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Techno-Economic Analysis of Clean Hydrogen Production Plants in Sicily: Comparison of Distributed and Centralized Production

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Abstract: This paper presents an assessment of the levelized cost of clean hydrogen produced in Sicily, a region in Southern Italy particularly rich in renewable energy and where nearly 50% of Italy's refineries are located, making a comparison between on-site production, that is, near the end users who will use the hydrogen, and centralized production, comparing the costs obtained by employing the two types of electrolyzers already commercially available. In the study for centralized production, the scale factor method was applied on the costs of electrolyzers, and the optimal transport modes were considered based on the distance and amount of hydrogen to be transported. The results obtained indicate higher prices for hydrogen produced locally (from about 7 €/kg to 10 €/kg) and lower prices (from 2.66 €/kg to 5.80 €/kg) for hydrogen produced in centralized plants due to economies of scale and higher conversion efficiencies. How-ever, meeting the demand for clean hydrogen at minimal cost requires hydrogen distribution pipelines to transport it from centralized production sites to users, which currently do not exist in Sicily, as well as a significant amount of renewable energy ranging from 1.4 to 1.7 TWh per year to cover only 16% of refineries' hydrogen needs.

Keywords: clean hydrogen; levelized cost of hydrogen (LCOH); energy transition; techno-economic analysis

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1. Introduction

In 2022, about 83% of the hydrogen used globally, mainly for industrial use, was obtained by reforming natural gas and by coal [1], processes that generate significant amounts of environmental emissions such as carbon dioxide but are currently the cheapest available. However, there are also other ways to obtain hydrogen, such as through thermochemical processes such as pyrolysis and gasification or through electrolysis, a process that, to be truly sustainable, would have to be powered by electricity from renewable sources, such as wind or photovoltaic energy. If the electricity used is produced from renewable sources, the hydrogen is commonly labeled as green, since its production does not produce direct carbon dioxide emissions that contribute to climate change, although there is no universally accepted definition and the EU is moving away from these types of color-based classifications [2]. The clean or renewable hydrogen thus produced can be used in "hard-to-abate" industrial sectors, that is, those for which electrification is technically difficult and uncompetitive because of, for example, the high temperatures required by some industrial processes. Other interesting applications are in the transport sector and as a chemical storage of electricity.

At the present state, clean hydrogen production facilities are not yet competitive with conventional ones from an economic point of view [3], but the expected reduction in the cost of electrolyzers, the huge progress in the efficiency of photovoltaic cells and wind generators, and the consequent lowering of the cost of kWh from renewable sources could quickly change the scenario.

For instance, the global weighted average levelized cost of electricity (LCOE) of large-scale photovoltaic (PV) systems decreased by 89% between 2010 and 2022, from 0.445 USD/kWh to 0.049 USD/kWh, a year-on-year decrease of 3% in 2022, while the global weighted average capacity factor for new utility-scale solar PV increased from 13.8% in 2010 to 16.9% in 2022. For onshore wind energy, on the other hand, the LCOE decreased by 69% over the same time interval, from 0.107 USD/kWh to 0.033 USD/kWh, with the average capacity factor increasing from 27% to 37%. Finally, for offshore wind, the levelized cost of energy decreased by 59% to 0.081 USD/kWh in the same time interval, while the overall average capacity factor rose to 42% [4].

Southern Italy, especially Sicily, is rich in precisely these two renewable energy sources that could be harnessed for the production of clean hydrogen. Moreover, Sicily is home to 45.7% of Italy's refineries [5], an industrial sector in which hydrogen is already used. Hence, the initiative to create "Hydrogen Valleys" in Sicily, namely hubs for renewable hydrogen spread throughout the territory that can contribute to the island's energy self-sufficiency, has been undertaken and financed by the regional government, with the aim of reducing imports and strengthening the Sicilian power system, which currently has some weak points. In detail, large wind farms connected to the HV system sometimes cannot deliver their energy production to the grid for dispatching issues and are curtailed by the TSO, while PV plants production causes power flow inversion (from MV to HV) when demand is too low. In this scenario, placing electrolyzers in close proximity to renewable power plants, the excess of electricity production can be used to power the electrolyzers. In this way, the hydrogen production works as a chemical storage, which can be used later as a raw material in the chemical and steel industries, as a fuel to provide high-temperature heat, or can be converted back into electricity to be fed back into the grid when needed through electricity generators (e.g., fuel cells). Models such as the one developed in [6] makes it possible to find the optimal location of power-to-gas plants in the considered area by combining automated GIS processing with cost function solving.

All these reasons have led to considerable interest in clean hydrogen, not only regionally and nationally, but also at the European level. Under European climate legislation, in fact, EU countries must reduce greenhouse gas emissions by at least 55% by 2030, with the goal of achieving climate neutrality, or zero net emissions, by 2050. To achieve these goals, it is necessary to increase energy production from renewable sources and energy efficiency and to start replacing fossil fuels with alternative fuels of renewable origin, such as green hydrogen [7].

Several realities are already active on the Sicilian Island, thanks in part to the financial support of the region, which issued a call for proposals at the end of 2022 to build renewable hydrogen production facilities on brownfield sites [8]. Within the timeframe set by the call, seven applications were received by the region; winning the funding were the initiatives submitted by the companies Agrobiofer Agricultural Society, Duferco Energia, Etna Hitech S.c.p.a. and Res Integra [9].

Duferco Energia's project, in particular, is a pilot plant created under a new collaboration agreement signed by Duferco with Portuguese company Fusion Fuel, which specializes in H_2 production technologies and will supply 50 units of its HEVO, an innovative green H_2 generation system developed by the Portuguese company using PEM electrolysis technology. The modules will be installed at the Duferco plant during 2024 and will be capable of producing about 46 tons of hydrogen annually [10].

Duferco itself, along with the refinery and A2A in the Milazzo industrial area, collaborate with ITAE, the Institute of Advanced Energy Technologies of the National Research Center (CNR). In these companies, the renewable energy produced by photovoltaic plants can be used by new-generation electrolyzers, powered by seawater, which produce green hydrogen that will also be used to recycle CO_2 from the production processes of the same companies and produce synthetic fuels for use in metallurgical and chemical processes, with extremely competitive costs [11].

Other active projects on the island include those of Enel Green Power and Sapio for a testing laboratory in Catania and a production plant in Carlentini, the electrolysis plant from water inside the Eni biorefinery in Gela and the plant of Sasol and Sonatrach in the petrochemical hub of Augusta.

Also in Sicily, a new project by Enel Green Power to use green hydrogen in heavy industry has come to life: the initiative, called "Sicilian Sustainable Steel", has been launched with the company Acciaierie di Sicilia, the only steel factory on the island, in the industrial area of Catania. The aim is to replace with green hydrogen 30% of the natural gas currently used in the rolling mill's reheating furnace, which meets most of the company's non-electrifiable energy needs: a way to significantly reduce the environmental impact of steel production. And it is precisely from the steel industry that a significant part of the total demand for green hydrogen will come from, since this sector is currently responsible, according to the IEA (International Energy Agency), for about 7% of global carbon dioxide emissions [12].

But how much does green hydrogen produced in Sicily cost? This article presents several case studies, comparing on-site production, also known as decentralized or distributed production, and centralized production, using the two commercially available electrolyzer technologies. In particular, the current state of the art of the various electrolyzer technologies developed so far is briefly discussed in Section 1.1; Section 1.2 contains a review of the scientific literature regarding technical-economic evaluations of clean hydrogen production plants; in Section 1.3 the case studies are presented in detail; Section 2 contains the equations and data for the calculations; in Section 3 the results are presented; finally, in Section 4, the results and the conclusions are discussed.

1.1. Electrolyzers: The State of the Art

There are four electrolyzer technologies that have been developed so far: alkaline (ALK), proton exchange membrane (PEM), anion exchange membrane (AEM) and solid oxide (SOEC). There is also a fifth technology, the proton-conducting ceramic electrolyzer (PCC), whose development, however, is slowed by technical difficulties associated with fabrication. They also have rather poor thermomechanical properties, like SOEC electrolyzers [13].

The International Energy Agency (IEA), in its recent report Tracking Clean Energy Progress (TCEP) [14], analyzed the state of development of the different technologies, the implementation of which will be essential to achieve "net zero" by 2050, pointing out that alkaline, traditionally used in some sectors of the chemical industry, is the most mature but adding that today, to produce green hydrogen, alkaline and PEM (proton exchange membrane) are both commercialized and have reached the same "level of technological readiness" (TRL9).

The technology SOEC (Solid Oxyde Electrolysis) is further behind but is also rapidly reaching commercialization thanks to some important projects such as that of the Dutch refinery in Neste, where a 2.6 MW SOEC electrolyzer supplied by Sunfire, or that of NASA, which installed a 4 MW system at its California facility supplied by Bloom Energy.

AEM technology (anion exchange membrane) is the one with the lowest degree of development: it is already produced and commercialized, but only on a very small scale. The company Alchemr, however, already has a kW-scale AEM electrolyzer available in its catalog, mind Enapter is intent on starting massive production of this type of plant as early as later this year, thanks to a new production plant being built in Germany [15].

The IEA in its report also certified a remarkable growth in the capacity of globally installed electrolyzers at the end of 2023, capacity that reached a value of 3 GW, or four times the value reached at the end of the previous year.

Commercially available electrolyzers today, however, use demineralized water for the electrolytic reaction, and this, especially in view of increasing demand for hydrogen, may pose a problem for freshwater resources that are increasingly limited. For this reason, research is focusing on developing electrolyzers capable of operating with non-desalinized seawater, as this is a virtually unlimited resource. The water desalination operation would also increase costs: for green hydrogen it adds 1–2% to energy consumption and production cost [16].

The main obstacle to using seawater is the presence of chlorides, which corrode the catalysts and produce insoluble precipitates that slow down the electrochemical reaction, reducing the efficiency of the process. However, a team of researchers has developed a technique that allows ordinary commercial electrolyzers to be used directly with seawater, protecting the catalysts by coating them with a Lewis acid [17]. In another study reported in [18], however, a special type of catalyst made to work specifically directly with seawater was developed. These are new catalysts that require very little energy and could be used at room temperature. With the new technology, the authors claim, the cost of electrolyzers could be significantly reduced, making the cost of green hydrogen competitive with the cost of hydrogen obtained from fossil fuels. The next step is to make a full-size prototype with which to produce large quantities of H2 using the new approach.

1.2. Literature Review on Techno-Economic Evaluations of Green Hydrogen Production

Currently, the biggest obstacle for the deployment of green hydrogen is its cost (4.0–9.0 USD/kg in 2021 [19], 3.4–12.0 USD/kg in 2022 [1]). For this reason, there are many studies in which techno-economic evaluations are carried out such as to show what might be the best solution to reduce the levelized cost of hydrogen (LCOH).

