and it could play an important role in decarbonization, in particular if RES are exploited to feed the electrolysis process. In fact hydrogen is an optimal solution because it guarantees a long term storability and the possibility to decarbonize final sectors in which is technically not possible or not convenient, such as the high-temperature heat sector.

The present study aims at analyzing the techno-economic performance of an electrolysis plant for the production of green hydrogen in the Italian industrial scenario, in particular in the high-temperature heat sector. The electrolyzer is coupled with a photovoltaic plant for the renewable energy production; the performances of both PEM and alkaline electrolyzers are investigated. A case study coming from the ceramic sector is analyzed and two main scenarios are considered: the plant with a tank for the hydrogen storage and the plant with a battery for the electricity storage. The technical analysis provides the performances of alkaline and PEM electrolyzers (e.g., load factor, specific consumption curves, hydrogen production) in the two scenarios, considering a natural gas-hydrogen mixture with a mixing rate that goes from 5% to 50% vol. of hydrogen. The model is based on a given hourly profile of natural gas consumption. The economic feasibility of the study includes the calculation of the Payback Time (PBT), Net Present Value (NPV) and Levelised Cost Of Hydrogen (LCOH).

The results reveal that there is a significant difference in the amount of working hours and the size of the electrolyzer in the two cases; furthermore the results show a good flexibility of the electrolyzer in guaranteeing blending mixtures different from the one it is sized for. On the other side, the economic analysis shows the need of public incentives to enhance the integration of green hydrogen in the industrial sector.

1. Introduction

Hydrogen is one of the most promising clean and sustainable energy carriers and emits only water as a byproduct without any carbon emissions. Hydrogen having many attractive properties as an energy carrier and high energy density (140 MJ/kg) which is more than two times higher than typical solid fuels (50 MJ/kg). Presently, the entire worldwide hydrogen production is around 500 billion cubic meter per year. The produced hydrogen is mostly used in many industrial applications, such as fertilizers, petroleum refining processes, petrochemical, fuel cells, and chemical industries. Hydrogen has been produced from various renewable and non – renewable energy resources such as fossil fuels, especially steam reforming of methane, oil/naphtha reforming, coal gasification, biomass, biological sources and water electrolysis. Currently 96% of the global hydrogen production from non – renewable fossil fuels, in particular steam reforming of methane.

Nowadays has taken attention as an environmental friendly energy strategies which possibly to replace the current fossil fuel based energy production, this can be achieved by when the hydrogen is produced from the renewable water. Among many hydrogen production methods, eco – friendly and high purity of hydrogen (99.999%) can be obtained from electrolysis of water to produce pure hydrogen and oxygen [1].

The production of hydrogen as a solution in the decarbonisation process of the industrial sector is widely analyzed in several reports and under different operating conditions. *Hinkley et al.* analyzed the direct coupling of an electrolysis system with a photovoltaic plant exploring different scenarios: the article investigates the direct coupling taking into account the presence or the absence of storage batteries, then an economic studio is carried on considering the actual prices of all the components and comparing them with the projected costs in 2030 [2]. The study carried on by *Kakoulaki et al.* examines to what extent the currently carbon – intensive hydrogen production in Europe could be replaced by water electrolysis using electricity from renewable energy sources (RES), such as photovoltaic, onshore and offshore wind and hydropower. The study provides evidence on the option to decarbonize hydrogen production at a regional level; it shows that such transformation is possible and compatible with the ongoing transition towards carbon – neutral power systems in the European Union [3].

Hans van't Noordende et al. presented a technical study to reduce capital expenditures and deliver conceptual designs for water electrolysis facilities in the five main industrial clusters in Netherland. The study is carried on with both alkaline and PEM electrolyzers and it shows the major expenses and their distribution in an electrolysis project [4]. The Italian Ministry for economic development has redeemed a document with the preliminary stages about the National Hydrogen Strategy with the aim to introduce the theme in the PNIEC and in the EU hydrogen strategy within the Long term Strategy for the complete decarbonisation until 2050. The guidelines show the intention to reach some goals until 2030: a 2% penetration of hydrogen in the final energy demand, a reduction of 8 Mton of $CO_{2,eq}$, the installation of 5 GW of water electrolysis plant for hydrogen production, the investment of 10 billion euros for hydrogen, the increase of GNP of about 27 billion euros, the creation of 200,000 new working opportunities [5].

This thesis work has the following structure: in the remaining chapter of Section 1 the main electrolysis technologies and the hydrogen market potential are introduced. Section 2 presents the strategy that has been adopted to perform the techno – economic analysis. Section 3 introduces the case study and the main assumptions of the work. Results are presented in Section 4, with also a comparison between the main scenarios that has been taken into account.

1.1. Main electrolysis technologies

Today, electrolysis represents the most promising and viable way to produce green hydrogen. There are different basic principles to perform electrolysis and several technologies can be considered: alkaline electrolysis (AEL), proton exchange membrane electrolysis (PEMEL) and high – temperature electrolysis (HTEL).

1.1.1. Alkaline electrolysis

It represents the most diffused technology, since it is the first that has been introduced into the commercial market. Alkaline electrolyzers are made of aqueous liquid electrolyte that is typically 25 – 40 wt% potassium hydroxide (KOH). AELs use low cost Raney nickel, nickel – plated steel or nickel/stainless steel mesh electrodes. Microporous diaphragm permeable to OH- separates the product gases between the two electrodes. Water is present both at the anode and at the cathode. Hydrogen is released at the cathode. This technology operates at a temperature between 50 and 80 °C.
AELs are a very mature technology, the stacks guarantee a wide range of available capacities and are made of components that permit the decrease of capital costs and a large scale viability. The state – of – the – art electrolyzers are very durable and have a system lifetime of 30 – 40 years. The main disadvantages related to AELs consist in low current density, a slow response upon application of a transient load power and the presence of a corrosive liquid electrolyte, that may cause security issues [6].

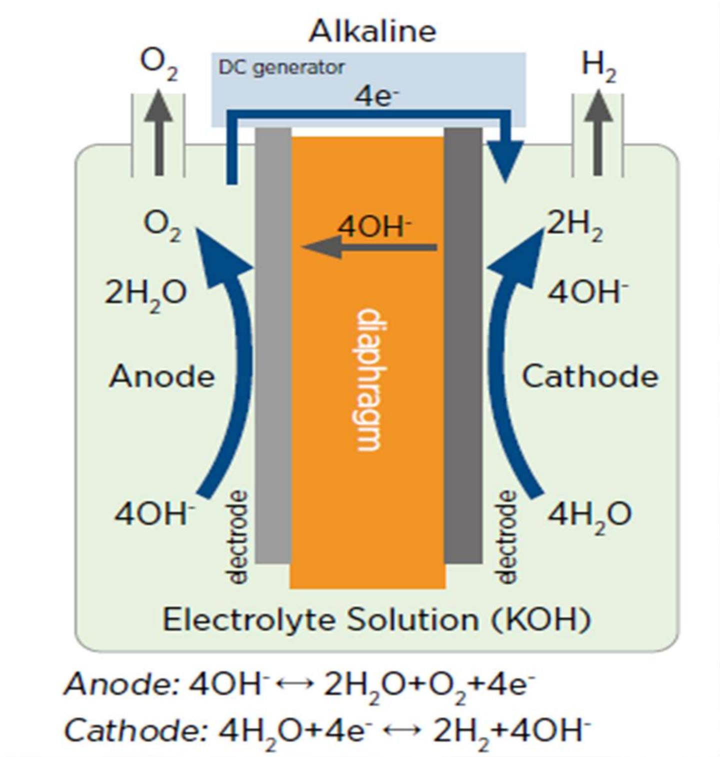

Figure 1. Alkaline electrolytic cell scheme [8].

For what concerns AELs, the water hydrogen generator includes an alkaline electrolyzer, a hydrogen separator, an oxygen separator, a gas cooler, a lye circulation pump, a lye cooler, a water storage tank, an alkali tank, control valves, and some other components.

When the equipment is started, the electrolyte is evenly mixed in the alkali tank, and then pressurized into the electrolytic tank through the pump to enter the entire hydrogen production system. After the liquid in the separator reaches the specified liquid level, the lye inlet valve is closed and the power is turned on. After the electrolysis, the hydrogen separator and the oxygen separator are respectively introduced from the hydrogen side of the electrolyzer and the oxygen side outlet in a gas – liquid mixed state. The gas is cooled from the upper part of the separator and discharged. The liquid merges into the bottom of the separator and recirculates. Since the water is reduced due to electrolysis, it is necessary to periodically replenish water into the hydrogen separator. Since the alkaline electrolyzer can only be operated at the same pressure, the hydrogen generator needs to be gradually pressurized to the set pressure by the regulating valve at the start, which causes the start – up time to be about 1 hour.

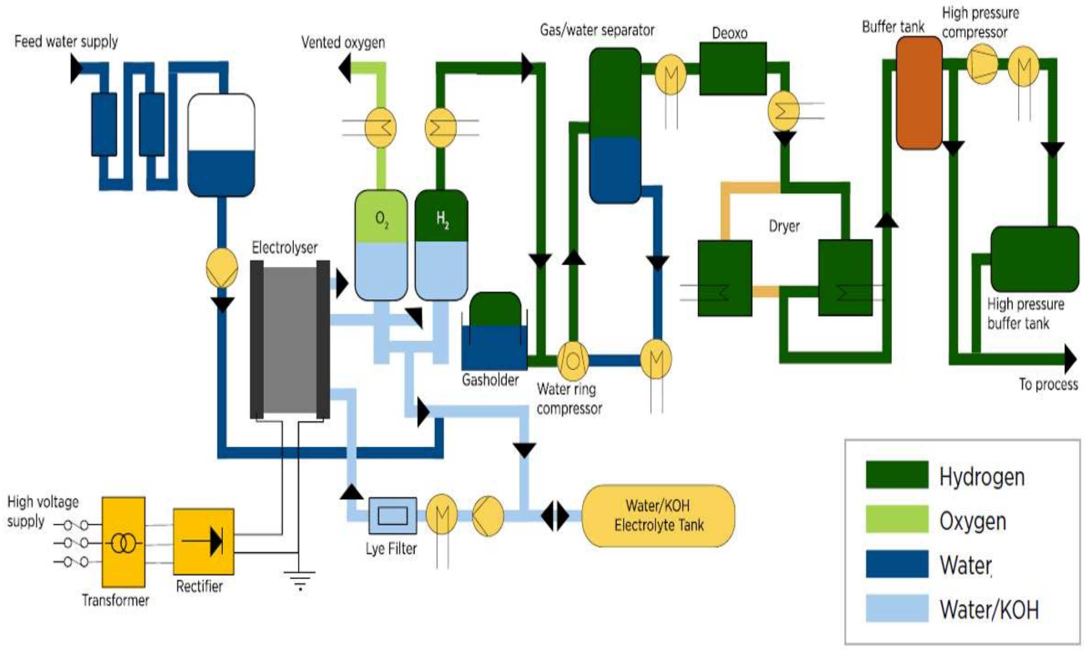

Figure 2. Alkaline electrolyzer balance of plant [8].

1.1.2. PEM electrolysis

It is one of the most popular electrolyzer technologies even though it is less diffused. PEMELs are made of a solid electrolytic conductor that is a Proton exchange membrane (Nafion) and porous graphite electrodes, hot pressed with a structure of Nafion and platinum. Iridium and platinum catalysts are respectively used at the anode and at the cathode. Water is fed into the anode, while the recombination reactions occur at the cathode. The operating temperature is between 50 and 80°C.

The solid electrolyte guarantees a very compact solution and permits to the electrolyzers to operate at high current densities and furthermore the hydrogen can be produced at high pressure. PEMELs also have a fast dynamic response to any change in the power input and are able to work in a wide range of partial loads.

Due to the highly corrosive acidic environment, PEMELs require rare catalysts and stack materials that increase the capital cost of the system; PEMELs have already been commercialized, however the technology is already under development and the state – of – the – art commercial systems register a lifetime between 5 and 20 years [6].

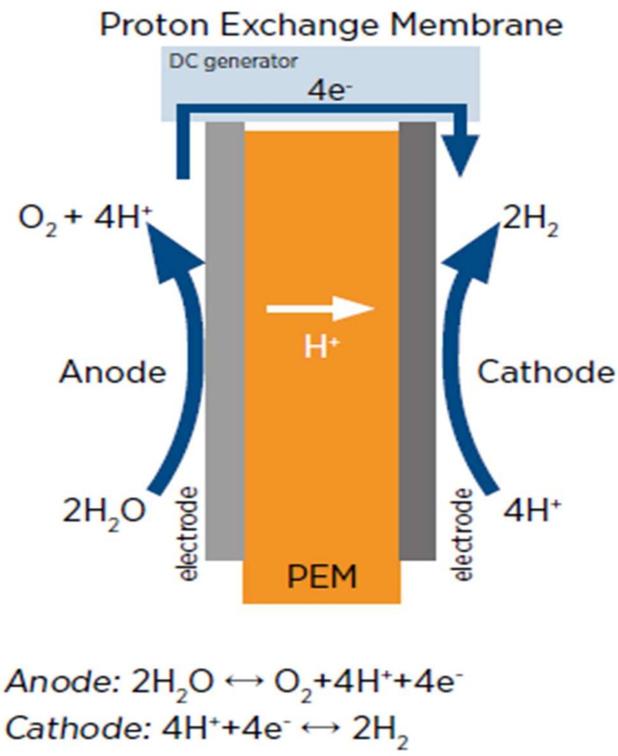

Figure 3. PEM electrolytic cell scheme [8].

Compared with the alkaline water hydrogen production system, the PEM hydrogen production system is relatively simple: the gas aftertreatment device is relatively small, no special alkali tank is needed, and the water tank can also be used as an oxygen separator.

When the equipment is started, the water in the water tank is replenished to the set liquid level, and the circulation pump is turned on to circulate, and the water level of the hydrogen separator is observed to reach the designed position. When the liquid level is stabilized, the DC source is energized. Oxygen and water are separated into the water tank, and the oxygen is filtered through a molecular sieve to be discharged. Hydrogen and a small amount of water enter the hydrogen separator; after the water in the hydrogen separator reaches a certain liquid level, part of the water flows into the water tank.

The PEM electrolyzer can be operated under differential pressure. It does not need to be gradually regulated like hydrogen by alkaline water when starting up. The pressure of the regulating valve can be directly set to the specified pressure, and the equipment can be stabilized in 15 minutes [7].

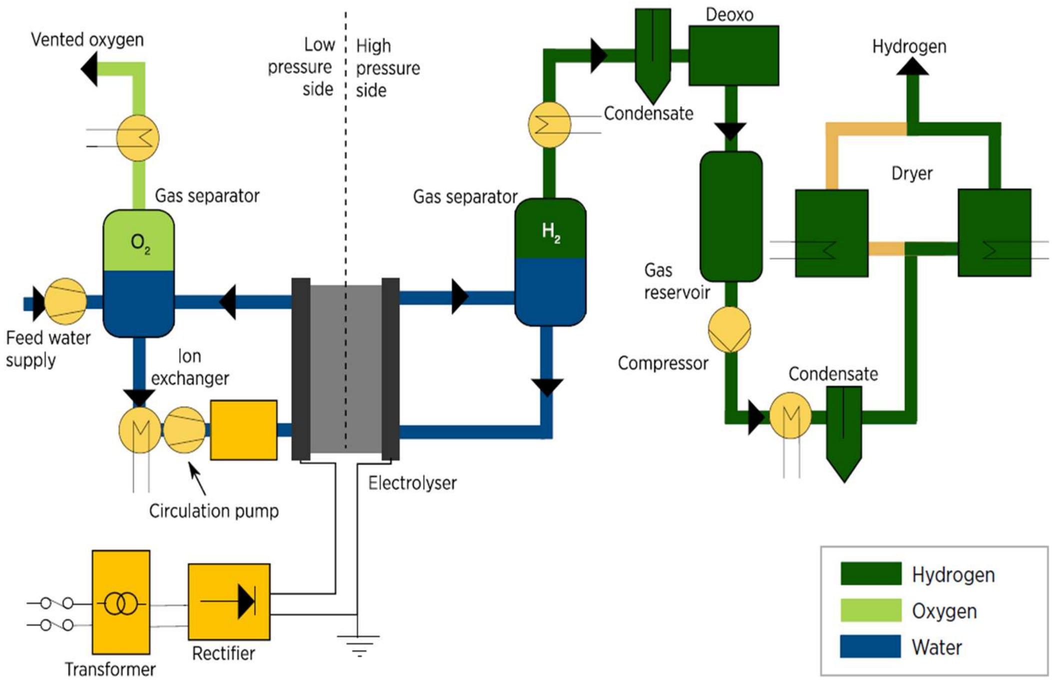

Figure 4. PEM electrolyzer balance of plant [8].