In [20] the combinations of three different renewable source plants (onshore photovoltaic, onshore wind, and offshore wind) with the two types of commercial electrolyzers, namely alkaline and proton exchange membrane (PEM) electrolyzers, were analyzed and the corresponding LCOH was evaluated for each. The study was conducted considering part-load operation of the electrolyzers to account for the variability of renewable production, and a sensitivity analysis was also conducted to assess the impact of the price of each plant component and the impact of capacity factor of renewable energy on the cost of hydrogen.

In [21] a sensitivity analysis on weather conditions was conducted for plants producing green hydrogen using a PEM electrolyzer. Cases where the electrolyzer is powered only by a photovoltaic system, only by a wind system, and by a mixed, wind/photovoltaic configuration were considered for different values of solar radiation and wind speed. In addition to LCOH, the payback period (PBP) was also evaluated.

In [22] an optimization model was presented to minimize the cost of green hydrogen produced with both stand-alone and grid-connected photovoltaic-wind hybrid systems, with or without the possibility of purchasing electricity from the grid. Calculations were performed considering the degradation of renewable generators during the system lifetime of 20 years.

In [23] techno-economic evaluations were carried out for different hydrogen production technologies, namely cracking, autothermal reforming and electrolysis. The three technologies use green ammonia, biogas and water as the primary sources for hydrogen production, respectively, while fuel cells for cracking and auto-thermal reforming and a grid-connected photovoltaic system for electrolysis were used for electricity supply. The lowest LCOH value of 6.28 €/kg was obtained for the case of hydrogen production from green ammonia using PEM-type fuel cells, while the highest value of 7.92 €/kg was obtained for hydrogen produced by photovoltaic-powered electrolysis.

In [24], on the other hand, the production technology is always the same, i.e., electrolysis powered by grid-connected photovoltaic system, but three different hydrogen production capacities of the plant (50, 100 and 200 kg/day) and four different shares of electricity from the grid (25%, 50%, 75% and 100%) were considered, energy that is therefore not exactly renewable, therefore the hydrogen produced cannot exactly be defined as green. The analysis was conducted in an Italian context, and the best value of LCOH (9.29 €/kg) was obtained for a production capacity of 200 kg/day of hydrogen with 50% of the required electricity supplied from the grid. The study showed that as the production capacity of the plant increases, the cost of hydrogen produced decreases, regardless of the energy mix.

One of the best results for the value of LCOH in Italy was obtained in [25] and is 3.82 €/kg. The province of Taranto was considered in the study, with a mixed supply of renewable energy from wind and photovoltaic plants. Twenty-two scenarios were analyzed with plant sizes varying between 0 kWp and 200 kWp, but without considering the costs associated with the purchase of demineralized water and the compression phase of the hydrogen produced.

Table 1 shows a schematic comparison of the studies found in the literature discussed so far.

Table 1. Literature review.

Ref.	Clean H2 Technology Production	LCOH	RES	End Use of H2	Country	Sensitivity on
[1]	Electrolysis with low-emission electricity	3.4–12.0 USD/kg (≈3.13–11.04 €/kg)	Solar PV, wind onshore, wind offshore	-	US	Regional variations in costs and renewable resource conditions
[19]	Electrolysis with renewable electricity	4.0–9.0 USD/kg (≈3.68–8.28 €/kg)	Solar PV, wind onshore, wind offshore	-	US	Regional variations in costs and renewable resource conditions
[20]	Electrolysis with alkaline and proton exchange membrane technologies	7.25–13.44 USD/kg (≈6.67–12.36 €/kg)	Solar PV, wind onshore, wind offshore	-	KR	Price of each component and capacity factor of renewable energy
[21]	Electrolysis with proton exchange membrane technology	1–8 USD/kg (≈0.92–7.36 €/kg). PBP: 2.85–19.75 years	Solar PV, wind, solar PV + wind	-	-	Weather, degradation rate of wind turbines and PV panels
[22]	Electrolysis with alkaline and proton exchange membrane technologies	4.74–16.06 €/kg	Stand-alone/grid connected PV + wind	-	ES	Type of electrolyzer
[23]	Cracking of green ammonia, autothermal reforming of biogas and electrolysis	6.28–7.92 €/kg	Solar PV	Hydrogen Refueling Station	IT	Type of H_2 technology production
[24]	Electrolysis with alkaline technology	9.29–12.48 €/kg	Solar PV	Hydrogen Refueling Station	IT	H2 production capacity; shares of EE from grid
[25]	Electrolysis with unspecified technology	3.82 €/kg	Solar PV + wind	Renewable Hydrogen Community	IT	Plant size
This study	Electrolysis with alkaline and proton exchange membrane technologies	2.66–10 €/kg	Solar PV, wind	Refineries	IT	PV plant size, presence of storage, interest rate, type of electrolyzer

1.3. Motivation and Literature Gap

The objective of this study is to determine the levelized cost of clean hydrogen produced in Sicily, a region in Southern Italy chosen because it is particularly rich in renewable energy, particularly wind and photovoltaics, and refineries, an industrial sector where hydrogen is already used but produced from fossil sources. For the study, the two electrolyzer technologies commercially available today, namely alkaline and PEM electrolyzers, are considered, making a comparison between on-site production (decentralized or distributed production) and centralized production. In the case of on-site production, the supply of renewable energy for the electrolyzers is through a dedicated photovoltaic system, which is easier to install at industrial sites than a wind power plant, and a sensitivity analysis is performed on the size of the system, interest rates, and the presence of the battery storage system for excess electricity produced by the photovoltaic system. In the study for centralized production, on the other hand, the energy produced by wind power plants and, most importantly, economies of scale on electrolyzer costs, a factor neglected in the studies found in the literature, were also taken into account by considering the optimal transport modes based on distance and the amount of hydrogen to be transported.

The case studies are summarized in the diagrams shown in Figure 1.

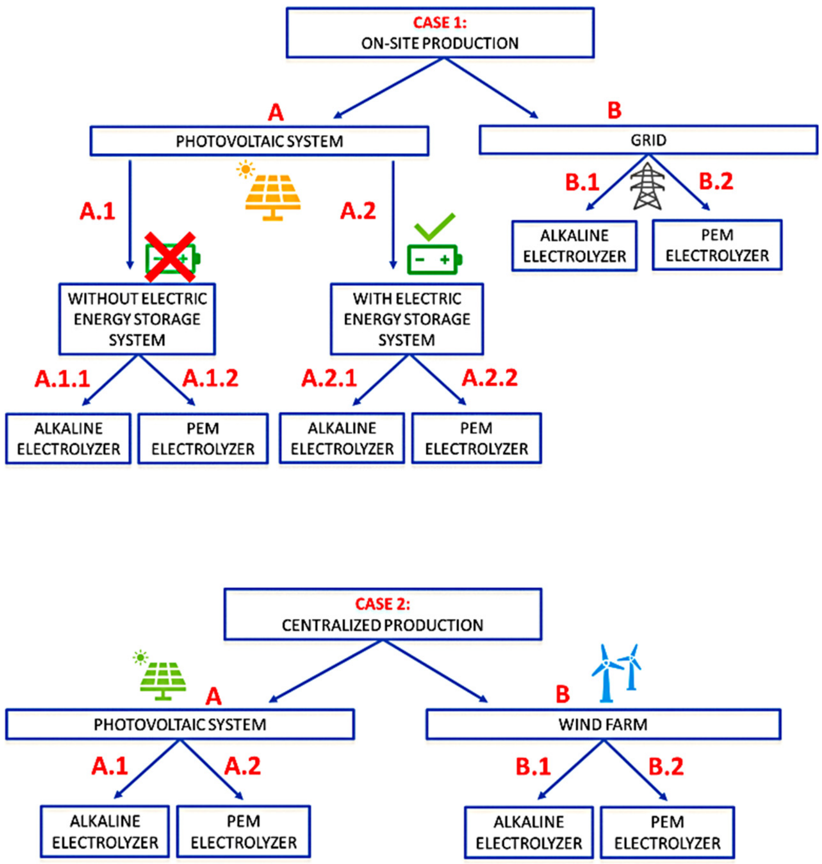


Figure 1. Case studies.

2. Materials and Methods

For the case study of localized or distributed production, 1 MW electrolyzers are considered. This value coincides with the minimum size foreseen by the regional call aimed at the selection of project proposals for the realization of renewable hydrogen production plants in disused industrial areas financed with National Recovery and Resilience Funds resources [8]. Always in accordance with the values in that call, for the supply of renewable energy, photovoltaic plants are considered, with and without a lithium-ion battery storage system, having an installed capacity of at least 20% of the power of the electrolyzer.

As it will be seen later, the hydrogen leaving the electrolyzer has a maximum pressure of 30 bar; however, this pressure is insufficient to be able to store, transport or use the hydrogen. It is necessary to compress it. A compression system must therefore be added to the system. Equation (1) was used to determine the size of the compressor in this study [24]:

$$S_{compr} = \frac{\dot{m}_{H2} \cdot L_{is,c}}{\eta_{is,c} \cdot \eta_m \cdot \eta_e} \tag{1}$$

where

- S_{compr} is the rated size of the compressor [kW];
- $\dot{m}_{H2}$ is the hydrogen mass flow rate [kg/s];
- $L_{is,c}$ is the specific work of the compressor [kJ/kg];
- $\eta_{is,c}$ is the isentropic efficiency (80%);
- η_m is the mechanical efficiency (98%);
- η_e is the electric generator efficiency (96%);

The specific work of the compressor is given by the following Equation (2):

$$L_{is,c} = \frac{k}{k-1} \cdot R_{H2} \cdot T_{in} \cdot \left[\left(\frac{p_{out}}{p_{in}} \right)^{\frac{k-1}{k}} - 1 \right] \quad (2)$$

where

- k is the ratio between the specific heat at constant pressure and the specific heat at constant volume and is equal to 1.4 for hydrogen;
- R_{H2} is the hydrogen gas constant (4.12 kJ/kgK);
- T_{in} is the temperature of the hydrogen entering the compressor;
- p_{out} is the pressure of the hydrogen leaving the compressor;
- p_{in} is the pressure of the hydrogen entering the compressor;

The hydrogen outlet pressure (p_{out}) considered in this study is 200 bar, i.e., the pressure at which hydrogen is usually compressed for industrial or laboratory use [26].

In all case studies analyzed, operation of the electrolyzers in the power ranges defined by the manufacturers is considered, rather than operation only at full load, in on-off mode, as done previously in [27].

Regarding the location of the plant for on-site production, the city of Milazzo (Messina) was chosen for two reasons: it is located by the sea, so it lends itself well to accommodate electrolyzers using seawater in the future, and it is home to an important industrial area for Sicily where hydrogen could be used for various purposes. In detail, one of Sicily's refineries is located in Milazzo.

In this case study, the following Equation (3) is used to evaluate the levelized cost of hydrogen ($LCOH$):

$$LCOH = \frac{\sum_{t=1}^{n} \frac{CAPEX_t + OPEX_t - Rev_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{H_{2t}}{(1+r)^t}} \quad (3)$$

where $CAPEX_t$ are the investment costs incurred in year t, $OPEX_t$ are the operating costs incurred in year t, Rev_t are the revenues obtainable in year t from the sale of excess electricity produced by the PV systems feeding the electrolyzers, H_{2t} is the hydrogen produced in year t, n is the plant lifetime, and r is the real discount rate of the project.

$CAPEX$ and $OPEX$ terms were evaluated for the following plant components: electrolyzer, compressor, PV system with and without storage. In detail, formulas used in this study for $CAPEX$ and $OPEX$ are illustrated in the following Equations (4) and (5).

$$CAPEX_t = \left(S_{ele} \cdot C_{ele} + S_{compr} \cdot C_{compr} + S_{PV} \cdot C_{PV} + S_{sto} \cdot C_{sto} \right) \cdot CRF \quad (4)$$

$$OPEX_t = S_{ele} \cdot C_{ele} \cdot OPEX_{ele} + S_{compr} \cdot C_{compr} \cdot OPEX_{compr} + S_{PV} \cdot C_{PV} \cdot OPEX_{PV} + S_{sto} \cdot C_{sto} \cdot OPEX_{sto} \quad (5)$$

In the previous equations, S indicates the size of the component, C is the unit investment cost, subscript ele indicates the electrolyzer, subscript $compr$ indicates the compressor, subscript PV indicates the photovoltaic system, subscript sto indicates the storage system, and CRF is the Capital Recovery Factor of the investment, given by Equation (6):

$$CRF = \frac{r \cdot (1+r)^N}{(1+r)^N - 1} \quad (6)$$

where N is the lifetime of the investment, set equal to 20 years for each component.

The values used for the previous equations are shown in Table 2.

Table 2. CAPEX and OPEX of plant components.

Component	CAPEX (C)	OPEX
Alkaline electrolyzer	500–1400 USD/kWe [28] (≈460–1288 €/kWe)	5% of investment [29]
PEM electrolyzer	1100–1800 USD/kWe [28] (≈1012–1656 €/kWe)	5% of investment [29]
Compressor	$36079.54 \cdot S_{compr}^{0.6038}$ € [23]	8% of investment [23]
Photovoltaic system	771 USD/kW [4] (≈709.32 €/kW)	13.2 USD/kW [4] (≈12.14 €/kW)
Lithium-ion battery storage system	207–228 €/kWh [30]	2.1–2.8 €/kWh [30]

For water consumed during electrolysis, AMAM (Azienda Meridionale Acque Messina) rates for industrial use of 2064 €/month plus 1.49 €/m^3 [31] were used as a reference, neglecting extra costs for obtaining distilled water.

In the first case studies, related to on-site production, the electrolyzers are powered by a photovoltaic system without storage, with the characteristics shown in Table 3. A photovoltaic system of the same size as the electrolyzer (1 MW_p) was chosen initially, and then increased to show how the cost of green hydrogen, the operating hours of the electrolyzer, and the amount of hydrogen produced annually varies with the size of the photovoltaic system.

Table 3. Photovoltaic system characteristics.

Location	**Milazzo (ME), Sicily**
Nominal power	1–2.7 MW_p
Slope	34°
Azimuth	−2°
System losses	14%
Technology	Crystalline silicon

The hourly production data were obtained through the online tool PVGIS [32]; optimal slope and azimuth values were also derived through this.

Table 4 shows the specifications of the alkaline electrolyzer taken into consideration for this study:

Table 4. Alkaline Electrolyzer specifications.

Nominal power	1 MW
System AC power consumption	5.1 kWh/Nm^3
Operation range	20–100%
Feeding water	1 L/Nm^3 H_2
Electrolyte	30% KOH aqueous solution
H_2 purity	>99.998% after gas cleaning
H_2 nominal flow rate	200 Nm^3/h
H_2 delivery pressure	27 to 30 bar (g), depending on configuration

Table 5 instead reports the specifications of the PEM electrolyzer.

Table 5. PEM (Proton Exchange Membrane) Electrolyzer specifications.

Nominal power	1 MW
System AC power consumption	4.9 kWh/Nm^3
Operation range	5–100%
Feeding water	<2 L/Nm^3 H_2
Electrolyte	polymeric membrane
H_2 purity	>99.999%
H_2 nominal flow rate	200 Nm^3/h
H_2 delivery pressure	30 bar

The PV plant production data were loaded into a MATLAB code, where the equations were implemented for the purpose of calculating the levelized cost of hydrogen (*LCOH*). In the code, a for loop was implemented to determine the amount of energy produced by the photovoltaic system that is consumed by the clean hydrogen production and compression plant and the hours of operation at part load and full load.

The energy consumed by the plant was then converted to hydrogen produced by considering the specific consumption of the plant, i.e., the kWh required to produce one Nm^3 of compressed hydrogen. These are given by the sum of the specific consumption of the electrolyzer, given in Tables 4 and 5, and the specific consumption of the compressor given by the ratio of its power, determined by Equation (1), to the flow of hydrogen leaving the electrolyzer.

In the case, on the other hand, of centralized production, the assumption is made that the hydrogen electrolysis and compression plants are installed in particularly sunny and windy areas of Sicily and supplied with renewable energy that is valued through the LCOE (levelized cost of energy). The formula for calculating *LCOH* then becomes as follows:

$$LCOH = \frac{\sum_{t=1}^{n} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{H_{2t}}{(1+r)^t}} \tag{7}$$

where the cost of renewable energy is then included in operating expenses. The latter, in addition, must include the cost of transporting the hydrogen to the end user, which can be done through two different solutions: by tanker trucks, transporting hydrogen compressed in cylinders at 200–700 bar, and by dedicated pipelines. Depending on the volume of hydrogen transported and the distance traveled, transportation costs can be optimized by choosing between the two solutions [33], as shown in Figure 2.

The major advantage expected from centralized production is the low cost of production given by the greater efficiencies of large-scale plants and by economies of scale on electrolyzers. To account for the variability of unit costs of electrolyzers as a function of size, the scale factor or cost/capacity method is applied, which consists of the following logarithmic relationship [34]:

$$C_b = C_a \left(\frac{S_b}{S_a}\right)^f \tag{8}$$

where C_a and S_a represent the cost and size of the known reference component, respectively, S_b is the size of the component whose cost C_b is to be derived, and f is the scale factor applied to the considered component. Although this law is commonly known in literature as the six-tenth law, for both alkaline and proton exchange membrane electrolyzers a scale factor value of 0.75 was adopted [34].

For centralized clean hydrogen production, the most suitable areas for plant installation were evaluated, namely the sunniest and windiest areas in Sicily, determined through the Global Solar Atlas [35] and Global Wind Atlas [36] tools, respectively, and shown in Figures 3 and 4.

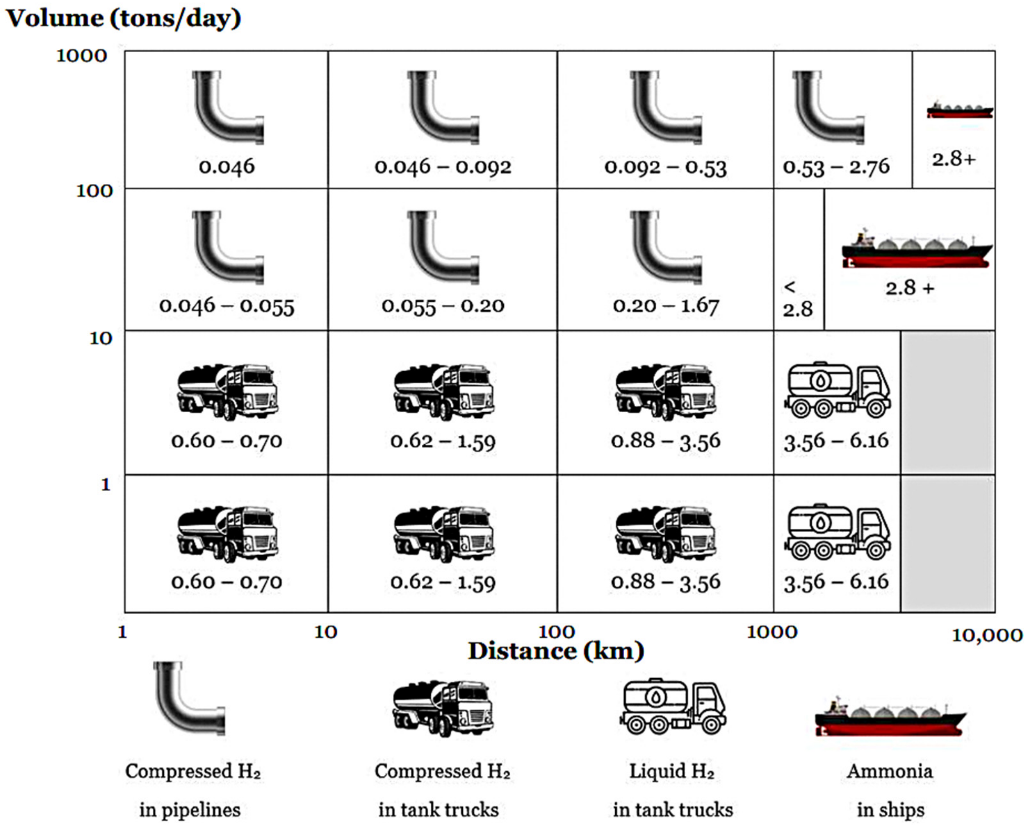


Figure 2. Schematic comparison of hydrogen transport cost (€/kg) among different transport solutions, in relation to the volume to be transported and the distance to be traveled (Authors' elaboration from [33]).

Figure 3. Solar resource distribution and photovoltaic energy potential in Sicily (Authors' elaborations on Global Solar Atlas [35] images).