1.1.3. High – temperature electrolysis

The most common high – temperature technology is the solid oxide electrolyzers (SOEL). They work in a range between 800 – 1000°C, therefore they must be fed with steam instead of water. Steam is reduced at the cathode to give hydrogen and oxygen anions. The electrolyte is solid and it is made of yttria – stabilized zirconia. Anode and cathode are porous and made of ceramic materials.

Today, commercial systems are up to 150 kW with current densities that are still low. Moreover, due to the high temperature up to 1000°C, commonly used materials like ceramics do not withstand high pressures. In addition, warm – up times are long and so HTEL cannot be used in frequent start – stop mode. Due to the enounced characteristics, HTELs will not be taken into account in the following analysis [6].

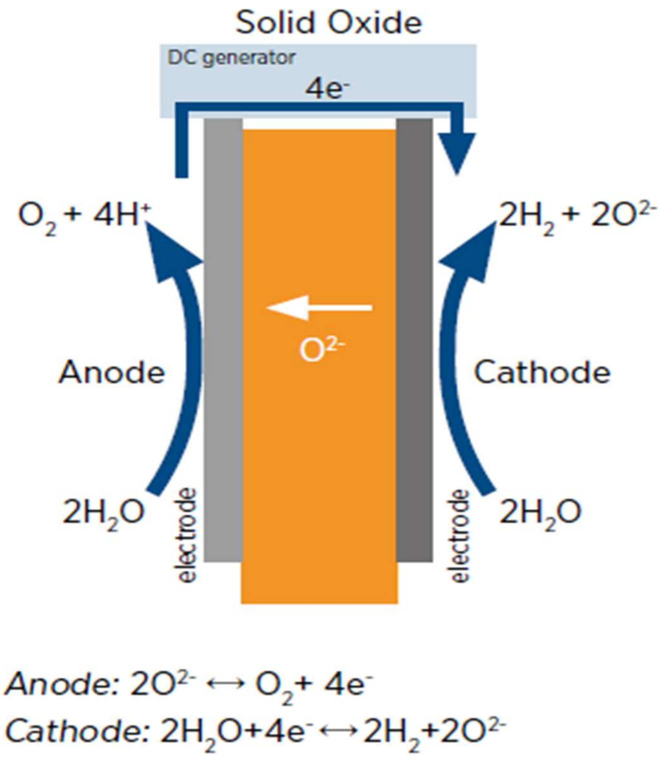

Figure 5. Solid oxide electrolytic cell scheme [8].

1.1.4. Summary and application of the different technologies

The key parameters of the electrolyzer technologies are summarized in Table 1. With some fixed parameters, the hydrogen production rate is independent of stack size, as larger stacks are not more energetically efficient at converting hydrogen. The production rate is also independent of stack size, as doubling the number of stacks at the same loading level will simply double the hydrogen production rate.

Although the thermodynamic conditions are similar, PEM electrolyzers are slightly less efficient than alkaline ones during steady – state operations considering also auxiliary systems due to increased kinetic losses. The low – pressure designs have a higher hydrogen production rate than high pressure designs, since high pressure inhibits the reaction and lowers the efficiency of the stack. For a given load, PEM designs have a higher hydrogen production rate than alkaline designs. PEM designs are able to ramp between different loading levels and adjust to changing loads more quickly than alkaline; however PEM blocks are less economical, therefore they require a base load to use to produce large quantities of hydrogen [9].

Table 1. Alkaline, PEM and SOEC electrolyzers main parameters [15].

	AEL	PEM	SOEC
System efficiency [%][a)]	up to 65	Up to 65	up to 82
Current densities [A cm^{-2}]	0.2–0.6	1–3	0.3–1
Operating temperature [°C]	60–95	50–80	700–1000
Operating pressure [bar]	atm. – 32	atm. – 40 (demonstration up to 700)	1–3
Module size [kW]	5–6000	5–2500	–
System size [MW]	up to 100	up to 100	up to 0.15
CAPEX costs [€ kW^{-1}]	500–1200	1000–1800	1200–2000

a) based on H_u = 3 kWh Nm^{-3}> H_2

1.2. Hydrogen market overview

Hydrogen is one of the key players to tackle climate change and boost the energy transition toward a decarbonized world, it is an energy carrier that can be adopted in several sectors like hard-to-abate industries such as the chemical and petrochemical sectors, the steelmaking industries and the transportation sector to reduce their carbon footprint.

The EU hydrogen strategy aims for an integrated view of the value chain and establishing a supporting governance system and policy framework that promotes hydrogen deployment. It recognizes that green hydrogen is the only one compatible with a net zero emissions system, but it also recognizes that blue hydrogen will be useful during early stages of deployment to achieve lower costs and synergies for the infrastructure. The main explicit target is the 6 GW of electrolyzer capacity target by 2024, to produce up to 1 MtH2/yr and 40 GW by 2030. To reach the 2030 goals, levels of investment of EUR 24-42 billion for the electrolyzer are envisioned, besides EUR 220-340 billion for 80-120 GW of renewable capacity, EUR 65 billion for the infrastructure and EUR 11 billion for retrofitting existing natural gas plants. Electrolyzer CAPEX, the utilisation factor (operating hours) and electricity price are the main parameters determining the cost of producing green hydrogen [10].

The total annual production of hydrogen in Europe is in the range of 9.756 Mt. Hydrogen use today is dominated by industrial applications. The majority of hydrogen consumption is associated with two industries: oil refineries (ca. 52%) and ammonia production (ca. 43%) the rest is other industrial use (ca. 2%). In Europe, oil refineries account for approximately at 30% and ammonia at 50%. Together with methanol production (ca. 5%) and use in metal industries (ca. 3%), these four sectors correspond to 90% of the total hydrogen consumption in Europe [3].

Some 38 MtH2/yr, or 30% of the total global demand for hydrogen (in both pure and mixed forms), is consumed by refineries as feedstock, reagent and energy source. Refineries' existing large-scale demand for hydrogen is set to grow as regulations for sulphur content of oil products tighten. This provides a potential early market for hydrogen from cleaner pathways, which could lower the emissions intensity of transport fuels. Hydrotreatment and hydrocracking are the main hydrogen-consuming processes in the refinery: hydrotreatment is used to remove impurities (especially sulphur), hydrocracking is a process that uses hydrogen to upgrade heavy residual oils into higher-value oil products.

The chemical sector accounts for the second- and third-largest sources of demand for hydrogen today: ammonia at 31 MtH2/yr and methanol at 12 MtH2/yr, or 40% of total hydrogen demand in both pure and mixed forms. Demand for hydrogen for primary chemical production is set to increase from 44

Mt/yr today to 57 Mt/yr by 2030 as demand for ammonia and methanol grows. Demand for ammonia for existing applications is set to increase by 1.7% per year between 2018 and 2030 and to continue to rise thereafter.

The potential applications for hydrogen cover almost all facers of energy demand in the modern economy. Aviation, shipping, iron and steel and chemicals, have very high levels of potential future demand for hydrogen and hydrogen – based fuels and face new competitors from other low – carbon technologies. Other sectors offer opportunities for more rapid near – term deployment, such as refineries. Based on current plans, low – carbon hydrogen demand could pass 100 ktH$_2$/yr in existing industrial applications and gas grids by 2030; iron and steel, aviation and shipping have longer – term potential [11].

Table 2. Potential future applications of hydrogen [11].

Type of application	Application	Size of the 2030 opportunity (ktH2/yr)	Long-term potential scale
Major hydrogen uses today	Chemicals (ammonia and methanol)	Over 100	High
	Oil refineries and biofuels	Over 100	Medium
	Iron and steel (blending in DRI)	10-100	Low
New hydrogen uses for a clean energy system	Buildings (conversion to 100% hydrogen)	Over 100	High
	Road freight	Over 100	High
	Passenger vehicles	Over 100	Medium
	Buildings (blending in the gas grid)	Over 100	Low
	Iron and steel (conversion to 100% hydrogen)	10-100	High
	Aviation and maritime transport	Under 10	High
	Electricity storage	Under 10	High
	Flexible and back-up power generation	Under 10	Medium
	Industrial high-temperature heat	Under 10	Low

The Italian guideline document for the hydrogen plan establishes several ambitious goals for 2030, where the 2% of overall energy consumption is declared to be satisfied by the use of the hydrogen, deploying 5 GW electrolyzers which leads to a reduction of 8 Mton of CO_2 emissions; as for 2050, it is projected that up to 20% of energy consumption will be covered by hydrogen. The decarbonization of the natural gas sector can be tackled with the use of green hydrogen blended with natural gas. ENEA, in collaboration with Confindustria, redeemed an analysis of the national industrial potential for the use of hydrogen to achieve the ecologic transition: the document has been used in this study in order to identify the industrial sectors that are more adequate for the installation of an electrolyzer and the related green electricity source, such as a photovoltaic or wind park [12].

2. Methodology

In the context of the technologies that require hydrogen end use in industrial application, it can be employed as:

- Feedstock in industrial processes: that is in particular the case of refinery and chemical sector.
- Fuel for heating or to provide process heat in all the applications that require high temperature heat and cannot afford the direct use of electricity.
- Transport fuel, complementary to the electricity solution.

The selection of some suitable case studies has been carried on following some base criteria:

- The solution must belong to an industrial sector that needs an important amount of hydrogen for its applications or that can consider the implementation of hydrogen to decarbonize the processes.
- The analysis also included the availability of a wide area in order to install a renewable source of electric power; in case of a photovoltaic system, the rooftop installation has been considered as well.
- The industrial sectors considered must represent a near – term solution for the electrolysis implementation. No long – term potential sectors (eg. 10 years) have been taken into account.

In Figure 6 it is presented the schematic of the components, considering the hydrogen as a gas to blend with natural gas as an input of the high-temperature power plant.

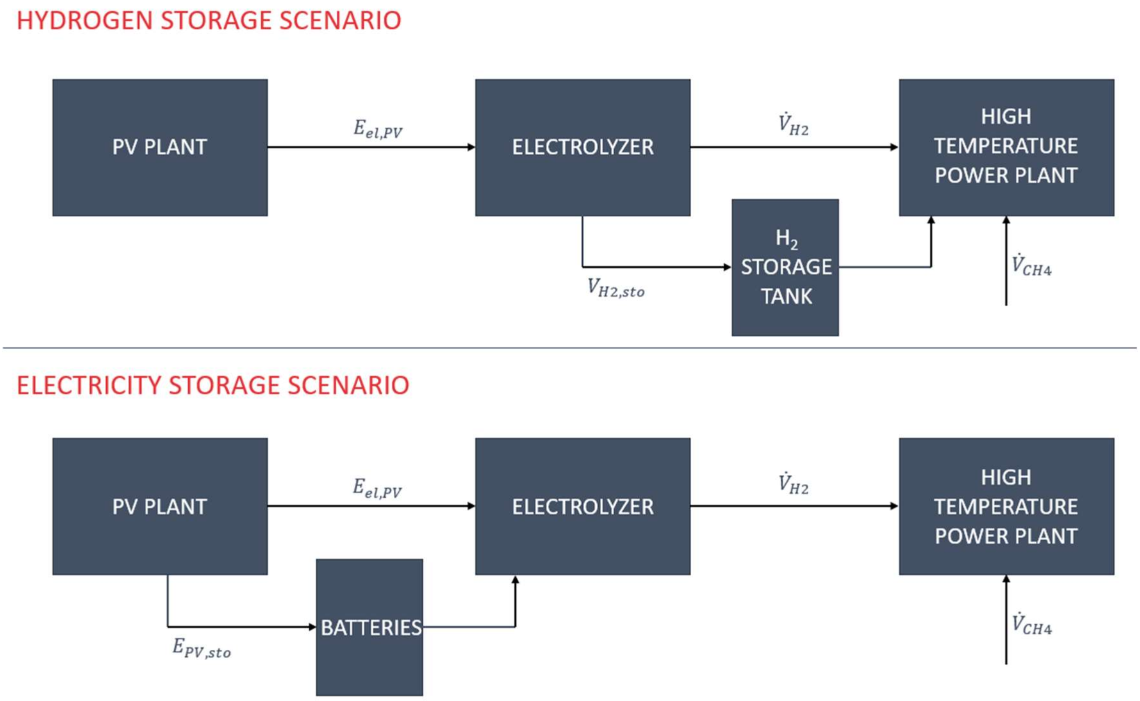

Figure 6. Schematic of the system structure and components.

In order to supply power to the electrolyzer for the hydrogen production, the installation of photovoltaic panels is considered. The electricity needed by the electrolyzer can also be taken by the network in some specific cases, however the annual amount of electricity produced must cover the energy needed for the production. The electricity production from renewables has a high variability throughout the day and its profile is extremely different from the electrolyzer energy request for hourly production, therefore some considerations are necessary and lead to two reference scenarios for the analysis of the case study, that consist in the presence of a hydrogen storage system or an electricity storage system.

In the hydrogen storage scenario, the electrolyzer system switches on only in the hours when electricity production is available. In this case the hydrogen production is maximized in a few hours per day and the excess of hydrogen is stored in order to be used when the photovoltaic system cannot work. The daily request of hydrogen must be satisfied in the reduced amount of hours that the solar power is available: for this reason a daily evaluation is performed and the electrolysis system must be sized in order to produce the requested hydrogen of every day. This solution permits to maximize the production of hydrogen per day, since almost all the photovoltaic electricity is exploited. If the electricity production is not sufficient to cover the hydrogen needs, it can be purchased by the grid.

In the electricity storage scenario the electrolyzer never shuts down and it guarantees an hourly hydrogen production that does not exceed the request by the plant, because of the absence of a tank for the excess of production. Therefore the electricity produced a few hours per day is stored in order to satisfy the hourly hydrogen request. If some days the photovoltaic electricity is not sufficient, it can be purchased by the electrical grid, because the hourly request of hydrogen must always be satisfied. As the hydrogen requirements are more constant than the photovoltaic profile, this solution guarantees a 24 hours usage of the electrolyzer, possibly at a quite constant load factor.

Both the reference cases are evaluated with different blending ratios, varying the percentage of hydrogen from 5 to 50%, with the aim to identify the main diversities or proportionality factors that correlate the different solutions. Furthermore, once the electrolyzer has been sized, its performances are studied for every blending ratio in order to understand and quantify the overperformances or underperformances given by a change in the natural gas – hydrogen proportions.