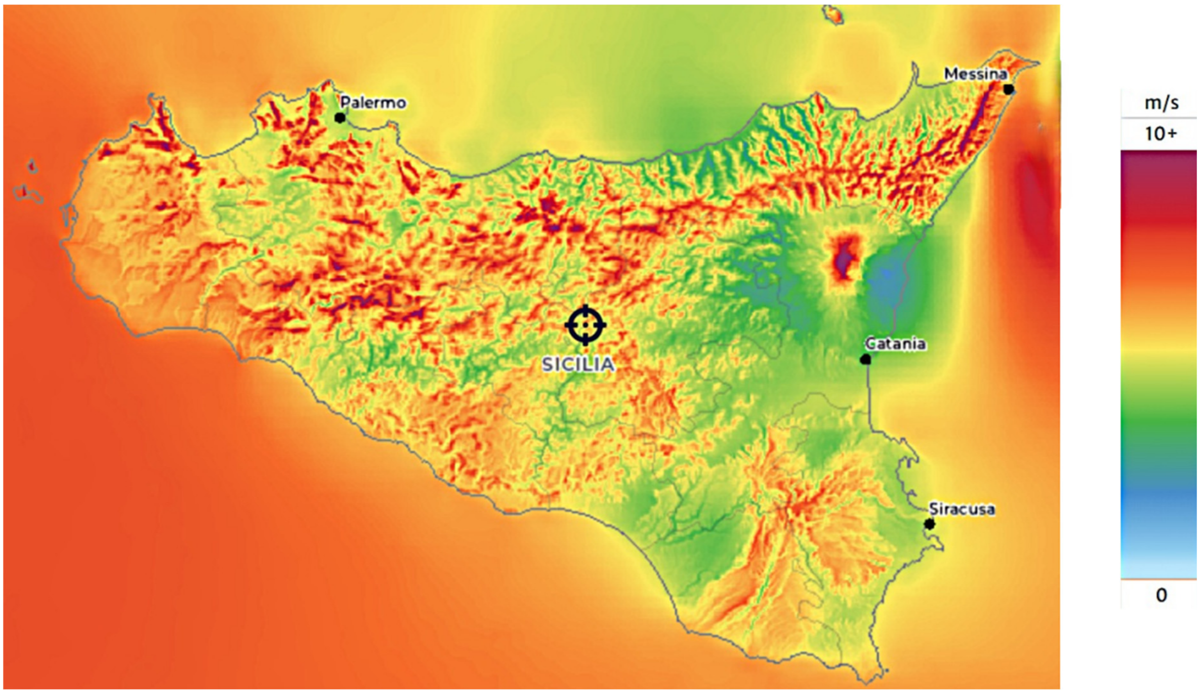


Figure 4. Distribution of the wind resource in Sicily (Authors' elaborations on Global Wind Atlas [36] images).

To size the plants, the demand for hydrogen to be met at the regional level was assessed, taking into consideration refineries, a sector where hydrogen is already used and where, therefore, demand does not need to be created. From the data reported in [37] for each Sicilian refinery, the total hydrogen consumption is 201,734.8 tons per year. Considering that commercially available large-scale alkaline technology electrolysis plants have conversion efficiencies of about 3.8–4.4 kWh/Nm^3 and considering that each Nm^3 of hydrogen is equivalent to 0.08988 kg, producing 201,734.8 tons of clean hydrogen would require more than 7 TWh of renewable energy, a disproportionate amount for Sicily.

For this reason, reference was made to the report [5] to size the plants. This study found that if the refining sector in Italy replaces 20% of current hydrogen production with electrolysis technology, it will contribute about 10% to the 2030 target for final energy consumption demand reported in the Hydrogen Strategy Guidelines (0.7 Mt/year to 2030). This implies the need to produce 72,000 tons per year of clean hydrogen.

In the same report, the geographical distribution of production sites for the refinery sector is provided, and 45.7% of these are located in Sicily, so a regional renewable hydrogen demand of 45.7% of 72,000 tons/year, or 32,904 tons/year, was assumed. This value is equivalent to 16% of total hydrogen consumption in Sicilian refineries.

Table 6 shows the amounts of clean hydrogen that will need to be used at each refinery to meet the target just discussed, which is 16% of each refinery's consumption derived from [37]. The last column also shows the daily demand for clean hydrogen, estimated assuming 300 operating days per year.

The large-scale electrolysis plants considered for centralized production have the characteristics shown in Table 7.

Table 6. Hydrogen demand of Sicilian refineries and amount of clean hydrogen needed to meet the target set by [5].

Refinery	Hydrogen Demand [Tons/Year] [37]	Renewable Hydrogen Needed [Tons/Year]	Daily Demand for Renewable Hydrogen [Tons/Day]
Gela Praoil	19,512.5	3182.59	10.60
Priolo ISAB SpA (sud)	28,578.81	4661.35	15.54
Melilli ISAB SpA (nord)	10,899.14	1777.71	5.92
Augusta Sonatrach	33,965.26	5539.91	18.47
Raffineria di Milazzo SpA (Eni)	108,779.1	17,742.44	59.14

Table 7. Specifications of large-scale commercial electrolysis plants.

Technology	Nominal Power	Power Consumption	Net Production Rate
Alkaline	100 MW	3.33 kWh/Nm^3	30,000 Nm^3/h
Proton exchange membrane	22.14 MW	4.5 kWh/Nm^3	4920 Nm^3/h

3. Results

3.1. Case 1: On-Site Production

3.1.1. Cases 1. A.1 (PV System without Electric Energy Storage System)

Calculations of the levelized cost of green hydrogen were conducted both considering the sale of excess electricity produced by the PV system, at a price of 0.05 €/kWh [38], and without considering it.

After calculating the LCOH in the case of a 1 MW electrolyzer fed by a PV plant of the same size, it was decided to repeat the calculations for a 1.666 MWp PV plant, to verify whether an electrolyzer size equal to 60% of the solar capacity is also an optimal solution in southern Italy, as well as in the case studies addressed in [39].

Other calculations were performed for PV systems up to 2.7 MWp, leaving the electrolyzer size unchanged. The results obtained, in terms of LCOH, annual hydrogen production and hours of operation of the electrolyzer are shown in Figures 5 and 6 for the alkaline electrolyzer and for the proton exchange membrane electrolyzer respectively.

As can be seen from the graphs, beyond a certain size of the photovoltaic system that feeds the 1 MW electrolyzer, a kind of saturation occurs so that increasing the size of the system further does not yield significant benefits, especially in terms of the cost of green hydrogen, which remains around 6.66–8 €/kg for the case A.1.1, 7–8 €/kg for the case A.1.2. In addition, without the sale of excess electricity to the grid, above a certain PV system size the cost of hydrogen increases slightly (blue curve in Figures 5a and 6a); this means that the increase in costs associated with the larger PV system is proportionally greater than the increase in hydrogen produced.

Unit costs of electrolyzers, being not too large in size, were assumed to be equal to the maximum values for the two technologies (1400 USD/kW$_e$ for alkaline and 1800 USD/kW$_e$ for PEM) and an interest rate of 8% was assumed as in [27].

Varying the interest rate, giving it the values of 3, 7 and 10% as in [28], the levelized cost of hydrogen varies, for both electrolyzer technologies, between about 5.50 €/kg and a little more than 9 €/kg without valorizing excess electricity, and between about 4 and 8 €/kg by selling excess energy to the grid (Figure 7). The data shown in Figure 7 refer to the case of electrolyzers and compressors powered by 2.6 MW photovoltaic system.

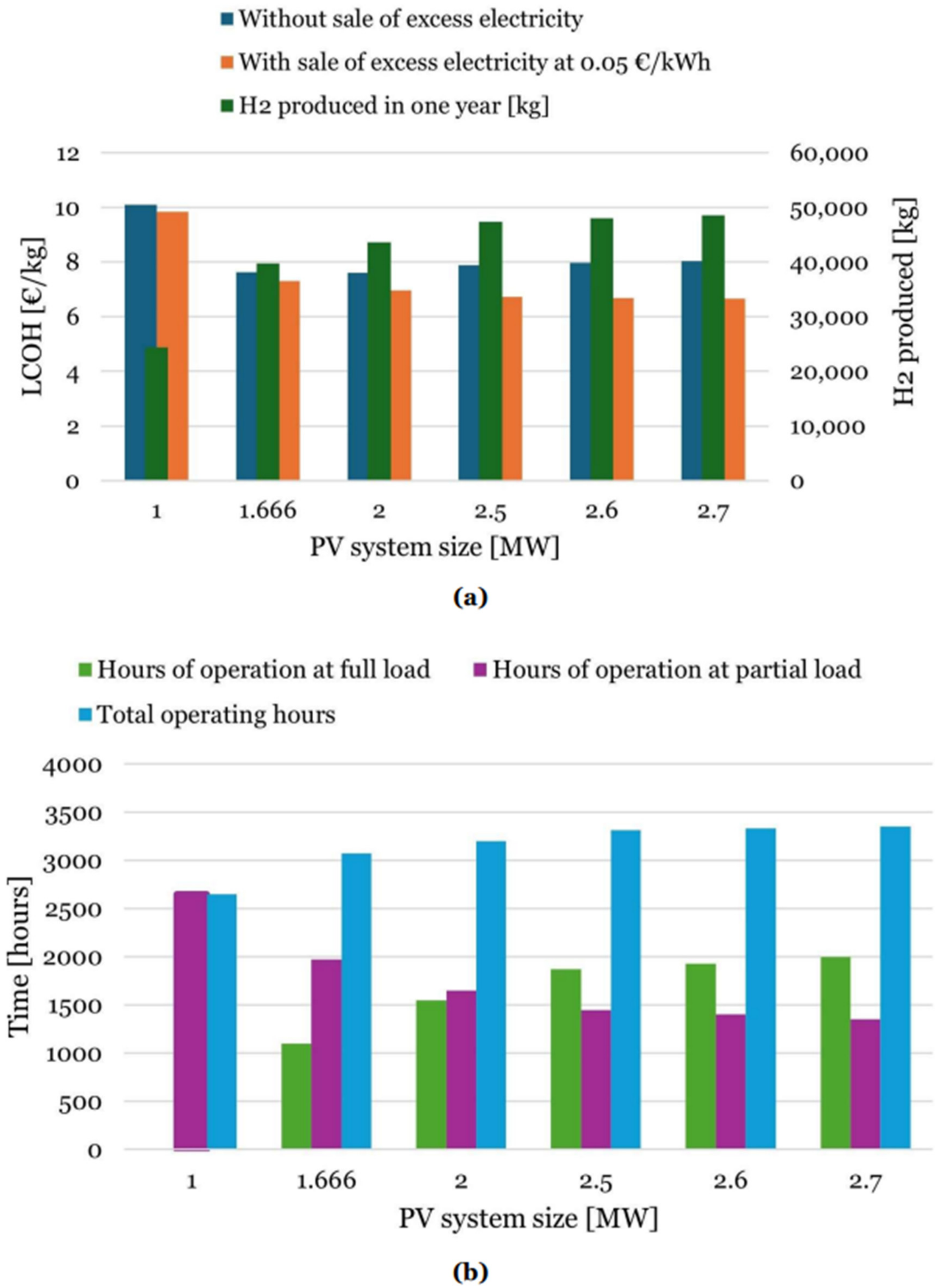


Figure 5. LCOH values, hydrogen produced (**a**) and hours of operation (**b**) for different sizes of PV system feeding the 1 MW alkaline electrolyzer.

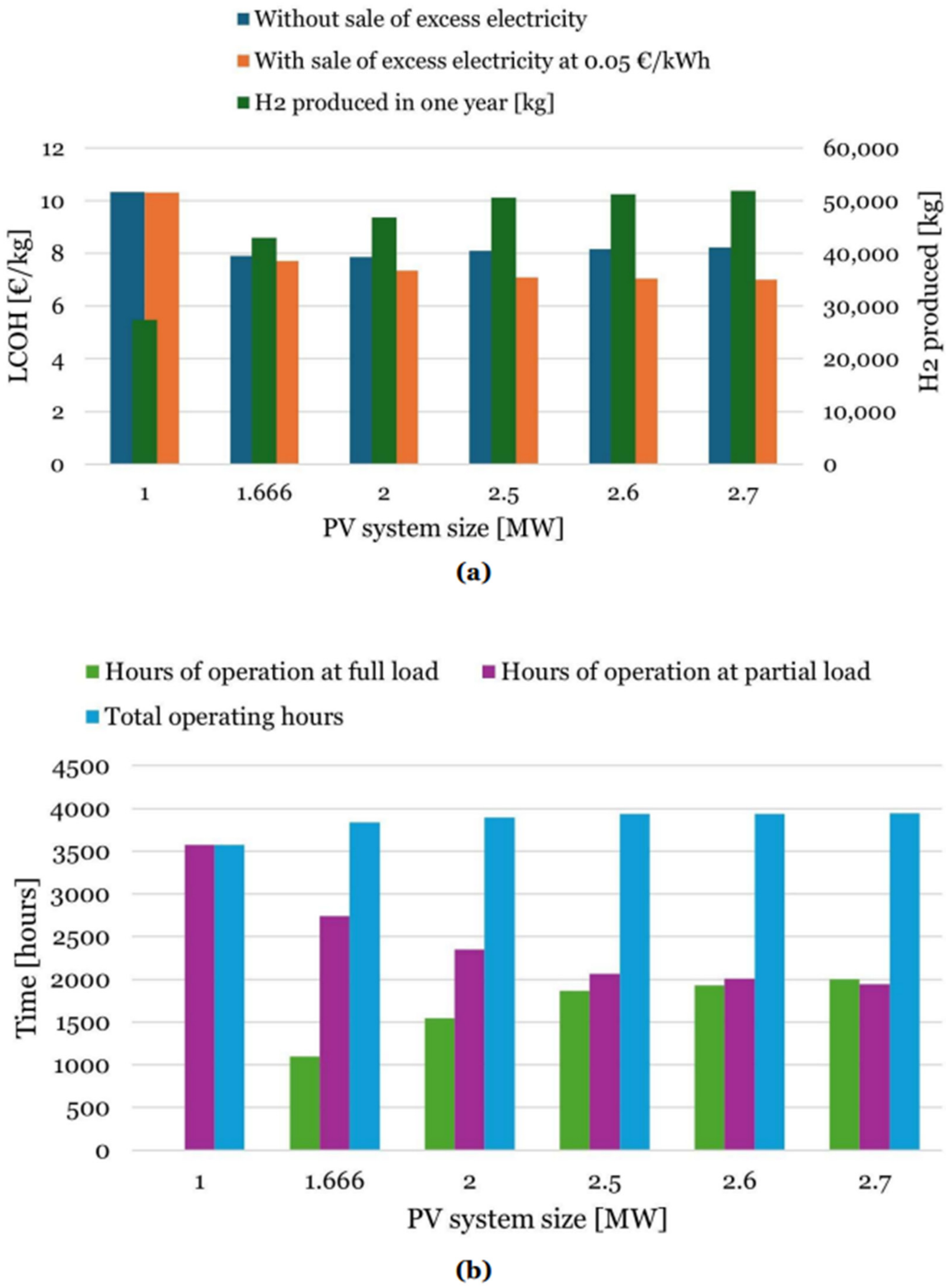
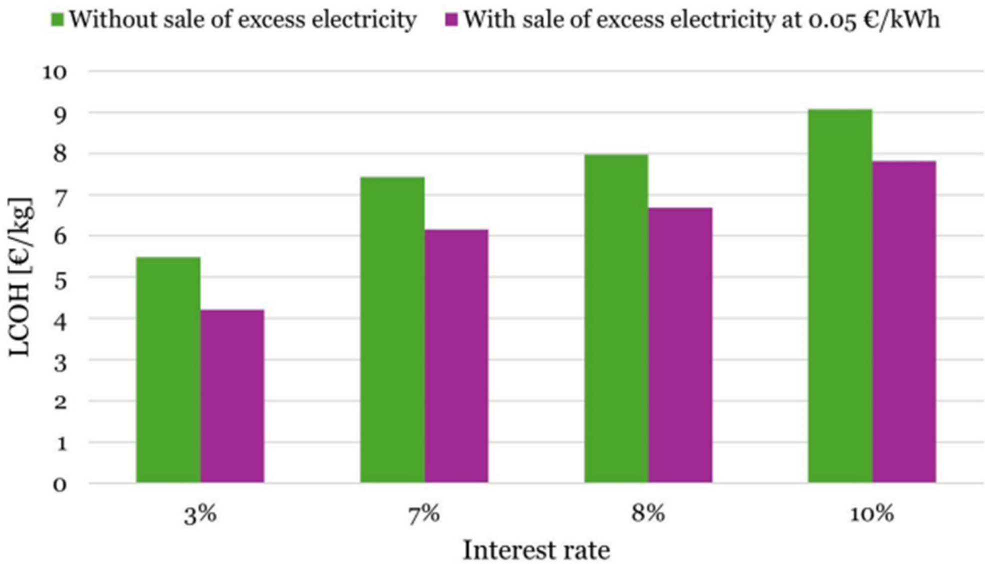
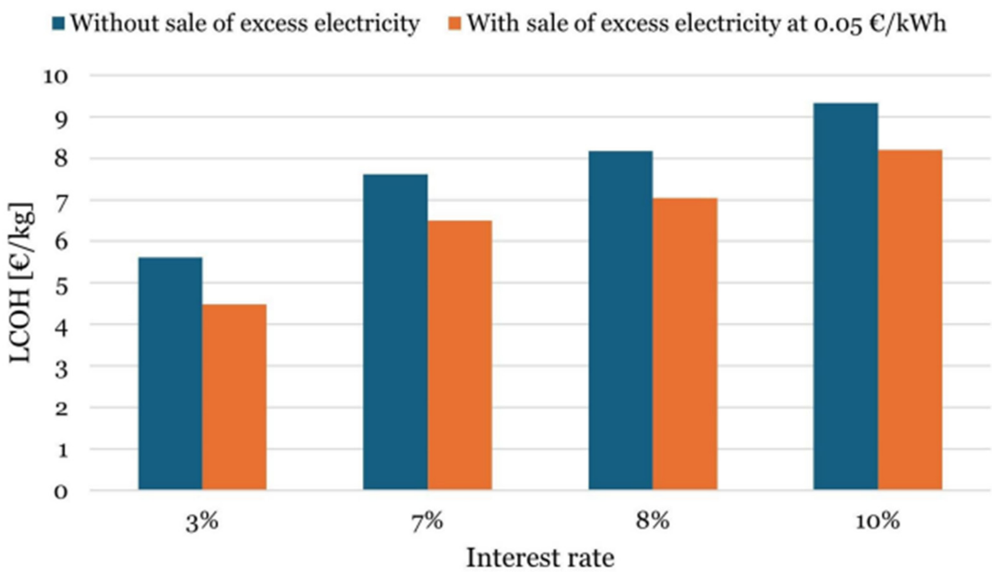


Figure 6. LCOH values, hydrogen produced (**a**) and hours of operation (**b**) for different sizes of PV system feeding the 1 MW PEM electrolyzer.



(a)



(b)

Figure 7. LCOH values for different rates of interest for systems with alkaline electrolyzer (**a**) and with proton exchange membrane electrolyzer (**b**).

3.1.2. Cases 1. A.2 (PV System with Electric Energy Storage System)

In the case studies presented in this section, electrolyzers and compressors are powered by photovoltaic systems equipped with storage systems consisting of lithium-ion batteries. The size of the batteries is chosen in such a way as to recover not only the photovoltaic energy in excess of the maximum energy required by the compressed hydrogen production plant, but also the energy less than the minimum energy required by the plant for its operation. This is done in such a way as to convert the maximum amount of renewable energy possible into hydrogen, without giving it up to the grid. Figure 8 shows the flows of energy produced by the photovoltaic system (E_{PV}), energy entering storage (ESS_{in}) and leaving storage (E_{out}), and energy consumed by the electrolysis and compression plant (E_{plant}) during a typical day.