The analysis has been carried on exploiting hourly data of natural gas consumption of the plant and hourly power profile of the photovoltaic plant. A temporal range of an year has been considered for the calculations. By studying the electricity storage scenario, all the evaluations have been done on hourly basis in order to satisfy the hydrogen request, while in the hydrogen storage scenario daily calculations have been performed, since the hydrogen production profile does not follow the hydrogen production profile.

In the hydrogen storage reference scenario, either PEM and alkaline electrolyzers have been studied and their performances are compared, while the electricity storage scenario has been observed only with the installation of a PEM electrolyzer: the reason of this choice depends on the natural gas consumption profile – and the hydrogen profile as a consequence – and the characteristics of the alkaline electrolyzers, that show inefficient performances upon transient applications.

2.1. Electrolyzer sizing

Throughout the whole study, both alkaline and PEM electrolyzer solutions are taken into account, therefore all the calculations must be performed for each case. For what concerns the electrolyzer size (P_{el}) calculation, a unique expression can be used for both solutions:

$$P_{el} = \frac{LHV_{H_2} \cdot \dot{V}_{H_2}}{\varepsilon \cdot LF} \tag{1}$$

Where:

- $\dot{V}_{H_2}$ is the hydrogen volumetric flow rate needed, that can be considered as a given data of the specific case study.
- LF is the load factor of the electrolyzer at a given flowrate, and it can be calculated as the ratio between the renewable energy fed and the electrolyzer's energy needed to produce the amount of hydrogen.
- LHV_{H_2} is the lower heating value of hydrogen.
- ε is the efficiency of the electrolyzer, as indicated in the technical sheet.

By analyzing the efficiency curves presented in the study conducted by *Marocco et al.* [13], it is possible to extract – for both alkaline and PEM electrolyzers – the equations that relate the load factor of the electrolyzer with its efficiency:

$$\varepsilon_{PEM} = 7.1272 \cdot LF^5 - 21.84 \cdot LF^4 + 25.75 \cdot LF^3 - 14.633 \cdot LF^2 + 3.9965 \cdot LF + 0.1247 \tag{2}$$

$$\varepsilon_{ALK} = 3.4883 \cdot LF^5 - 11.516 \cdot LF^4 + 14.858 \cdot LF^3 - 9.4089 \cdot LF^2 + 2.8906 \cdot LF + 0.2551 \tag{3}$$

In order to size the electrolyzer, some evaluations has been taken: the system must be able to produce enough hydrogen even in the worst conditions possible, therefore it is sized with an important margin over that conditions in order to consider potential contingencies. Since some starting evaluations change among the reference scenarios analysed, also the worst conditions vary in those cases:

- Hydrogen storage scenario: in this case it is fundamental to satisfy the daily needs of hydrogen, therefore the worst case possible is represented by the day with less photovoltaic potential coupled with the day with the highest hydrogen request.
- Electricity storage scenario: because of the possibility to store the electricity produced in order to use it in case of lack of solar radiations, the worst case possible is simply represented by the highest hydrogen request in the whole year.

Once the worst conditions have been identified, a proper value of the load factor in that conditions must be selected, with the aim of leaving a safety margin in case of contingencies. In particular, the electrolyzer is properly sized to work at the 80% of its rated power (LF = 0.8) in the most critical conditions.

For what concerns the specific consumption of the electrolyzer, it can be calculated as follow:

$$SC = \frac{LHV_{H_2}\left[\frac{kWh}{Nm^3}\right]}{\varepsilon\,[\%]} \tag{4}$$

Therefore, by knowing the curves by the study of *Marocco et al.,* it is straightforward to calculate the specific consumptions as a function of the load factor of the system:

$$SC_{PEM} = 329.94 \cdot LF^6 - 1189.5 \cdot LF^5 + 1716.3 \cdot LF^4 - 1263.4 \cdot LF^3 + 500.04 \cdot LF^2 - 101.17 \cdot LF + 13.923 \tag{5}$$

$$SC_{ALK} = 89.689 \cdot LF^6 - 348.53 \cdot LF^5 + 549.4 \cdot LF^4 - 450.3 \cdot LF^3 + 203.5 \cdot LF^2 - 48.202 \cdot LF + 9.8377 \tag{6}$$

The specific consumption is one of the main parameters of the electrolyzers because it is usually indicated by the main electrolyzer's sellers in the technical data sheets and the curve representing function is showed in Figure 7 for both PEM and alkaline electrolyzers.

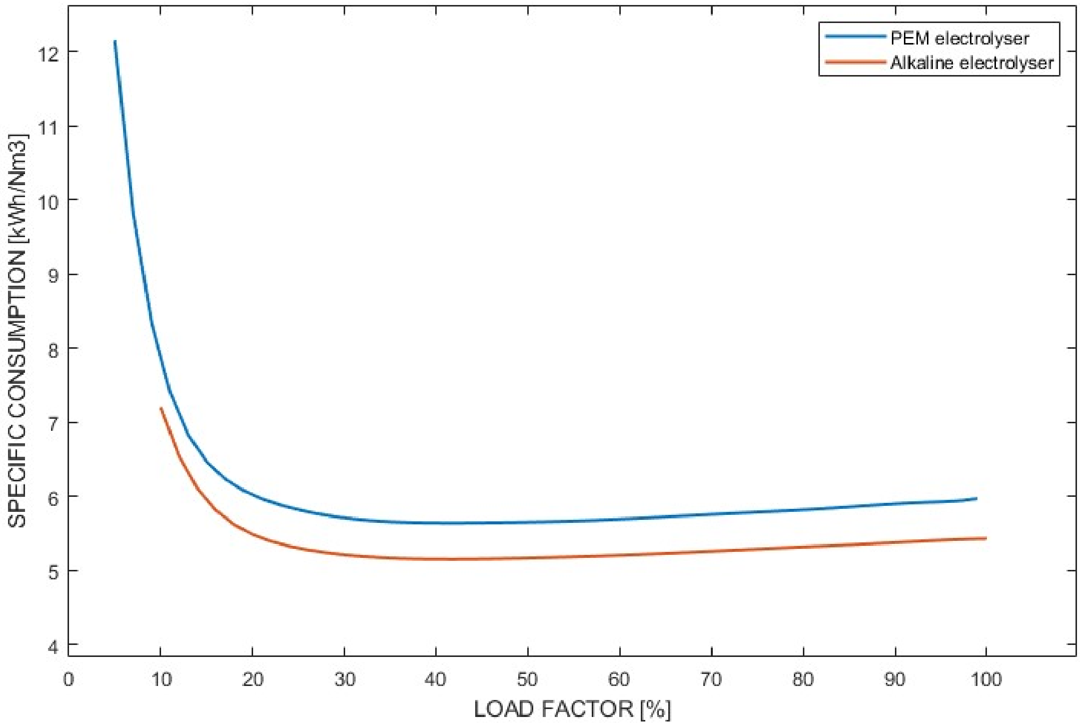

Figure 7. Efficiency curves of PEM and alkaline electrolyzers [13].

Once the size of the electrolyzer is determined, it is important to study the real working conditions over a long period, with the aim to verify that the system produces with a proper load factor and specific consumption. To do that, an iterative process can be carried out: starting with a hypothetic load factor (eg. LF_0), the specific consumption can be obtained by (5) and (6). The power necessary to produce the hydrogen can be calculated as follow:

$$P\ [kW] = SC_0 \left[\frac{kWh}{Nm^3}\right] \cdot \dot{V}_{H2} \left[\frac{Nm^3}{h}\right] \tag{7}$$

By applying the definition of load factor, a new value can be determined:

$$LF_1 = \frac{P\ [kW]}{P_{el}\ [kW]} \tag{8}$$

In this way it is possible to perform the iteration loop until the convergence around the instantaneous values of load factor and specific consumption are reached and the real operation of the electrolyzer is found. This procedure permits to understand the real working conditions of the electrolyzer, as a direct dependence from the hydrogen hourly volumetric flowrate request.

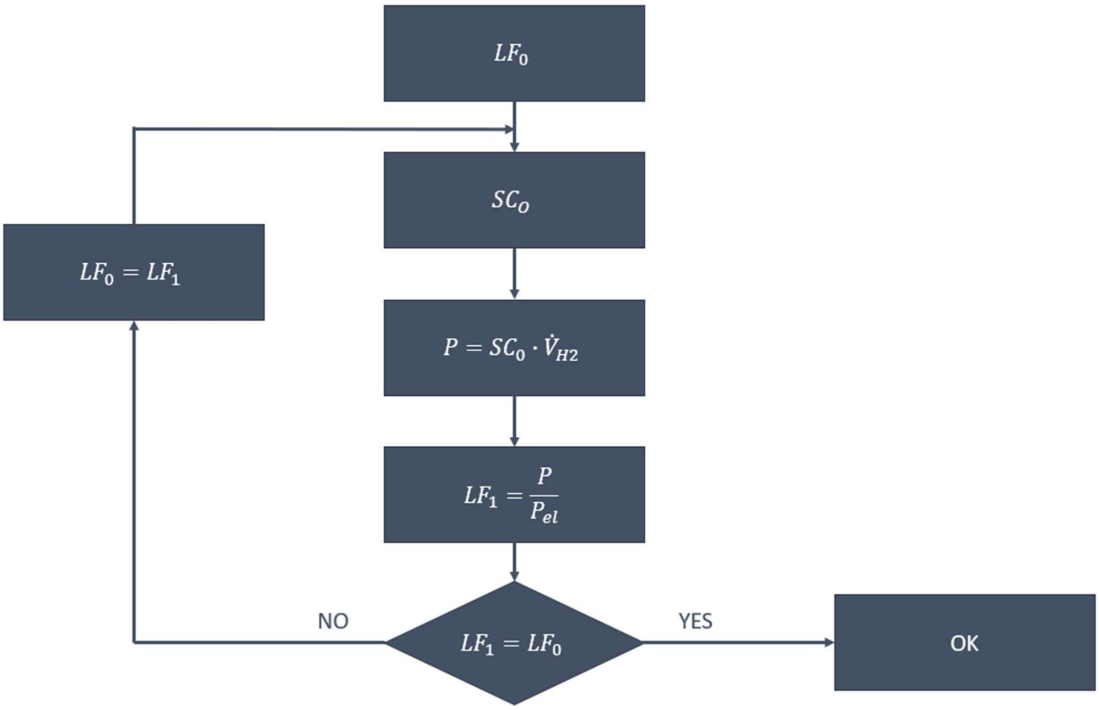

Figure 8. Scheme of the iterative process for the hourly electrolyzer working conditions.

Once the real operation hour per hour of the system has been defined, it is possible to make some considerations about the mean value of load factor and specific consumption, moreover it is also important to understand how the working conditions vary with respect to the mean ones. To study this aspect the standard deviation can be used, and it is calculated as follow:

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N}} \tag{9}$$

Where N is the number of values, x_i represents each value of the parameter (i.e. load factor or specific consumption) and $\bar{x}$ is the mean value of that parameter.

2.2. Photovoltaic plant sizing

The photovoltaic plant must be sized to satisfy the energy request from the electrolyzer and, in order to avoid purchasing an excessive amount of electricity from the grid, it has been decided to size it with a margin of around 5% of annual production with respect to the annual electrolyzer request.

$$E_{PV,year}\,[kWh] = 1.05 \cdot \sum E_{el,need} \tag{10}$$

The margin has been selected arbitrarily, considering the photovoltaic plant installed only to supply the electrolyzer but with a proper allowance in case of contingencies or unexpected requests.

To guarantee the above-mentioned margin, a sensitivity analysis has been performed to investigate the proportions that link the PV plant and the electrolyzer: in the hydrogen storage scenario the photovoltaic plant must be 0.95 the size of the electrolyzer, while in the electricity storage scenario it must be 2.75 times the electrolyzer.

The specific hourly profile of the photovoltaic production has been extrapolated from PV-GIS annual data, calculating the mean values of the last 10 years.

2.3. Hydrogen storage tank sizing

In the hydrogen storage solution an hydrogen tank is considered and it is sized big enough to store the maximum daily hydrogen production surplus. The tank has been sized with a 20% safety margin arbitrarily chosen, since the hydrogen request may be variable between the years.

$$V_{tank}[m^3] = 1.2 \cdot \max\left(V_{H2,prod,i} - V_{H2,request,i}\right) \tag{11}$$

Where $V_{H2,prod,i}$ is the daily hydrogen production and $V_{H2,request,i}$ is the daily hydrogen request.

2.4. Battery sizing

In the electricity storage solution a battery is considered and it is sized big enough to store the maximum daily excess of electricity production with respect to the relative electricity consumption. The battery has been sized with a 20% safety margin arbitrarily chosen, since the electricity request – related to the hydrogen request – may be variable between the years.

$$Battery\ size[kWh] = 1.2 \cdot \max(E_{PV,prod,i} - E_{PV,request,i}) \quad (12)$$

Where $E_{PV,prod,i}$ is the daily PV production and $E_{PV,request,i}$ is the daily electricity request.

2.5. High-temperature plant mixture calculations

In most of the industrial applications, the hydrogen is used as an energy vector in a mixture with natural gas, that is currently used in the plants. The volume blending ratio has been assumed with the hypothesis that the gas mixture H_2/NG flowrate supplies the same thermal power of the pure natural gas solution; from this flowrate it is possible to calculate the hydrogen volume percentage from which to obtain the flowrate of both gases at the different blending ratios.
The thermal power supplied by the natural gas can be calculated:

$$P_{NG}\ [kW] = LHV_{NG}\left[\frac{kWh}{Nm^3}\right] \cdot \dot{V}_{NG}\left[\frac{Nm^3}{h}\right] \quad (13)$$

Once the blending percentage has been defined for the project, the Lower Heating Value of the mixture can be defined:

$$LHV_{mix} = B \cdot LHV_{H2} + (1-B) \cdot LHV_{NG} \quad (14)$$

Finally, on the basis of the chosen Heating Value, the volume flowrate of the mixture is found as follow:

$$\dot{V}_{mix}\left[\frac{Nm^3}{h}\right] = \frac{P_{NG}\ [kW]}{LHV_{mix}\ \left[\frac{kWh}{Nm^3}\right]} \quad (15)$$

This kind of calculation leads to the observation that the percentage of natural gas savings does not correspond to the percentage of hydrogen into the mixture, because the Lower Heating Value of natural gas is much higher than the Lower Heating Value of hydrogen ($LHV_{NG} = 35.88\ \frac{MJ}{Nm^3}$, $LHV_{H2} = 11.09\ \frac{MJ}{Nm^3}$).
The natural gas savings are calculated as a difference between the current natural gas consumption profile and the natural gas present in the mixture and the reduction of CO_2 emissions can be directly calculated from savings.

$$V_{NG,saving}\ [m^3] = V_{NG,consumption} - (1-B) \cdot V_{mix} \tag{16}$$

$$CO_2\ saving\ [kg] = V_{NG,saving} \cdot \rho_{CH4} \cdot \frac{MM_{CH4}}{MM_{CO2}} \tag{17}$$

Where ρ_{CH4} is the density of the natural gas, MM is the molar mass of natural gas and CO_2 respectively.

2.6. Economic assessment

An economic analysis must be carried out during the study, with the aim to investigate the economic viability of the project. The economic model calculates the CAPEX and OPEX of the project, the Levelised Cost Of Hydrogen (LCOH) based on a Net Present Value (NPV) assessment and the Interna Rate of Return (IRR) of the project.

$$CAPEX\ [€] = Electrolyzer\ cost + PV\ cost + storage\ cost \tag{18}$$

$$OPEX\ [€] = O\&M\ cost + stack\ replacement\ cost + battery\ replacement\ cost \tag{19}$$

The CAPEX includes the electrolyzer cost, the photovoltaic plant cost and the storage facilities, while the OPEX includes the operation and maintenance costs, the stack replacement cost and the battery replacement cost (if present). The Net Present Value is useful to calculate the present value of future cash and evaluate the project:

$$NPV = \sum_{t=0}^{N} \frac{C_t}{(1+i)^t} \tag{20}$$

Where t is the year of the cashflow, C_t is the net cashflow in the period t, N is the lifetime of the project, i is the discount rate.