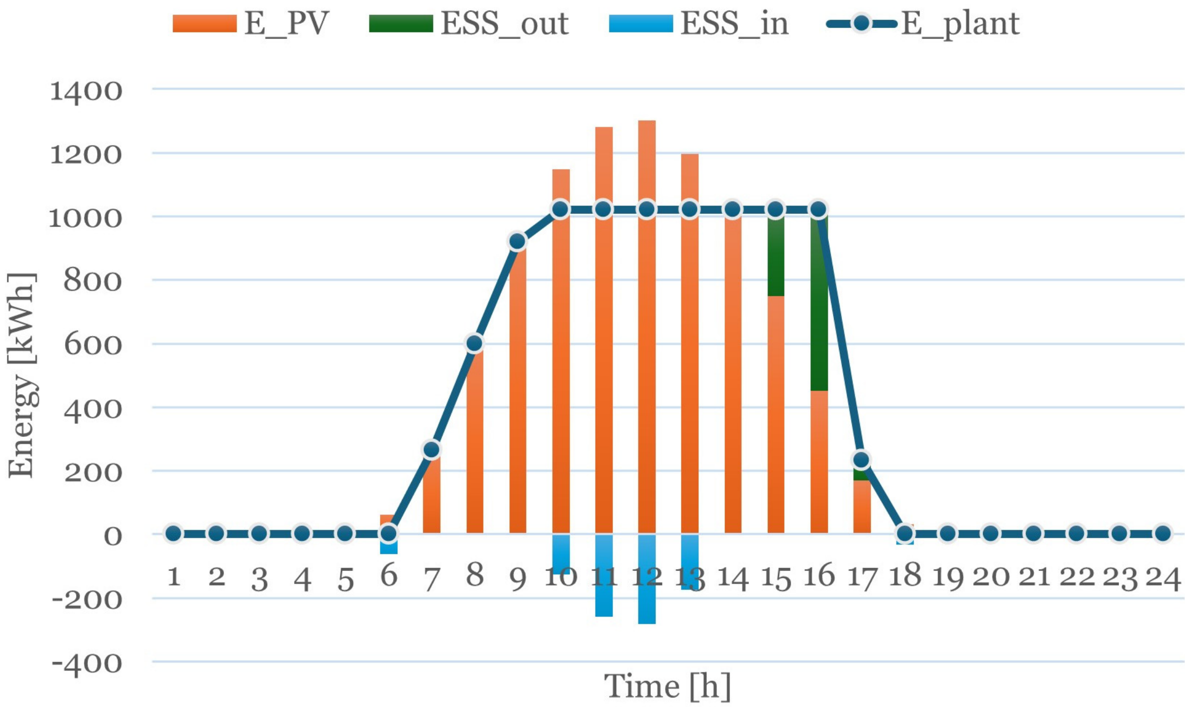


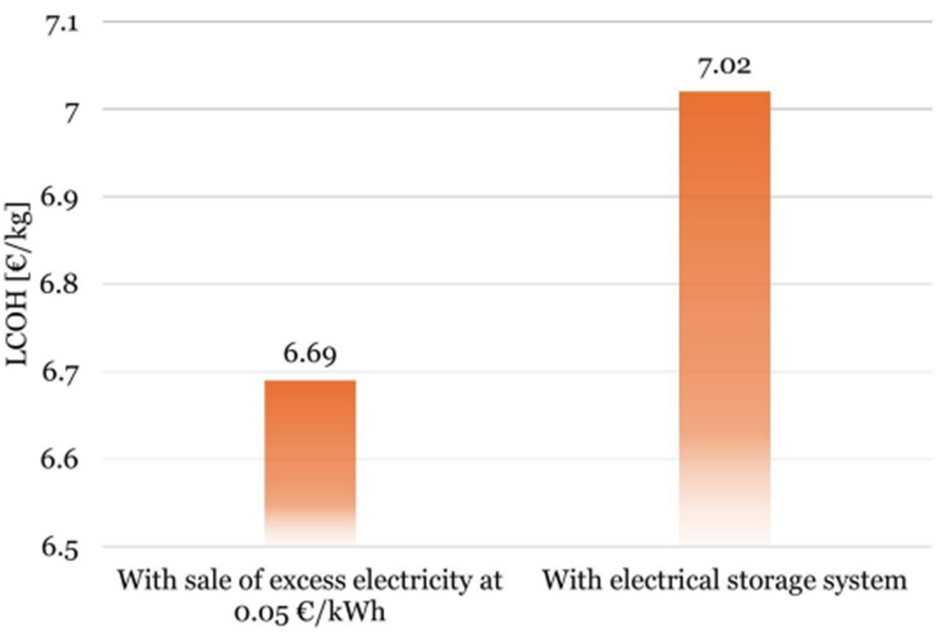
Figure 8. Energy flows for green hydrogen production plant with alkaline electrolyzer powered by PV system equipped with storage system.

The graphs shown in Figure 8 refer to a 2.6 MW photovoltaic plant, also installed in Milazzo, equipped with 920 kWh storage to power the 1 MW alkaline electrolyzer hydrogen production plant. Thanks to the presence of the batteries, the plant can run at full load for 7 h a day, compared to the 5 h that the same photovoltaic plant without storage could have provided. The operating hours at part load are thus reduced by two units per day. Overall, the hydrogen produced in a year increases by almost 10 tons, but the cost, compared to case A.1.1 in which the electrolyzer is powered by the PV system of the same size without storage, with the excess energy sold to the grid, increases slightly, from 6.69 €/kg to 7.02 €/kg.

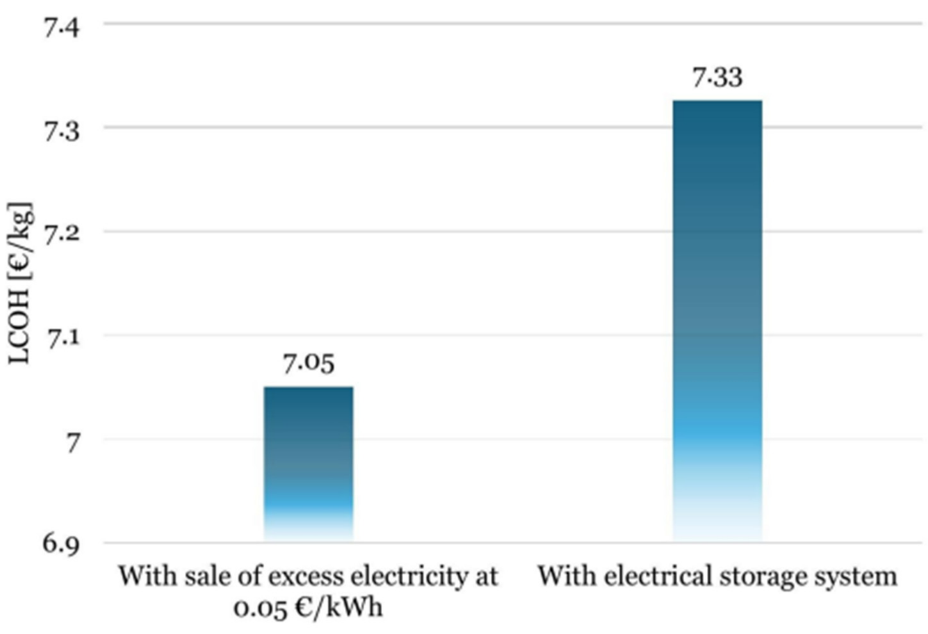
Similar results are obtained in the case of proton exchange membrane electrolyzer: the main difference is the storage size which, in this case, is smaller and equal to 850 kWh due to the ability of the PEM electrolyzer to operate in a wider range of powers. The hydrogen produced annually increases by almost 9 tons, while the levelized cost is 7.33 €/kg, which is 0.28 €/kg more than in the case without storage where excess energy is sold. The results just described are shown in Figure 9.

Figure 10 shows the percentage distributions of CAPEX and OPEX for the clean hydrogen production plant powered by photovoltaic system with batteries with both alkaline technology (a) and PEM technology (b).

It can be concluded that the presence of storage allows the production of hydrogen to be increased by about 17–20%, but from an economic point of view, although batteries only affect 5–6% of CAPEX and OPEX expenses as shown in Figure 10, it would be better to sell the excess energy to the grid rather than storing it to produce additional hydrogen.



(a)



(b)

Figure 9. LCOH values for different destinations of excess electricity produced by the 2.6 MW photovoltaic plant feeding the electrolysis and compression plant with alkaline technology (**a**) and PEM technology (**b**).

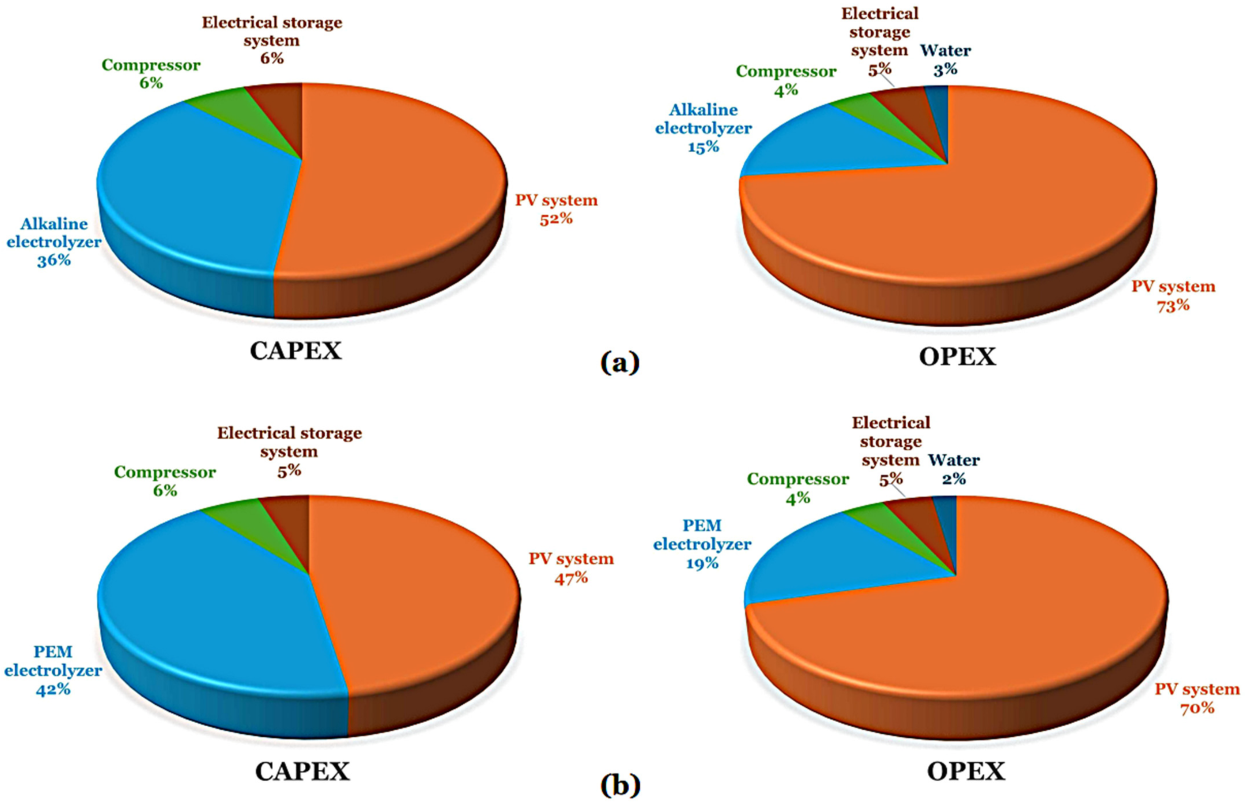


Figure 10. CAPEX and OPEX allocation in the case of clean hydrogen production plant with alkaline technology (**a**) and PEM technology (**b**) powered by photovoltaic system with batteries.

3.1.3. Cases 1. B (Grid-Powered Plants)

This section reports the results obtained, in terms of LCOH, by powering the hydrogen electrolysis and compression plant with electricity from the grid, i.e., nonrenewable energy.

In this case, the investment and operating expenses associated with the renewable power plant are eliminated and replaced by the cost due to the purchase of power from the grid. This cost is 0.24 €/kWh, average electricity prices in Italy, in the first half of 2023, excluding VAT and other recoverable taxes and levies for non-household consumers reported in the Eurostat database [40].

As can be seen from the curves shown in Figure 11, the costs of nonrenewable hydrogen produced by electrolysis are much higher than the costs of clean hydrogen shown in Figures 5 and 6, remaining above 14 €/kg even under the completely ideal assumption in which the plant operates at full power for all hours of the year. Using electrolyzers to produce hydrogen with electricity from the grid is, therefore, not only environmentally unsustainable but also uneconomic.

The situation would be different, however, if electrolyzers were fed from the grid during periods of imbalance compensation. In this case, in fact, the hydrogen produced would be recognized as renewable, in accordance with the European directive [41], and the electrolysis plants would provide a service that, once remunerated, will result in a lower cost for the hydrogen produced. This topic will be addressed in a subsequent study.

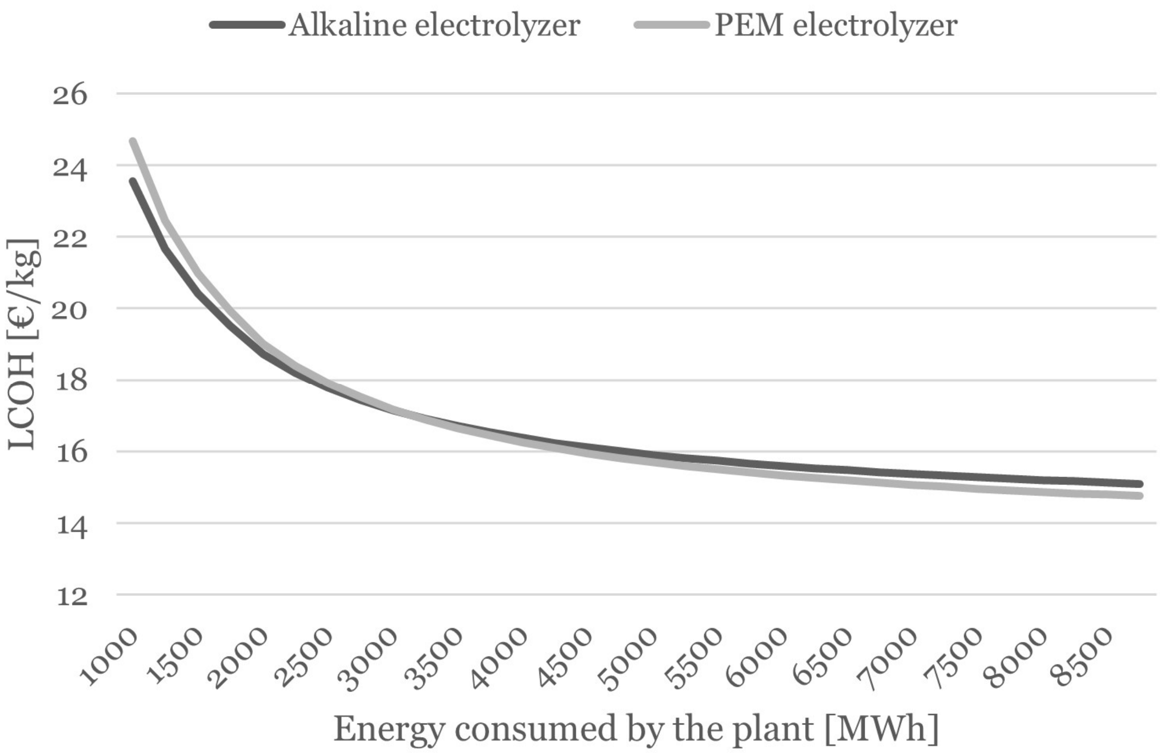


Figure 11. LCOH obtained by feeding the plant with electricity from the grid.

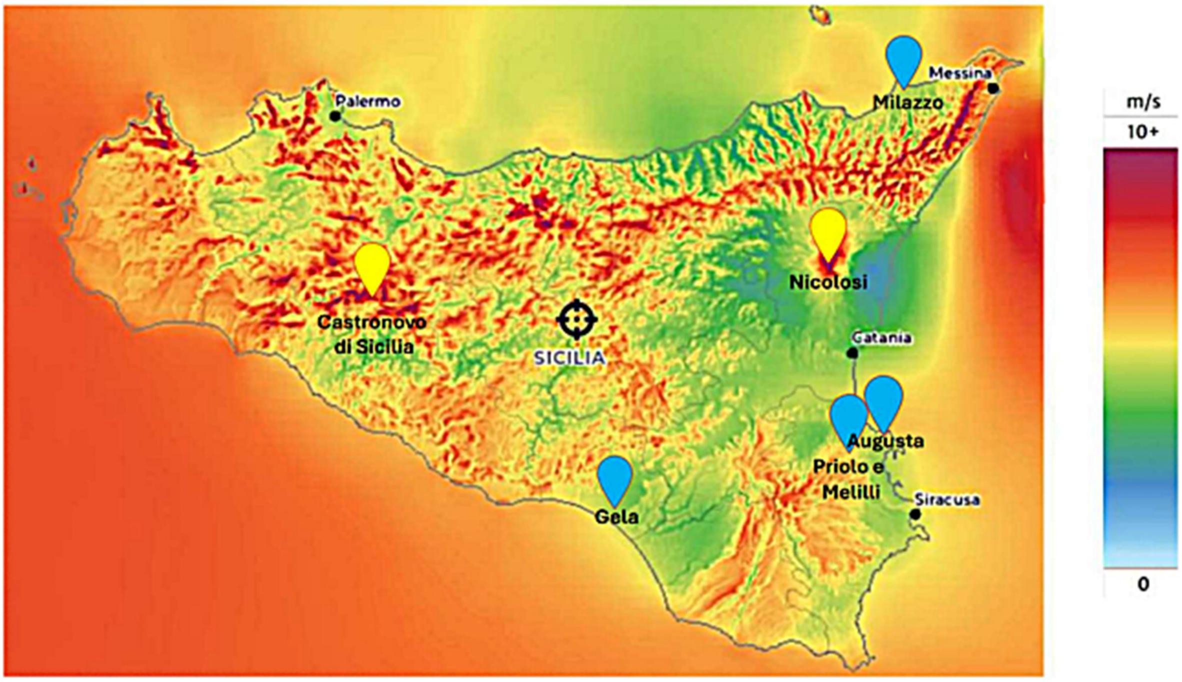
3.2. Case 2: Centralized Production

3.2.1. Cases 2. A.1 and 2. B.1 (Alkaline Systems Powered by Solar PV and Wind Energy)

Assuming a load factor of the electrolyzers equal to 40%, i.e., 3504 operating hours, and considering the production rate of the plant shown in Table 7, equal to 30,000 Nm^3/h, to satisfy the established demand for clean hydrogen with alkaline technology, 4 plants will be necessary to 100 MW, each located in the points marked in yellow in Figure 12, respectively for production from wind energy and solar energy. In light blue are marked the cities where the refineries are located, where the hydrogen will be used.

Taking into account the economy of scale, evaluated with Equation (8) assuming S_a equal to 1 MW and C_a equal to 1,400,000 USD, and the best conversion efficiencies of the system considered, the cost of producing renewable hydrogen obtained from photovoltaic energy, valued at the average cost evaluated by the data reported in [28] and equal to 60.52 €/MWh, is 2.72 €/kg, while the cost of producing hydrogen from wind energy, valued at 56.20 €/MWh, is 2.56 €/kg.

To these figures must be added transportation costs, which are estimated based on the distance and amount of hydrogen to be transported according to Figure 2 in the materials and methods section. The costs that refineries will then incur to purchase the necessary hydrogen are summarized in Table 8, where, for each city with refineries, the nearest centralized production sites were considered:



(a)

(b)

Figure 12. Location of centralized renewable hydrogen production facilities, in yellow, from wind power (**a**) and solar photovoltaic (**b**) and location of hydrogen utilization sites, in light blue.

Table 8. Cost of renewable hydrogen produced in centralized plants with alkaline technology and transported to the end user.

Site of Use	Production Site	Renewable Source	Distance [km]	Optimal Transportation Solution	LCOH [€/kg]
Gela	Misterbianco	PV	100	Tank trucks	4.31
	Castronovo di Sicilia	Wind	130	Tank trucks	4.15
	Santa Croce Camerina	PV	50	Tank trucks	3.82
Priolo Gargallo	Nicolosi	Wind	84	Pipelines	2.70
	Misterbianco	PV	52	Pipelines	2.85
	Santa Croce Camerina	PV	85	Pipelines	2.86
Melilli	Nicolosi	Wind	68	Tank trucks	3.29
	Misterbianco	PV	51	Tank trucks	3.82
	Santa Croce Camerina	PV	91	Tank trucks	3.70
Augusta	Nicolosi	Wind	62	Pipelines	2.66
	Misterbianco	PV	47	Pipelines	2.85
	Santa Croce Camerina	PV	100	Pipelines	2.92
Milazzo	Nicolosi	Wind	100	Pipelines	2.76
	Misterbianco	PV	109	Pipelines	2.92
	Castronovo di Sicilia	Wind	217	Pipelines	3.11

3.2.2. Cases 2. A.2 and 2. B.2 (PEM Systems Powered by Solar PV and Wind Energy)

Considering the characteristics of large-scale PEM technology electrolysis systems shown in Table 7 and assuming, also in this case, a load factor of the electrolyzers equal to 40%, 22 systems are needed to meet the regional demand for clean hydrogen set for refineries, to be divided among the four established centralized production locations and shown in Figure 12. Taking into account, again, the economy of scale, evaluated with Equation (8) assuming S_a equal to 1 MW and C_a equal to 1,800,000 USD, and the best conversion efficiencies of the large-scale system, the production cost of renewable hydrogen obtained from photovoltaic energy, valued at the average cost estimated from the data reported in [28] and equal to 60.52 €/MWh, is 4.21 €/kg, while the production cost of hydrogen from wind energy, valued at 56.20 €/MWh, is 3.99 €/kg.

Production costs that are, therefore, higher than in the case of alkaline technology systems. To these must, in addition, be added the costs due to transportation, estimated as in the previous cases on the basis of the distances and volumes to be transported, in accordance with the data shown in Figure 2 and Table 6. The values of LCOH thus obtained are given in Table 9, where, for each city with refineries, the nearest centralized production sites were considered.

Table 9. Cost of renewable hydrogen produced in centralized plants with PEM technology and transported to the end user.