The Internal Rate of Return (IRR) represents the discount rate value that makes the discounted cash flow equal to the investment cost, therefore it makes the NPV equal to zero; this index is particularly useful in order to examine the actual viability of the project.

$$\sum_{t=0}^{N} \frac{C_t}{(1+IRR)^t} = 0 \tag{21}$$

LCOH is derived from the total CAPEX and OPEX over the project lifetime divided by the total hydrogen produced over that lifetime and it is used to compare the unit cost of different renewable energy technologies:

$$LCOH = \frac{\sum_{t=0}^{N} \frac{I_t + O_t}{(1+i)^t}}{\sum_{t=0}^{N} \frac{H_t}{(1+i)^t}} \tag{22}$$

Where I_t is the initial investment, O_t is the operating costs in the time t, H_t is the annual hydrogen production.

3. Case study

For the selection of the Italian sectors that are more suitable for the production of green hydrogen, the document redeemed by ENEA, in collaboration with Confindustria [12], has been the most relevant source: it provides the main data about the mean size of plants, their related consumption, CO_2 emissions, the hydrogen needs as a function of the blending ratio and the hypothetical size of an installed electrolyzer. A further research is then performed by means of the Atlaimpianti tool by GSE, that registers the renewable power plants situated in the national territory, and other tools to calculate the potential of the areas for renewable energy production.

The analysis for the production of green hydrogen has finally been conducted on a company of the ceramic industrial sector located in Emilia Romagna, with a natural gas yearly consumption of 1,981,300 Nm^3 and at least 4 hectares of available space, considering both fields and rooftop. For all the evaluations, the natural gas consumption on hourly bases is given and it is presented in Figure 9. The given data present a behaviour that depends on the tile production profile, that varies at different hours of the day. Moreover two production stops of fourteen days are present and they correspond to Christmas holidays and the central weeks of august. The maximum daily natural gas consumption over the year is 435.5 Nm^3, that corresponds to 4434 kW, while the minimum is 28.8 Nm^3 equal to 292.8 kW. The mean natural gas consumption per day is 242.8 Nm^3 corresponding to a power consumption of 2472 kW.

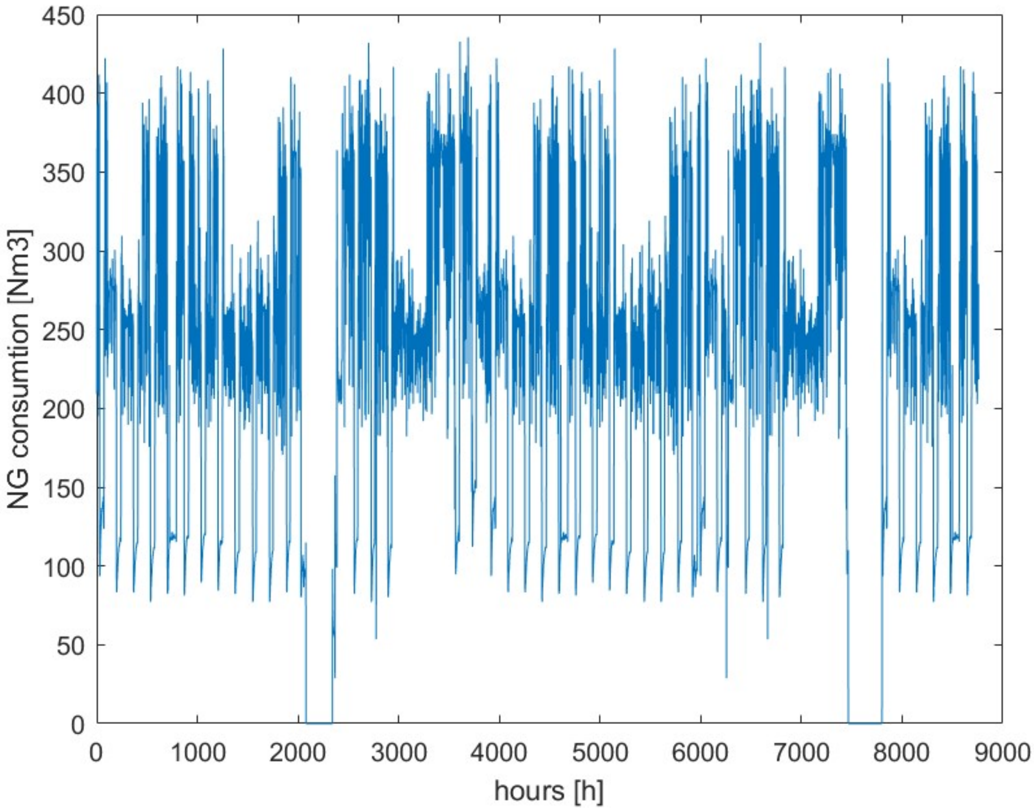

Figure 9. Natural gas consumption hour profile.

The natural gas consumption profile shows that the furnace never shuts down, so there is a continuous request of gas that must be satisfied; for this reason, in the case study the hydrogen must always be available to guarantee the design mixture with the natural gas. However the photovoltaic production profile presents a different behaviour, with peaks and non-production hours, and in Figure 10 it is also visible that the winter months are characterized by a reduced number of production hours with respect to the summer months.

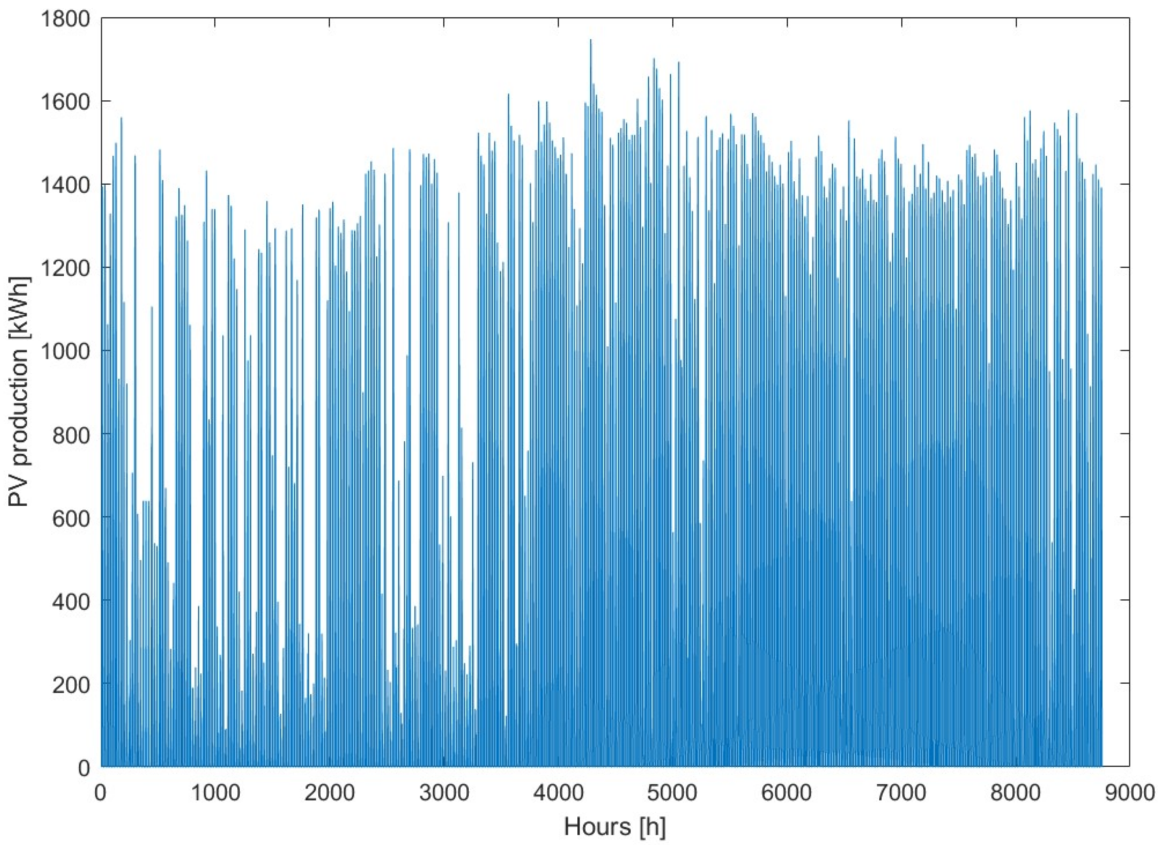

Figure 10. Photovoltaic production hour profile.

The electrolyzer energy request reflects the hydrogen need from the furnace, so it has a different profile compared to the photovoltaic plant. Figure 11 shows the comparison between the daily profile of the two systems along the 24 hours, useful to understand their coupling in the operation.

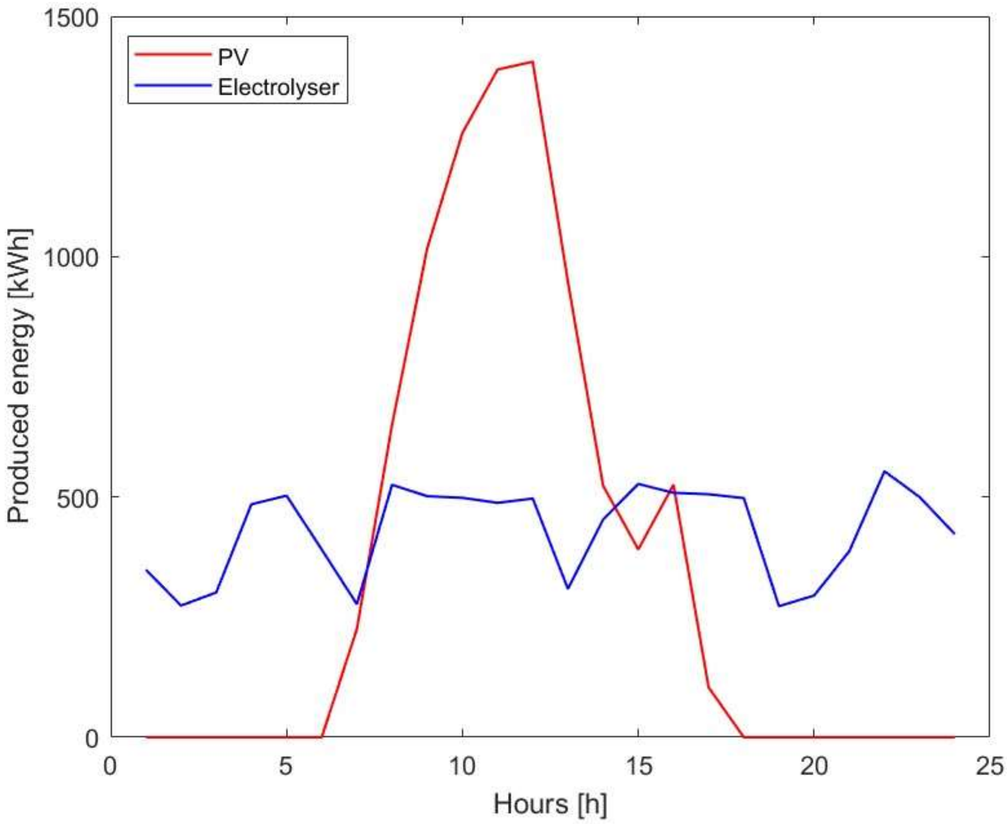

Figure 11. Comparison between photovoltaic and electrolyzer energy profile in a day.

For every investigated scenario of the case study – hydrogen storage with PEM and alkaline electrolyzer and electricity storage with PEM electrolyzer – an economic analysis is carried out and it consists in the calculations of the payback time, net present value and return of investment by taking into account the savings derived from a reduction of natural gas and CO_2 emissions, in addition to the possibility of using the excess of photovoltaic energy. The input economic parameters are presented in Table 3.

Table 3. Economic parameters of the model.

Model parameter	Value	Reference
Lifetime of the project [years]	25	[14]
Alkaline electrolyzer cost [€/kW]	700	[15]
PEM electrolyzer cost [€/kW]	1300	[15]
Photovoltaic system cost [€/kW]	800	[14]
Hydrogen storage tank cost [€/Nm^3]	40	[16]

Battery cost [€/kWh]	300	[17]
Battery lifetime [y]	10	[16]
Battery replacement [€/kWh]	300	[16]
PEM stack lifetime [h]	60,000	[16]
Alkaline stack lifetime [h]	80,000	[16]
Stack replacement [% CAPEX]	35%	[16]
O&M costs [% CAPEX]	2%	[14]
Natural gas price [€/Nm^3]	0.25	[12]
CO_2 ETS quote price [€/t_{co2}]	60	[12]
Electricity price [€/kWh]	0.17	[14]
Discount rate [%]	5	[14]

4. Results

The working behaviour on a yearly basis of the electrolyzer has been analyzed for the hydrogen storage scenario and the electricity storage scenario by applying the model introduced in Section 2. The photovoltaic production hour profile and the natural gas consumption profile provided by the company were used. The techno – economic data of Section 3 have been applied. The solution with a mixture composed with a 20% of hydrogen is considered as a reference case, since it represents the maximum blending that can feed an industrial ceramic plant without structural modifications to the furnace, according to Confindustria [12].

4.1. Technical results

The main results related to the reference cases are presented in Table 4.

Table 4. Main results of the simulation with standard parameters.

Parameter	H_2 STORAGE, PEM	H_2 STORAGE, ALK	ELECTRICITY STORAGE
Blending ratio [%]	20	20	20
Electrolyzer size [kW]	2112	1929	735.7
PV size [kW]	2001	1833	2023
Mean Electrolyzer Load Factor [%]	32.77	32.78	43.79
Mean specific consumption [kwh/Nm^3]	5.83	5.32	5.76
Storage tank size [m^3]	2436	2436	-
Battery size [kWh]	-	-	13,721
Annual hydrogen production [Nm^3]	459,800	459,640	459,800
Annual Natural Gas savings [Nm^3]	142,120	142,120	142,120
Annual CO_2 savings [ton]	256.8	256.8	256.8
Annual PV excess production [MWh]	125.5	115.6	164.3

In Figure 12 it is reported the number of working hours of the electrolyzer in the different scenarios. The electricity storage scenario represents the solution in which the system works for the highest amount of hours (8160 hours per year), in fact the electrolyzer constantly produces the requested quantity of hydrogen, independently from the operating conditions of the photovoltaic plant. In the hydrogen storage scenario, the electrolyzer follows the photovoltaic energy production, therefore it produces hydrogen for a reduced amount of hours per day. In particular the PEM electrolyzer works for a slightly higher amount of hours with respect to the alkaline one – 3378 hours against 2952 hours per year – and this behaviour happens because of the ability of the former to work at lower load factor conditions in comparison with the latter. It is foreseeable that this important gap of operating hours between the two reference scenarios will lead to a more frequent need to stack substitution in the electricity storage solution.

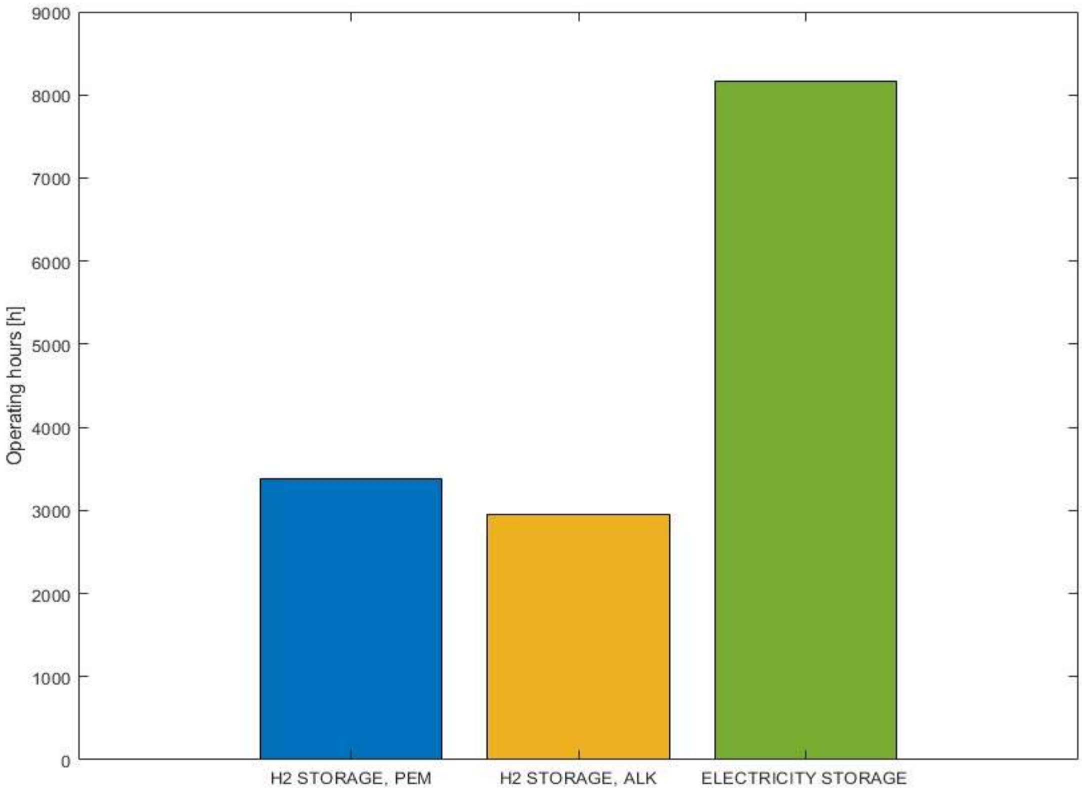

Figure 12. Electrolyzer's operating hours in the reference scenarios.

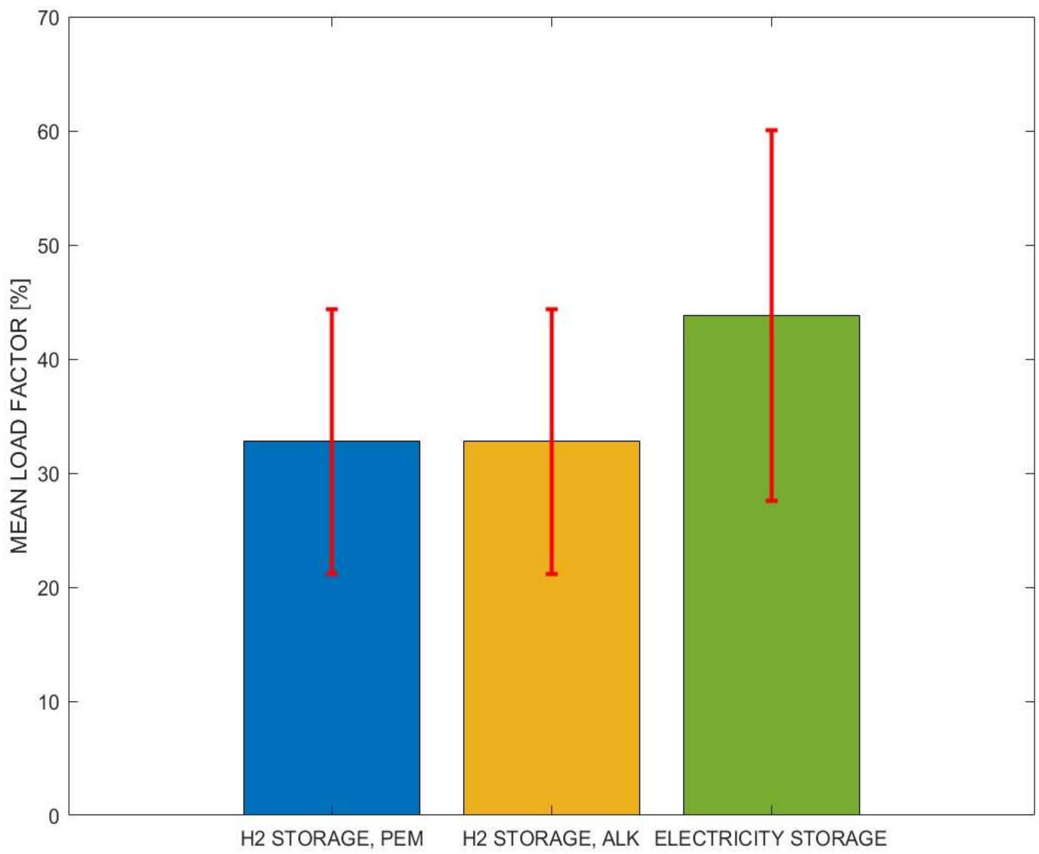

Figure 13. Mean Load Factors and standard deviations (red lines).

For what concerns the performances of the electrolyzer during the operating hours, the mean load factor (LF) and the mean specific consumption (SC) along the year and their standard deviation have been calculated and plotted. While the mean load factor of either PEM and alkaline electrolyzer in hydrogen storage scenario is approximately the same and it corresponds to 32.7%, in the electricity storage scenario the mean load factor is considerably higher, in fact the electrolyzer is designed to satisfy the hourly hydrogen request instead of following the energy peaks of the photovoltaic production therefore its size is smaller in case of unchanged initial conditions. Furthermore it is visible from the standard deviation plot that the electrolyzer in the electricity storage scenario has a wider variation of the load factor: this result leads to the conclusion that the hydrogen request profile presents wider oscillations with respect to the photovoltaic production profile, that is exploited for the hydrogen storage case.

For what concerns the mean specific consumption, the best performances are guaranteed by the alkaline electrolyzer in the hydrogen storage reference scenario, as understandable by the efficiency curves represented in Figure 7. The

PEM electrolyzer presents the same performances in both scenarios. On the contrary to the load factor analysis, the electricity storage scenario presents the most stable values, with a standard deviation that is less significant. This countertrend behaviour is explained by the mean load factor result and its standard deviation, since they both lie in the area of the efficiency curve that presents a plateau, while the load factor of the hydrogen storage analysis presents values below 25% where the curve ramps up.

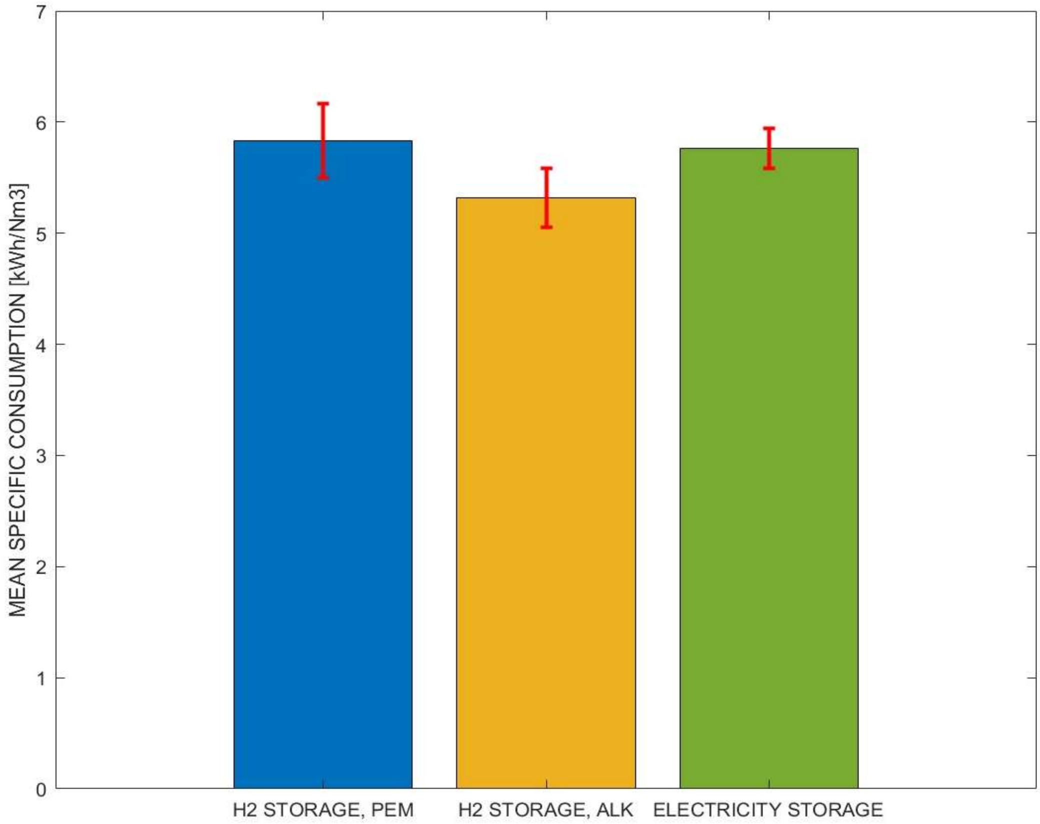

Figure 14. Mean Specific Consumptions and standard deviations (red lines).

In order to handle possible contingencies, given by a low photovoltaic productivity or a high hydrogen request by the furnace, the electrolyzer has been sized to work with an 80% load factor in the worst condition possible, based on the hourly data available. This design value guarantees to manage possible emergencies and it has an importance on the size of the electrolyzer, therefore it has been performed a study to understand its impact on the main working parameters of the plant.

Figure 15 shows that by increasing the design load factor – therefore reducing the size of the electrolyzer, since the value represents the operating point in the worst conditions – there is a consequent increase in the mean operating load factor. PEM and alkaline curves for the hydrogen storage scenario are overlapped, while the curve relative to electricity storage scenario presents higher values justified by the lower size of the electrolyzer. Since the two factors have a linear relation, the trend of the mean specific consumption by changing the design load factor follows the efficiency curves presented in Figure 7. It is significant to observe that the PEM electrolyzers of the two different scenarios follow a different trend and they both tend to a plateau: this behaviour is always explained by the efficiency curve, that flattens when the electrolyzer reaches an operating point around 30%. The results about the mean specific consumption are clarified in Figure 16.

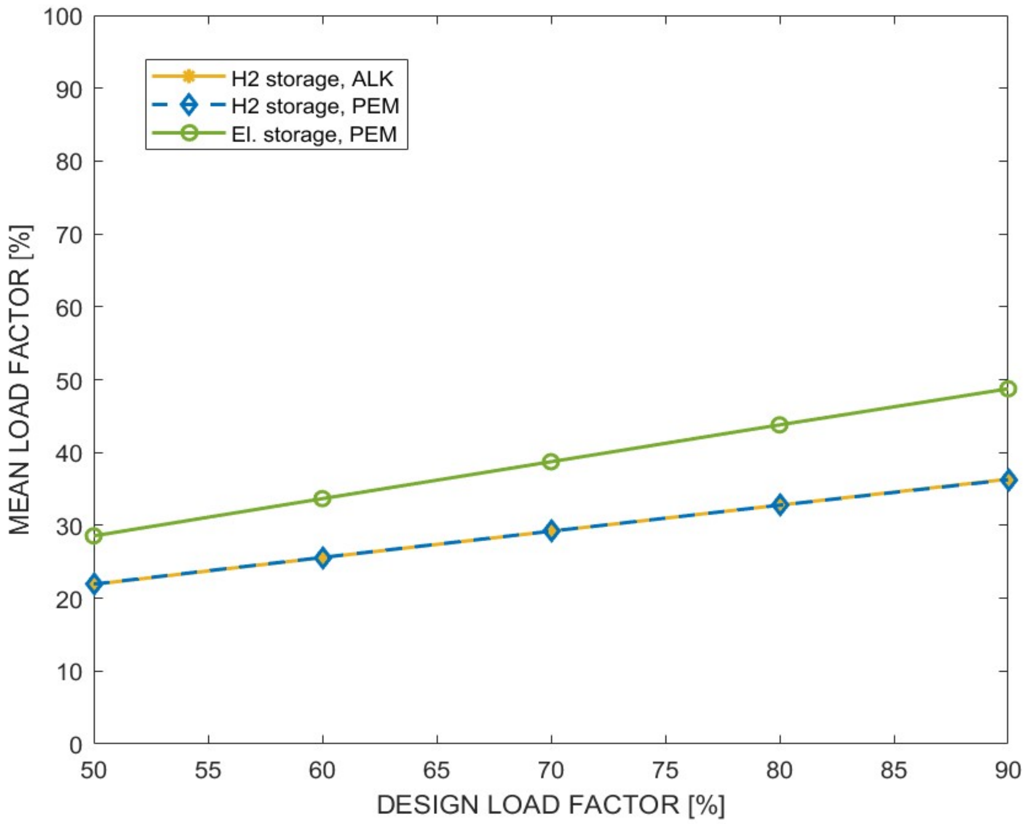

Figure 15. Mean operating load factor by varying the design load factor.

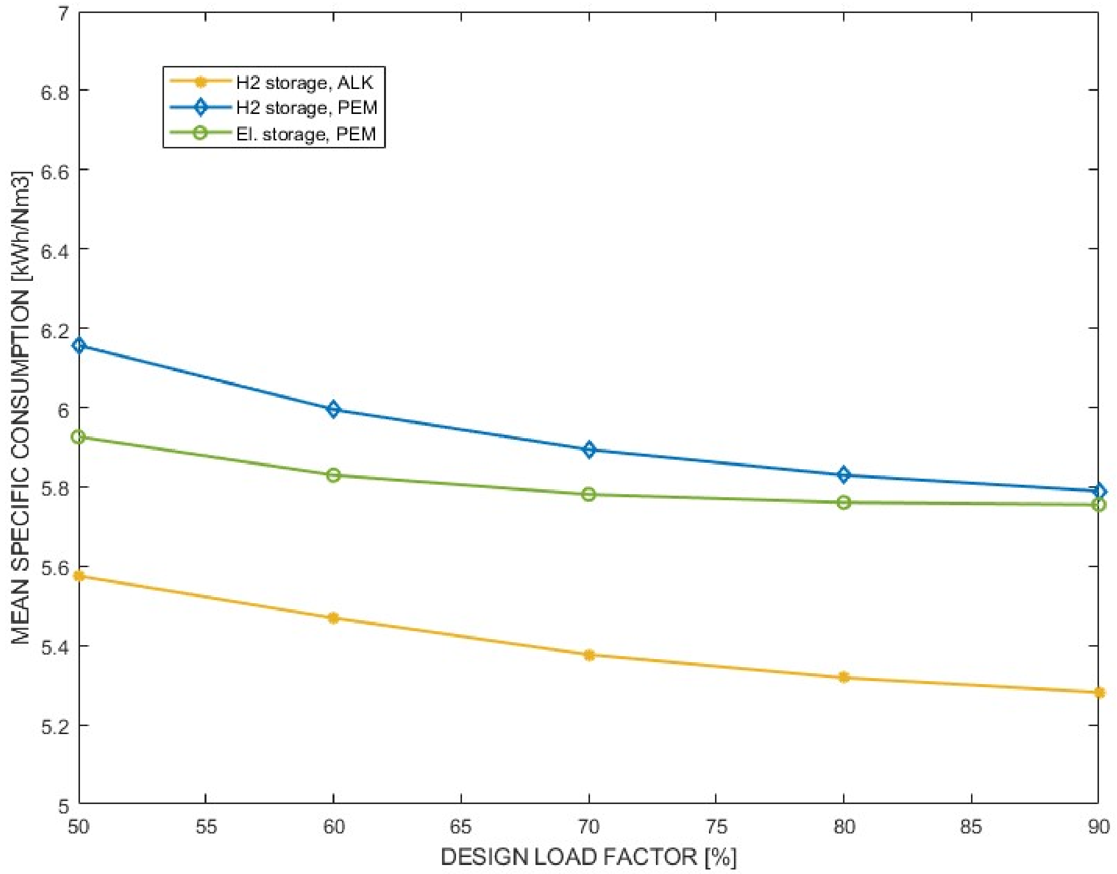

Figure 16. Mean specific consumption by varying the design load factor.

4.2. Variable blending ratio results

After the analysis on the performances – independent from the blending ratio – it has also been studied the impact of the composition of the mixture on the size of the electrolyzer. The main differences between the reference scenarios have been investigated as well. The electrolysis system has been properly designed for every selected blending and the photovoltaic system is sized as well. The results are reported in Figure 17.

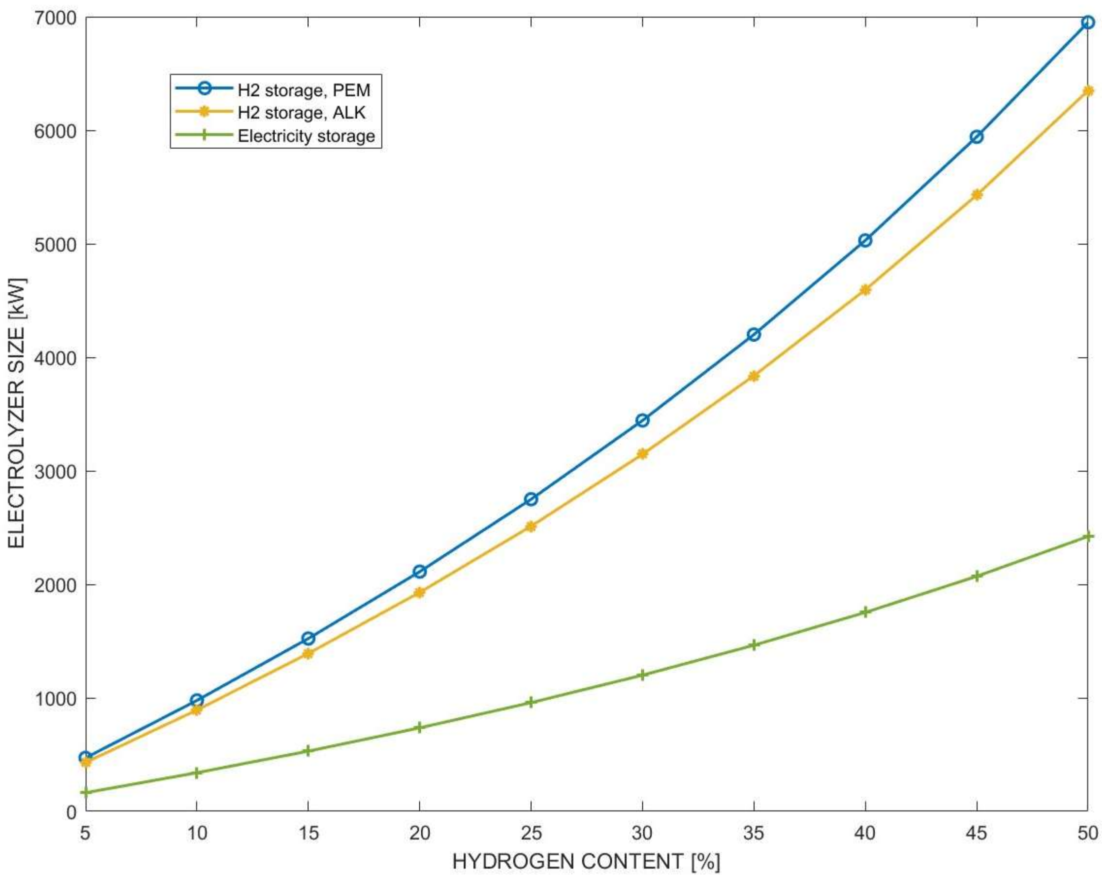

Figure 17. Electrolyzer size as a function of blending.

The electrolyzer size has an almost linear increase with the hydrogen content in the fuel mixture. As deduced from the previous results, the PEM electrolyzers installed in the electricity storage scenario are considerably smaller than the ones sized for the other scenario: this difference depends by the behaviour of the photovoltaic energy profile with respect to the hydrogen request profile. For what concerns the hydrogen storage scenario, the PEM electrolyzer needs a bigger build in comparison with the alkaline one, as widely justified by the efficiency curves presented in 2. Methodology that shows better performances for the latter. A similar size trend can be observed for what regards the photovoltaic plant dimensions, that grow with a quasi-linear proportionality with the mixing rate. For what concerns the comparison between photovoltaic and electrolyzer size, it has already been said that a linear proportionality guarantees the proper dimensions of the photovoltaic plant, with a production margin of around 5% with respect to the annual needs of the electrolyzer. The photovoltaic plant presents a smaller size when coupled with the alkaline electrolyzer, that currently guarantees better performances and a lower specific consumption, but on the other side it has the same dimensions in both scenarios when coupled with the PEM electrolyzer, although the latter is considerably smaller in the electricity storage scenario; the main reason of this behaviour derives from the sizing criteria of the photovoltaic that depends by the annual energy request from the electrolyzer and it is independent from the hourly request and the kind of storage facility installed.

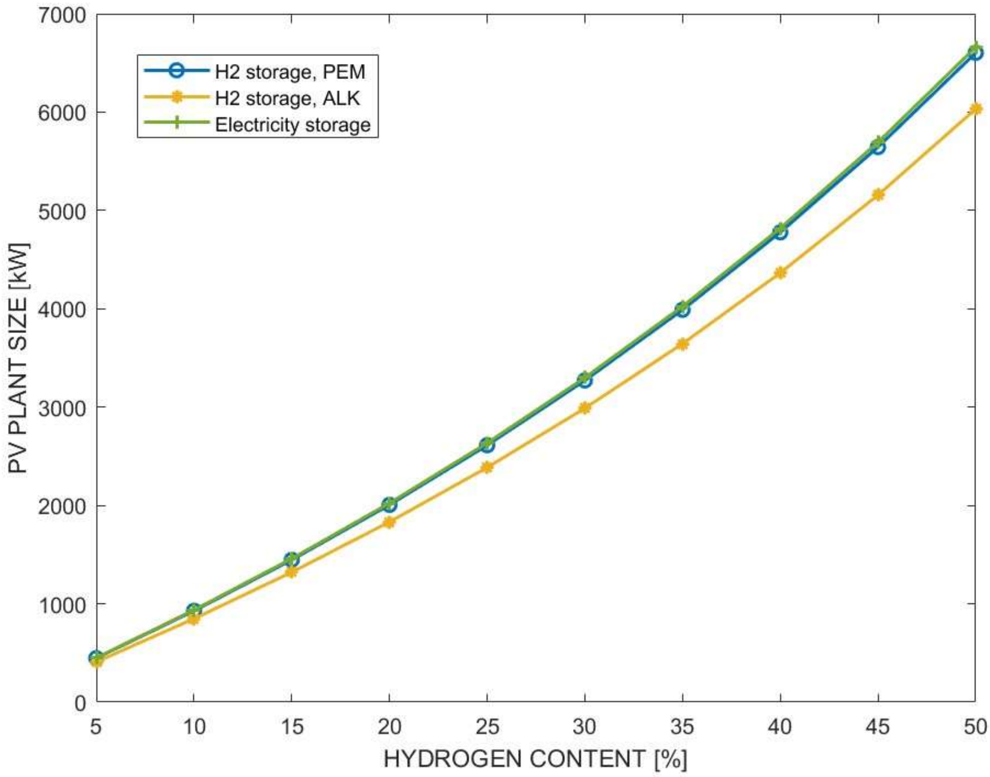

Figure 18. PV plant size as a function of blending.

As a following step of the technical analysis, it has been investigated the working principles of the electrolyzer at different blending ratios. Once the whole system has been sized to work with a predetermined blending, its performances are analyzed with a mixing rate that goes from 5% to 50% vol. of hydrogen. As foreseeable, the electrolyzers with a small size are not able to produce enough hydrogen to guarantee the highest blending ratios: after a certain mixture composition the system presents a plateau in the hydrogen production, that indicates that the electrolyzer has reached its maximum production capacity. The achievement of this limit coincides with the reduction of natural gas and CO_2 emissions savings and the saturation of the electricity consumption. This behaviour is represented in Figure 19 as an example, for a PEM electrolyzer sized to guarantee a blending ratio of 20% vol. of hydrogen in the mixture.

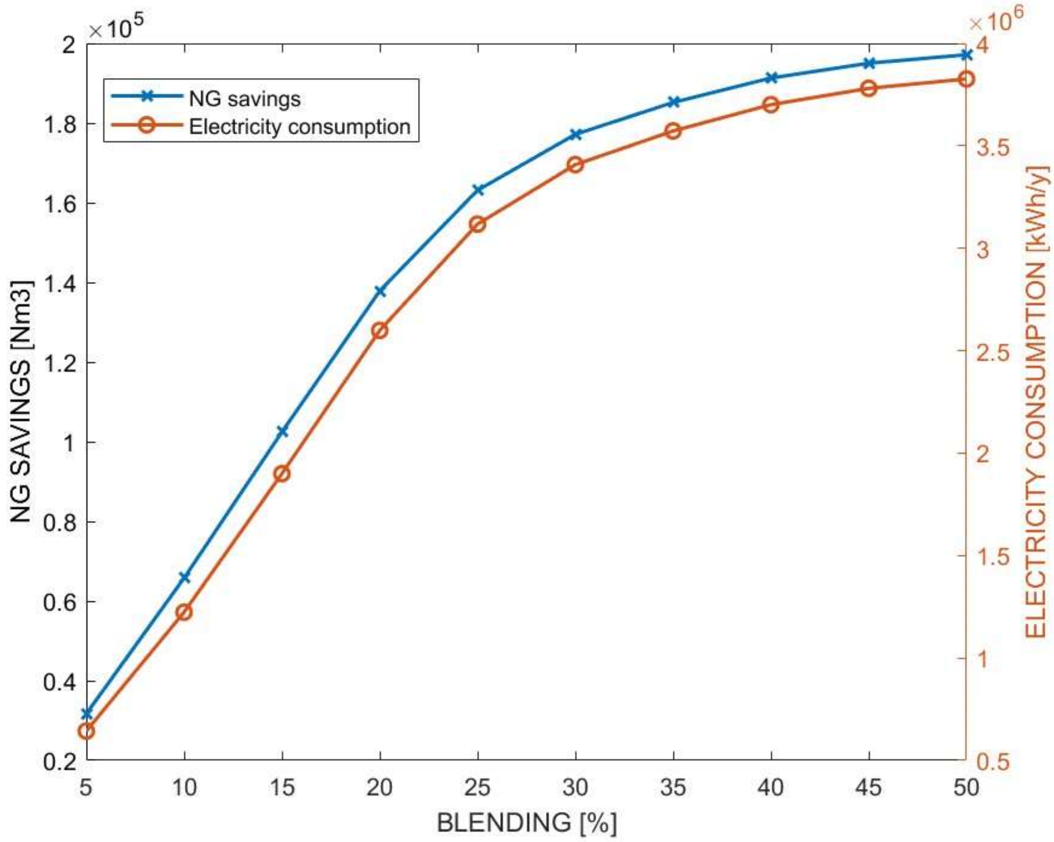

Figure 19. Natural gas savings and electricity consumption at variable blending.

An electrolyzer sized to guarantee the highest blending ratios is always able to guarantee the proper hydrogen production for lower mixing rates. On the other hand, it is interesting to observe that the electrolyzers are able to cover a higher hydrogen request than the one they are sized for, therefore there is the possibility to undersize the plant and work with more elevated load factors. This kind of analysis has been carried out without taking into account the size of the photovoltaic plant: if the electrolyzer is oversized there is a considerable excess of energy, while if it is undersized electricity must be purchased from the grid. For what concerns the hydrogen storage tank, it must be designed proportionally to the maximum possible production of the electrolyzer, while batteries do not need a resize, since electricity can eventually be reused or sold to the grid.

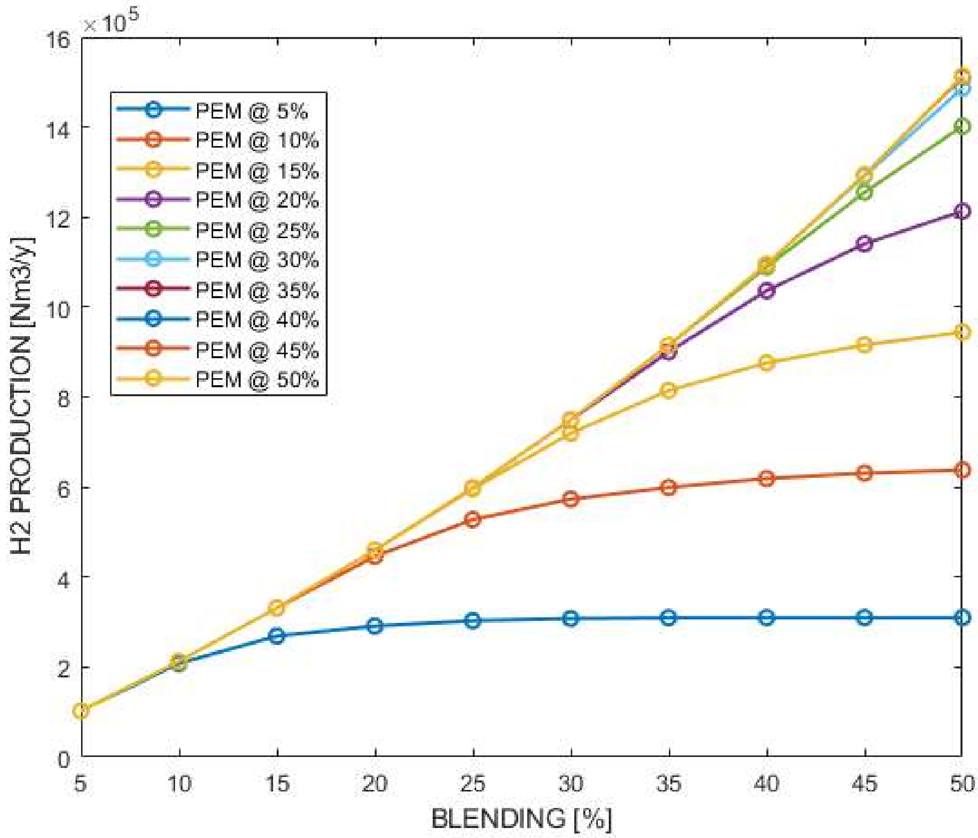

Figure 20. PEM electrolyzers behaviour at every blending.

Table 5. Performances of different sized electrolyzers at a 50% blending. Values above 50% have not been calculated.

ELECTROLYZER SIZE	MAXIMUM GUARANTEED BLENDING		
	H_2 Storage, PEM	H_2 Storage, ALK	Electricity storage, PEM
5% ELECTROLYZER	15.76%	16.63%	12.34%
10% ELECTROLYZER	28.99%	29.78%	23.04%
15% ELECTROLYZER	37.62%	38.85%	31.78%
20% ELECTROLYZER	44.01%	45.07%	37.79%
25% ELECTROLYZER	47.94%	48.56%	43.2%
30% ELECTROLYZER	49.55%	49.77%	47.19%
35% ELECTROLYZER	49.97%	49.99%	49.03%
40% ELECTROLYZER	50%	50%	49.97%
45% ELECTROLYZER	> 50%	> 50%	> 50%
50% ELECTROLYZER	> 50%	> 50%	> 50%

Table 5 it is visible that the electrolyzers behave similarly in the different scenarios, however the PEM electrolyzer used with the electricity storage presents slightly worse performances, caused by the fact that in this scenario the system already works at an higher mean load factor and therefore it assures a more restricted margin to operate at higher mixing rates. For what concerns the electrolyzer sized to work at a 50% of mixing rate, it can surely guarantee an higher blending ratio, however the simulation has been stopped to a 50% blending limit.

4.3. Economic results

For what concerns the economic analysis of the case study, the main results are reported in table. As for the technical analysis, the reference case is represented by an electrolyzer sized to work with a mixing rate of 20% of hydrogen.

Table 6. Main results of the economic analysis.

Parameter	H_2 STORAGE, PEM	H_2 STORAGE, ALK	ELECTRICITY STORAGE
Investment [€]	4,235,900	2,913,700	6,617,900
Electrolyzer cost [€]	2,533,700	1,350,300	882,880
PV cost [€]	1,604,700	1,466,000	1,618,600
Storage cost [€]	97,454	97,454	4,116,400
Annual costs [€]	50,675	27,005	17,658
Annual revenues [€]	74,047	72,359	80,637
NPV [€]	-4,293,400	-2,480,700	-6,177,100
IRR [%]	-24.79	-9.81	-71.49
PBT [years]	> 25 years	> 25 years	> 25 years
LCOH [€/kg]	9.16	6.01	12.55

As it is evident in Table 6, the investment results no convenient in each analyzed scenario due to an elevated investment cost and annual revenues that are not sufficient to cover the initial capital expenditure. However the levelized cost of hydrogen could be considered quite competitive, especially in the hydrogen storage scenarios. In particular the scenario that involves the alkaline electrolyzer is the less expensive thanks to the higher economic competitiveness of that kind of technology. The trend of the Net Present Value of the project is shown in Figure 21 and it highlights the impact of the replacements on the cost-revenues structure: the electricity storage scenario represents the most affected case study due to the substitution of either the battery and the stack, that in this conditions must be replaced with more frequency because the electrolyzer works for a considerably higher amount of hours.

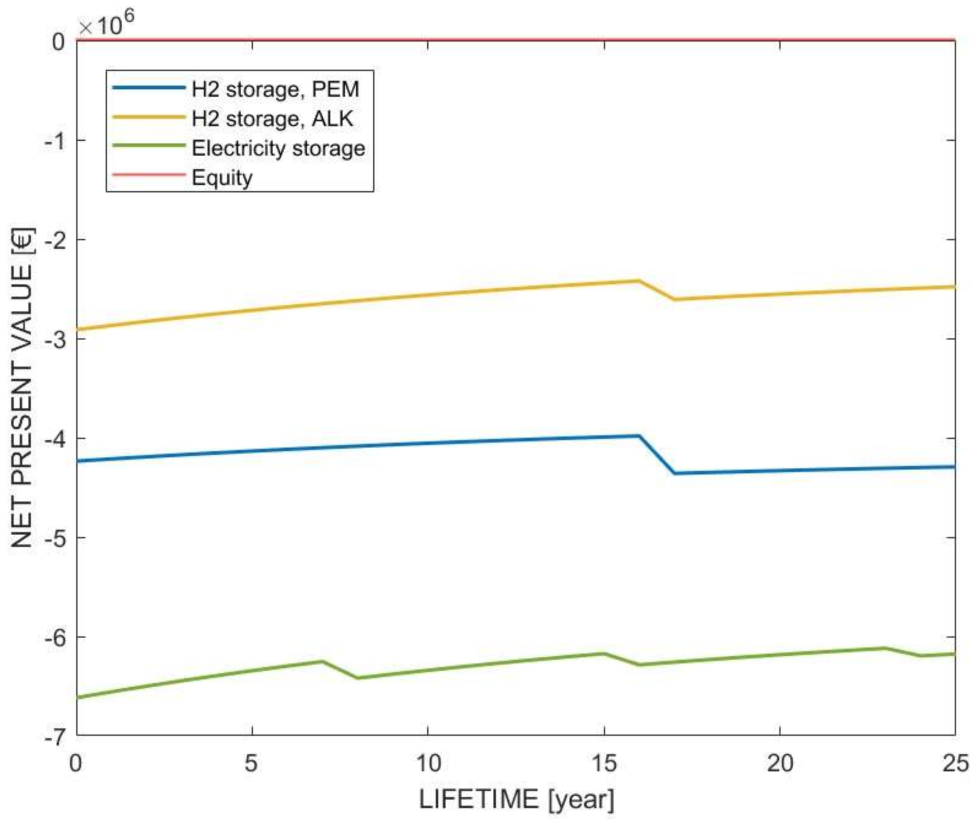

Figure 21. Trend of the NPV in the scenarios analyzed.

The analysis of the main reasons of the difficulties to make the investment affordable brings to the observation of the structure of the investment, with the aim to understand how each component impacts on the case study.

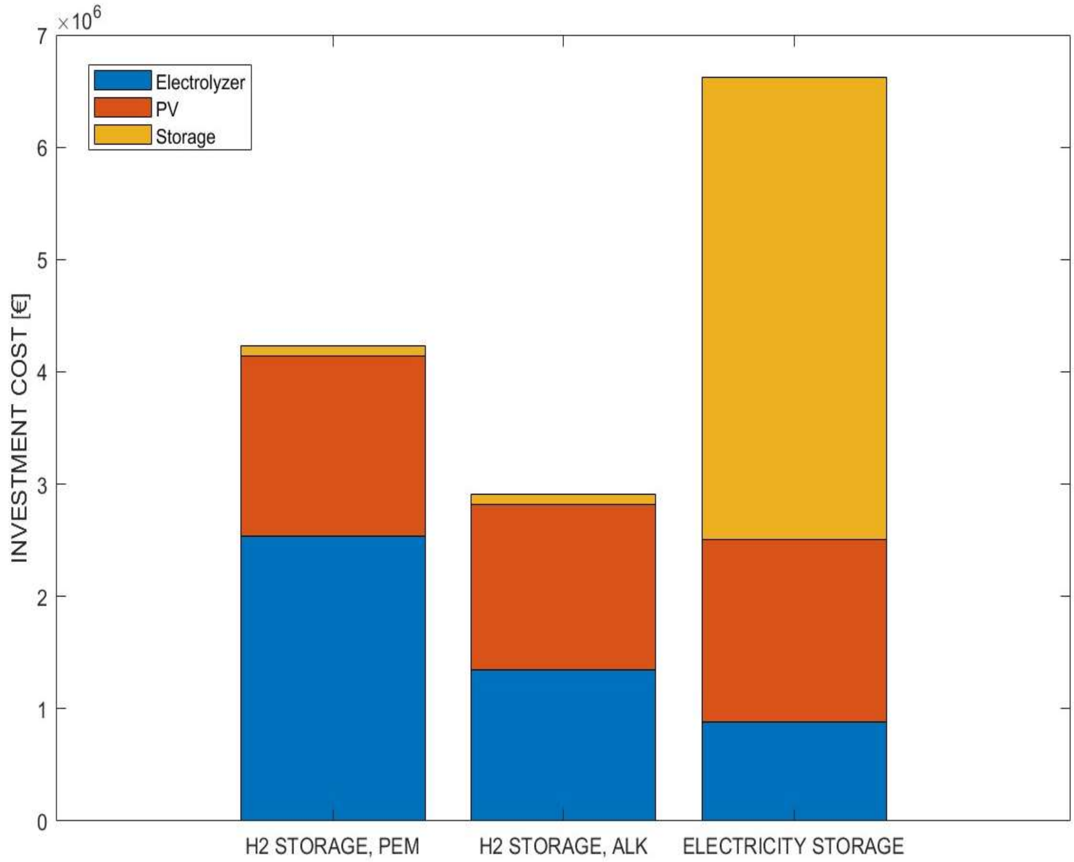

Figure 22. Investment breakdown in the main scenarios.

It is possible to deduce from the Figure 22 that the electrolyzer impact is strictly related to its size, since the PEM utilized in the hydrogen storage scenario is bigger than the one installed in the electricity storage scenario and in fact it represents an important share of the investment. The choice of the electrolyzer technology is also relevant since nowadays the alkaline stacks present more competitive costs and specific consumption values that permit to undersize the electrolyzer for the same production rate with respect to PEM. By observing the investment breakdown of the electricity storage scenario, it is visible the impacting role of the battery cost, that represents more than half of the whole investment, making the project impossible to sustain. Not only the battery cost is too elevated (i.e. 300 €/kWh) in comparison with the other costs, also it is less competitive if compared with the cost of a storage tank that must face the same hydrogen production. The same analysis has been developed to study the impact of the different components of the investment and the OPEX on the cost of production of the hydrogen: the relative impact of the investment shares is slightly the same already seen for CAPEX, while it is visible that the OPEX has a reduced relevance in the electricity storage scenario. The effect of the OPEX on the Levelized Cost of Hydrogen is strictly related to the stack replacement cost, therefore it is proportional to the electrolyzer size. The results are presented in Figure 23.

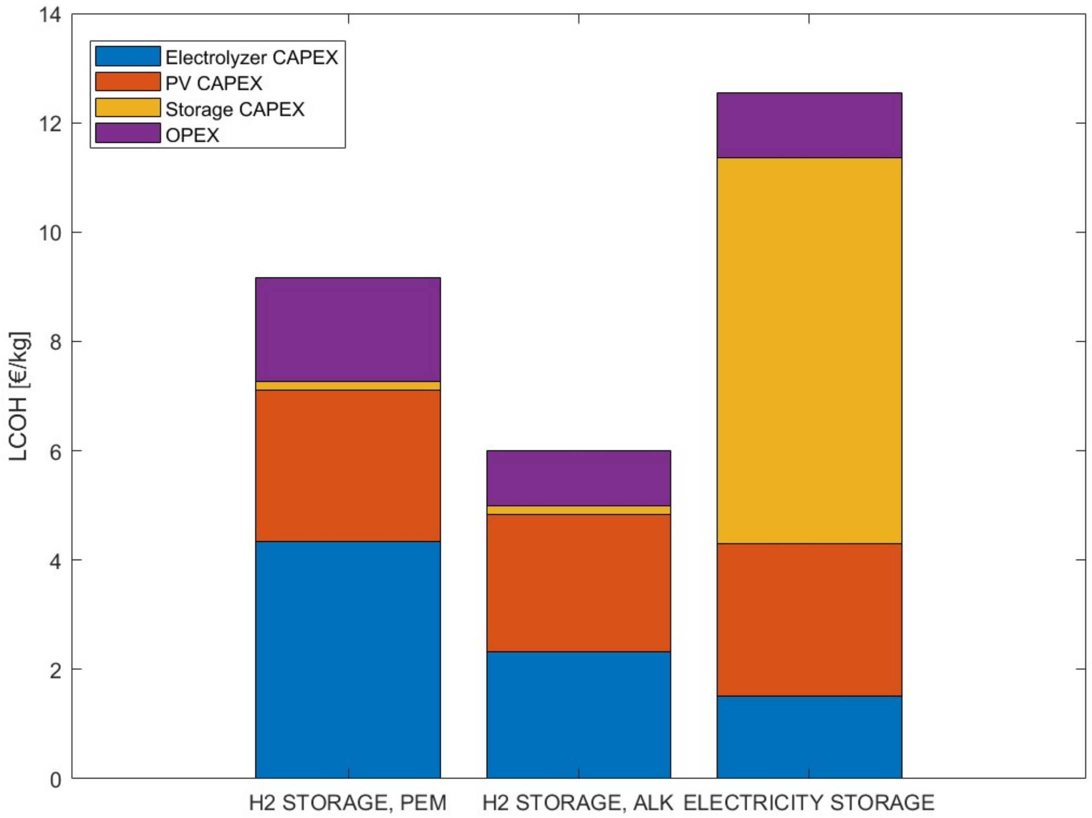

Figure 23. LCOH breakdown in the main scenarios.

An analysis of the revenues structure has been carried out to observe the main aspects to optimize the profitability of the project. The results are represented in Figure 24 and they involve three main sectors:

- Savings from natural gas consumption.
- Savings from electricity consumption due to excess production from photovoltaic.
- Savings from ETS quotes due to less CO_2 emissions.

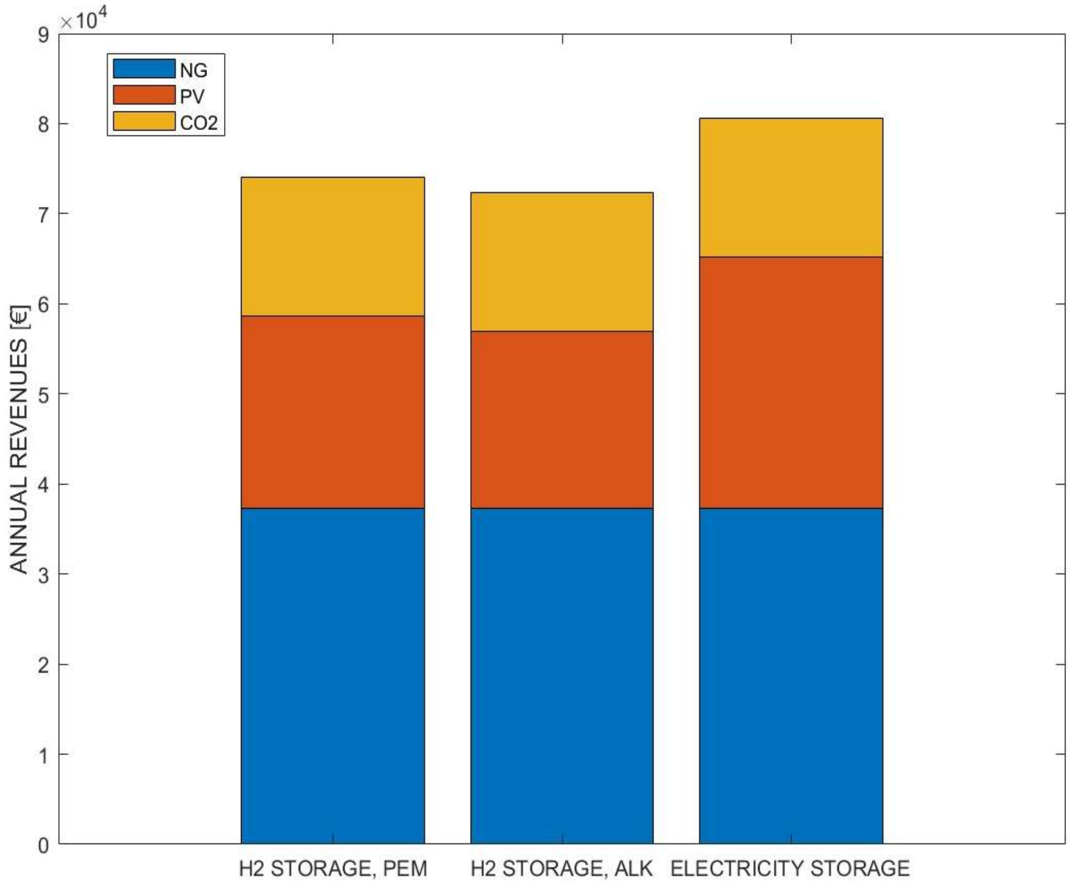

Figure 24. Revenues breakdown structure in the main scenarios.

The savings coming from the reduction of natural gas consumption represents the majority of the revenues. The natural gas and CO_2 savings represent a similar value in all scenarios, since the hydrogen production is slightly the same as it is dictated by the thermal power needed by the furnace. The electricity savings related to the photovoltaic excess production are the most variable parameter of the revenues, in fact by changing the margin of production it is possible to increase the incomes. This kind of analysis brings to a possible solution to make the investment sustainable, and it consists in the increase of the photovoltaic production margin in order to enlarge the related revenues. The easiest way to achieve this goal is to increase the ratio between the photovoltaic plant size and the electrolyzer size. The volumetric mixing rate of hydrogen is always kept at 20%. The results of the Net Present Value regarding the hydrogen storage scenario for both PEM and alkaline electrolyzers are presented in Figure 25 and Figure 26.

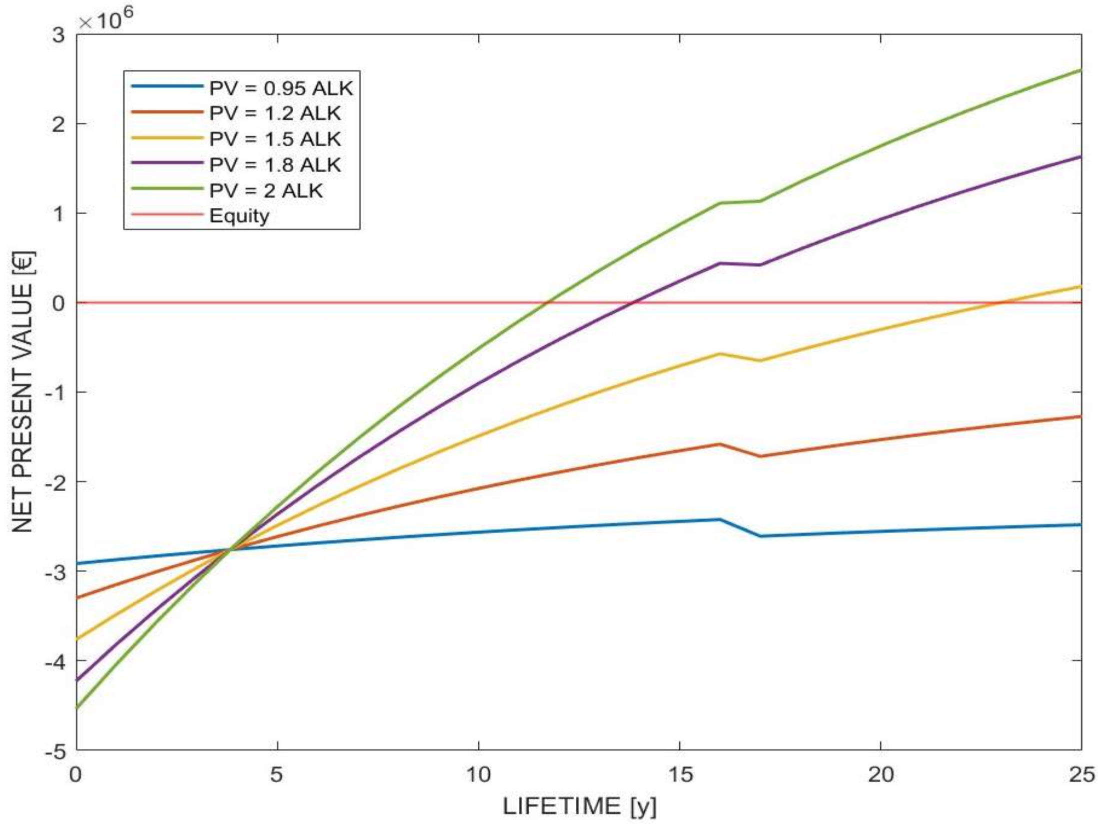

Figure 25. NPV trend for different PV-ALK electrolyzer ratios.

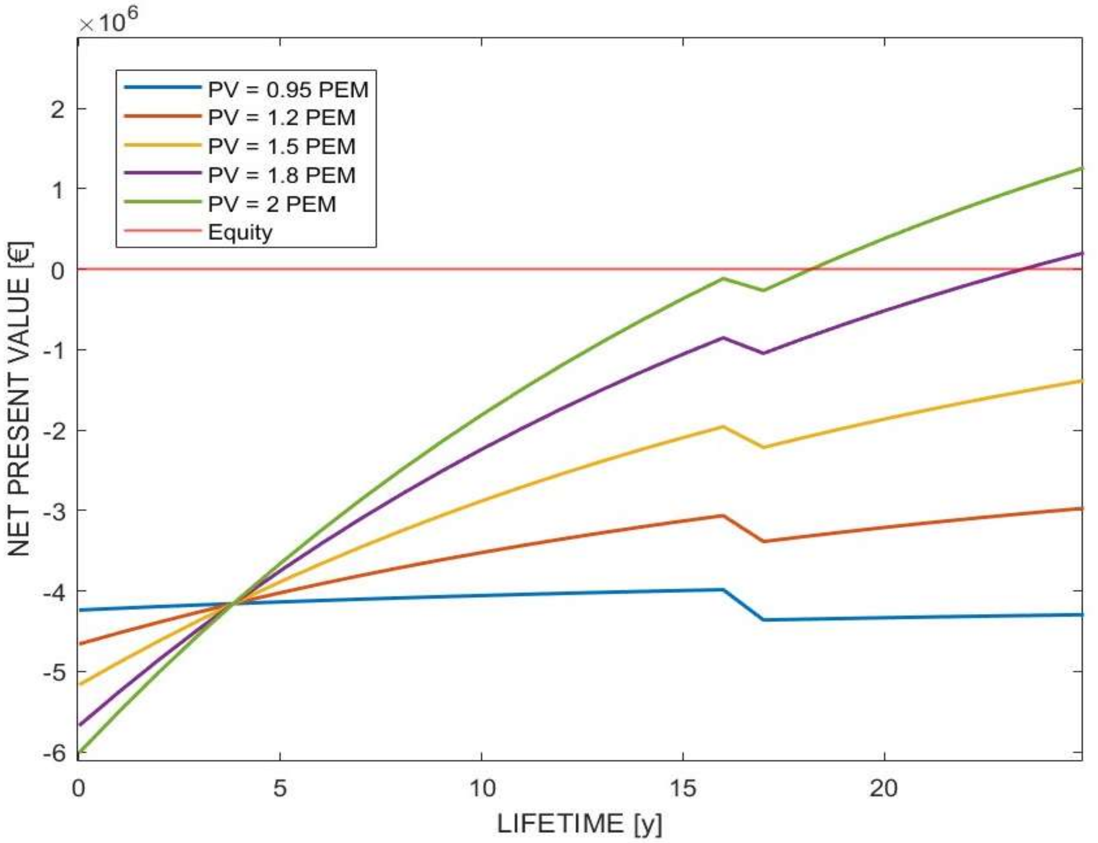

Figure 26. NPV trend for different PV-PEM electrolyzer ratios.

In order to have a convenient investment, it is necessary to have a photovoltaic plant that is at least 1.8 times the PEM electrolyzer and 1.5 the alkaline one, so the installation of an alkaline electrolyzer represents a more profitable investment. The numeric results for both cases with a 1.8 ratio between photovoltaic and electrolyzer are presented in Table 7.

Table 7. Results from a PV-electrolyzer ratio of 1.8.

Parameter	H_2 STORAGE, PEM	H_2 STORAGE, ALK
Investment [€]	5,617,700	4,225,400
PV margin [%]	49.61	49.63
NPV [€]	20,758	1,613,300
IRR [%]	5.38	8,67
PBT [years]	24	14
LCOH [€/kg]	11.63	8.26

A further increase of the photovoltaic reflects in higher revenues and a shorter payback time. In conclusion, only a part of the photovoltaic energy can be used to feed an electrolyzer, in order to have a profitable investment. The photovoltaic plant must be oversized with respect to the electrolyzer energy needs with the aim to save more electrical energy and increase the revenues. Since the investment cost raises with the photovoltaic resize, the Levelized Cost of Hydrogen for both cases also increases, therefore the size of the photovoltaic must not be excessive. Another issue is represented by the dimensions of the photovoltaic plant, indeed the available space for industries is usually limited and it does not afford oversized plants.

This kind of approach is not suitable for the electricity storage scenario, because the battery size is proportional with the excess of electric energy produced and at the actual prices it represents the biggest share of the capital expenditure of that case study. That approach may be conducted only with a reduced cost of batteries, i.e. 100 €/kWh, that represents a foreseeable price for a 2030 scenario [17]. With this price for batteries and a PV plant that is five times the electrolyzer, it is possible to reach a payback time of 21 years, with a Net Present Value of around 83,000 €.

5. Conclusions

A techno-economic analysis of hydrogen for high-temperature heat generation has been performed for the case study of a ceramic industry in Italy. The simulation has been based on hourly data of natural gas consumption based on a reference year (thermal load of the industrial furnaces). The case study has been examined analysing two reference scenarios – hydrogen storage and electricity storage – and using both PEM and alkaline electrolyzers for the production of hydrogen from a locally available PV plant. The aim of the hydrogen-based installation was the reduction of natural gas consumption and CO_2 emissions of the furnace by feeding it with a mixture containing a certain percentage of hydrogen.

The technical analysis revealed that the installation of an electrolyzer guarantees a reduction of natural gas consumption, that is around 7% by considering a mixing rate of 20% vol. of hydrogen. As a consequence, the emissions are reduced as well. Nowadays the alkaline electrolyzers present the best performances for what concerns the hydrogen output over the photovoltaic production – 5.32 kWh/Nm^3 against 5.82 kWh/Nm^3 of PEM, with the same mean load factor – and that allows to slightly reduce the size of the device.

The two different scenarios allow a good elasticity in the choice of the electrolyzer dimensions: In the hydrogen storage scenario the PEM is 2112 kW and the alkaline electrolyzer 1929 kW, while in the electricity storage scenario the PEM size is 735.7 kW. The design load factor of 80% as been confirmed as an optimal value, since it guarantees a better safety margin than a 90% load factor and a better specific consumption value compared to lower value.

The study regarding a variable blending ratio has been useful to understand the operational limits of the electrolyzer: it has been deduced that an electrolyzer sized to work for a predetermined blending can operate also for higher mixing rates, if properly fed with electricity, without the need to resize it.

For what concerns the economic analysis of the case study, it showed that every scenario analyzed presents a negative economic return, with annual revenues that go from 72,000€ for the alkaline electrolyzer to 80,000€ for a PEM with the electricity storage, with a cost of investment equal to 2,913,700€ for the first case and 6,617,900€ for the latter. Even though all the possibilities reveal an economic inconsistency, the alkaline electrolyzer represents the most convenient solution, since the maturity of the technology reflects on a lower price with respect to the PEM and it presents a LCOH of 6.01€/kg, the 34% less than a PEM in the hydrogen storage scenario and more than 50% less than a PEM in the electricity storage scenario. The electricity storage scenario revealed to be the less convenient due to the elevated cost of the storage batteries – 4,116,400€, the 62% of the whole investment – that is unsustainable for the revenues structure, although the smaller electrolyzer reduces that share of the CAPEX and the operating conditions guarantee the higher amount of working hours. The stack replacement also has an important impact, in particular in the electricity storage scenario, where the electrolyzer works more hours and faces three replacement over the lifetime of the project.

The analysis relative to the size of the photovoltaic plant was significative to demonstrate that the PV size-electrolyzer ratio that is optimal for system operation – that is 0.95 for the hydrogen storage scenario – is not sufficient from an economic point of view, where it amounts to at least 1.8 to have an affordable project. By increasing the electricity savings of the furnace it is possible to get a positive investment. With the current prices, the installation of an electrolyzer coupled with a photovoltaic plant is convenient only if not all electricity produced by the latter is exploited by the electrolyzer, therefore the photovoltaic is oversized with respect to the energy needing. Only the 50% approximately of the PV production can be dedicated to an electrolyzer.

Further research may by focused to better understand the impact of an electrolyzer plant in the high-temperature industrial sectors: the coupling with a wind farm can be observed, since it presents a totally different power profile, or other renewable energy resources. It is also possible to investigate the possibility to increase the blending, with mixing rates that go over 50%, until reaching a furnace totally fed by hydrogen. With the increase of the blending ratio, it could also be interesting to observe the behaviour of the furnace, especially for what concerns the temperatures and the flue gases.

In conclusion, the absence of national incentives for the production of green hydrogen represents a decisive aspect for the investment on an electrolyzer system, since the economic savings given by the substitution of part of the natural gas used today are not sufficient to sustain the environmental reason of the reduction of CO_2 emissions. The current study revealed that the photovoltaic system represents a convenient solution to provide renewable energy, however it is not able to reduce the emissions in the high temperature sector without the production of hydrogen. The establishment of incentives and the continuous research for the optimization of the technologies could lead to a reduction of the current prices and they may play an important role in the installation of an electrolyzer for the decarbonization of the industrial sectors.

Bibliography

[1] V. H. S. Shiva Kumar, «Hydrogen Production by PEM Electrolysis - A review,» *Iol,* vol. 2, pp. 442 - 454, 2019.

[2] J. Hinkley e al., «Cost assessment of hydrogen production from PV and electrolysis,» CSIRO, Australia, 2016.

[3] G. Kakoulaki, «Green Hydrogen in Europe - A regional Assessment: Substituting existing production with Electrolysis powered by Renewables,» vol. 228, 2021.

[4] H. van't Noordende, «Baseline design and total installed costs of a GW green hydrogen plant,» Institute for Sustainable Process Technology (ISPT), 2020.

[5] Ministero dello sviluppo economico, «Strategia Nazionale Idrogeno: Linee Giuda Preliminari,» 2020.

[6] e. a. Reza Abbasi, «A Roadmap to Low-cost Hydrogen with Hydroxide Exchange Membrane Electrolyzer,» *Adv. Mater,* 2019.

[7] e. a. Yujing Guo, «Comparison between Hydrogen Production by Alkaline Water Electrolysis and Hydrogen production by PEM electrolysis,» 2019.

[8] IRENA, «Green Hydrogen Cost Reduction: scaling up Electrolyzers to Meet 1.5°C Climate Goal,» International Renewable Energy Agency, 2020.

[9] e. a. N. Cooper, «A Framework for the Design & Operation of Large-scale Wind-powered Hydrogen Electrolyzer Hub,» vol. 47, pp. 8671-8686, 2022.

[10] IRENA, «Introduction and Policy pillars,» International Renewable Energy Agency, Abu Dhabi, 2020.

[11] IEA, «The Future of Hydrogen,» International Energy Agency, Paris, 2019.

[12] CONFINDUSTRIA, «Piano d'azione per l'idrogeno: Potenzialità dell'industria nazionale nella prospettiva della transizione ecologica e mappatura dei potenziali Off-takers,» ENEA, 2022.

[13] e. a. P. Marocco, «Optimal design of stand-alone solutions based on RES + hydrogen storage feeding off-grid communities,» vol. 238, 2021.

[14] A. Christensen, «Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe,» International Council on Clean Transportation, 2020.

[15] e. a. A. Trattner, «Renewable Hydrogen: Modular Concepts from Production over Storage to the Consumer,» vol. 4, pp. 706-716, 2021.

[16] P. Marocco e e. al, «A study of the techno-economic feasibility of H2-based energy storage,» *Energt Conversion and Management,* vol. 211, n. 112768, 2020.

[17] I. Tsiropoulos, «Li-ion batteries for mobility and stationary storage applications,» JRC science for policy report, 2018.