Site of Use	Production Site	Renewable Source	Distance [km]	Optimal Transportation Solution	LCOH [€/kg]
Gela	Misterbianco	PV	100	Tank trucks	5.80
	Castronovo di Sicilia	Wind	130	Tank trucks	5.59
	Santa Croce Camerina	PV	50	Tank trucks	5.31
Priolo Gargallo	Nicolosi	Wind	84	Pipelines	4.14
	Misterbianco	PV	52	Pipelines	4.34
	Santa Croce Camerina	PV	85	Pipelines	4.35

Table 9. *Cont.*

Site of Use	Production Site	Renewable Source	Distance [km]	Optimal Transportation Solution	LCOH [€/kg]
Melilli	Nicolosi	Wind	68	Tank trucks	4.73
	Misterbianco	PV	51	Tank trucks	5.31
	Santa Croce Camerina	PV	91	Tank trucks	5.19
Augusta	Nicolosi	Wind	62	Pipelines	4.10
	Misterbianco	PV	47	Pipelines	4.34
	Santa Croce Camerina	PV	100	Pipelines	4.41
Milazzo	Nicolosi	Wind	100	Pipelines	4.20
	Misterbianco	PV	109	Pipelines	4.41
	Castronovo di Sicilia	Wind	217	Pipelines	4.55

4. Discussion of Results and Conclusions

This paper conducted a techno-economic analysis of clean hydrogen production plants in Sicily, a region that was chosen for two reasons: it is rich in renewable energy sources and it is the region where almost half of the refineries in Italy are concentrated, an industrial sector in which hydrogen is already used but produced from fossil sources. In the study, a comparison was made between on-site or distributed production, in which the hydrogen-producing plant is located at the end user, and centralized production, in which larger plants, which are affected by economies of scale and larger efficiencies, are located at areas of the region that are particularly sunny and windy but far from users.

The main evidence of the study is that, although the LCOH for the production of hydrogen from renewable energies in the Sicilian techno-economic context is still less convenient with respect to the production from fossil fuels, its value is highly dependent on the technologies and distances to be covered to reach the final user. Results have shown that green hydrogen have become attractive, with LCOH being down to 2.66 €/kg in the best scenario (centralized hydrogen production with alkaline electrolyzer and transported to the Augusta refinery) and up to 25 €/kg in the worst scenario (distributed hydrogen production with electricity from the grid).

More in detail, in the case of on-site production, the installation of photovoltaic systems, varying in size in the range of 1 MW_p to 2.7 MW_p, was considered, intended to feed 1 MW electrolysis plants, with hydrogen compression at 200 bar, making a comparison between different commercial electrolyzer technologies, namely alkaline and proton exchange membrane. The results showed that, with both technologies, the levelized cost of hydrogen (LCOH) varies between 7 €/kg and 10 €/kg, depending on the size of the PV system and the valorization of excess energy. A rate sensitivity analysis was then conducted, leaving the PV system size fixed at 2.6 MW, and it was seen that as the rate varied between 3% and 10%, hydrogen costs ranged between 4 €/kg and 8 €/kg.

Another analysis was conducted on the presence or absence of battery storage systems to store the excess energy produced by PV and convert it into additional hydrogen, rather than releasing it to the grid. The results showed that the presence of batteries allows a 17–20% increase in hydrogen production, but with an LCOH increase of about 4–5%.

In the case of on-site production, an assessment of hydrogen production with electricity from the grid was, in addition, performed and it was seen that the unit cost of energy in Italy does not make the production of hydrogen from electrolysis economically viable (LCOH higher than 14 €/kg), as well as not being environmentally sustainable, since energy from the grid is not fully renewable. Different conclusions could be drawn if energy from the grid were used in periods of grid imbalance compensation, in accordance with European directives, but this will be addressed in a later study.

For centralized production, on the other hand, the cost of hydrogen is affected by the beneficial effects of the economies of scale of electrolyzers and the higher efficiencies of larger stacks, while there are the costs associated with the mode of transport to the end user.

These were assumed to be equal to the optimal values found in the literature based on the distance and quantities of hydrogen to be transported. The best LCOH values obtained are those associated with hydrogen produced in centralized plants with alkaline systems and distributed in pipelines and range between 2.66 €/kg and 3.11 €/kg.

It should, however, be pointed out that at the moment there are no specific pipelines in Sicily for the transport of hydrogen and on which, it would therefore be necessary to invest. Another aspect to highlight is that, in order to produce only 16% of the hydrogen required by Sicilian refineries, 1.4 TWh to 1.7 TWh of renewable energy is needed, depending on the electrolysis technology. It turns out, therefore, that it is necessary to continue producing hydrogen from steam reformer or import renewable hydrogen produced elsewhere.

In future research, the methodology here illustrated will be applied to further geographical location with huge renewable energy potential, in order to compare the economic performance of green hydrogen production in different economic contexts or with different technologies, for example using biomass gasification.

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References

1. IEA. *Global Hydrogen Review 2023*; IEA: Paris, France, 2023.
2. EU Rules for Renewable Hydrogen: Delegated Regulations on a Methodology for Renewable Fuels of Non-Biological Origin | Think Tank | European Parliament. Available online: https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2023)747085 (accessed on 20 May 2024).
3. IRENA. *Green Hydrogen Supply: A Guide to Policy Making*; IRENA: Abu Dhabi, United Arab Emirates, 2021; ISBN 978-92-9260-344-1.
4. IRENA. *Renewable Power Generation Costs in 2022*; IRENA: Abu Dhabi, United Arab Emirates, 2023; ISBN 978-92-9260-544-5.
5. Confindustria, ENEA. *Piano d'azione per l'idrogeno—Focus Tecnologie Industriali*; ENEA: Roma, Italy, 2022.
6. La Guardia, M.; D'Ippolito, F.; Cellura, M. A GIS-Based Optimization Model Finalized to the Localization of New Power-to-Gas Plants: The Case Study of Sicily (Italy). *Renew. Energy* **2022**, *197*, 828–835. [CrossRef]
7. Climate Change: What the EU Is Doing—Consilium. Available online: https://www.consilium.europa.eu/en/policies/climate-change/ (accessed on 26 June 2024).
8. Ddg 2070 Del 30.12.2022 Pubbl. Il 30.12.2022—D.G.—Approvazione Dell'avviso Pubblico Finalizzato Alla Selezione Di Proposte Progettuali Volte Alla Realizzazione Di Impianti Di Produzione Di Idrogeno Rinnovabile in Aree Industriali Dismesse, Da Finanzia | Regione Siciliana. Available online: https://www.regione.sicilia.it/istituzioni/servizi-informativi/decreti-e-direttive/ddg-2070-30122022-pubbl-30122022-dg-approvazione-avviso-pubblico-finalizzato-alla-selezione-proposte-progettuali-volte-alla-realizzazione-impianti (accessed on 27 September 2023).
9. D.D.G. n 484 Del 16/05/2023. Available online: https://www.regione.sicilia.it/sites/default/files/2023-05/484-DDG%20approvazione%20graduatoria%20idrogeno(firmato).pdf (accessed on 25 June 2024).
10. HydroNews. Available online: https://hydronews.it/duferco-produrra-h2-green-nel-suo-stabilimento-siciliano-di-giammoro-grazie-alla-partnership-con-la-portoghese-fusion-fuel/ (accessed on 27 September 2023).
11. Focusicilia. Available online: https://focusicilia.it/rinnovabili-la-sicilia-punta-sullidrogeno-verde-per-le-imprese-629-mln-di-euro/ (accessed on 27 September 2023).
12. Enel Green Power. Available online: https://www.enelgreenpower.com/it/media/news/2022/07/idrogeno-verde-acciaierie-sicilia (accessed on 27 September 2023).

13. Chatenet, M.; Pollet, B.G.; Dekel, D.R.; Dionigi, F.; Deseure, J.; Millet, P.; Braatz, R.D.; Bazant, M.Z.; Eikerling, M.; Staffell, I.; et al. Water Electrolysis: From Textbook Knowledge to the Latest Scientific Strategies and Industrial Developments. *Chem. Soc. Rev.* **2022**, *51*, 4583–4762. [CrossRef] [PubMed]
14. Tracking Clean Energy Progress 2023—Analysis. IEA. Available online: https://www.iea.org/reports/tracking-clean-energy-progress-2023 (accessed on 27 September 2023).
15. HydroNews. Available online: https://hydronews.it/entro-fine-2023-la-capacita-di-elettrolisi-installata-a-livello-globale-superera-i-3-gw-secondo-lultimo-report-della-iea/ (accessed on 27 September 2023).
16. IRENA. *Geopolitics of the Energy Transformation: The Hydrogen Factor*; IRENA: Abu Dhabi, United Arab Emirates, 2022.
17. Guo, J.; Zheng, Y.; Hu, Z.; Zheng, C.; Mao, J.; Du, K.; Jaroniec, M.; Qiao, S.Z.; Ling, T. Direct Seawater Electrolysis by Adjusting the Local Reaction Environment of a Catalyst. *Nat. Energy* **2023**, *8*, 264–272. [CrossRef]
18. Loomba, S.; Khan, M.W.; Haris, M.; Mousavi, S.M.; Zavabeti, A.; Xu, K.; Tadich, A.; Thomsen, L.; McConville, C.F.; Li, Y.; et al. Nitrogen-Doped Porous Nickel Molybdenum Phosphide Sheets for Efficient Seawater Splitting. *Small* **2023**, *19*, 2207310. [CrossRef] [PubMed]
19. IEA. *Global Hydrogen Review 2022*; IEA: Paris, France, 2022.
20. Shin, H.; Jang, D.; Lee, S.; Cho, H.S.; Kim, K.H.; Kang, S. Techno-Economic Evaluation of Green Hydrogen Production with Low-Temperature Water Electrolysis Technologies Directly Coupled with Renewable Power Sources. *Energy Convers. Manag.* **2023**, *286*, 117083. [CrossRef]
21. Nasser, M.; Hassan, H. Thermo-Economic Performance Maps of Green Hydrogen Production via Water Electrolysis Powered by Ranges of Solar and Wind Energies. *Sustain. Energy Technol. Assess.* **2023**, *60*, 103424. [CrossRef]
22. Dufo-López, R.; Lujano-Rojas, J.M.; Bernal-Agustín, J.L. Optimisation of Size and Control Strategy in Utility-Scale Green Hydrogen Production Systems. *Int. J. Hydrogen Energy* **2023**, *50*, 292–309. [CrossRef]
23. Perna, A.; Minutillo, M.; Di Micco, S.; Jannelli, E. Design and Costs Analysis of Hydrogen Refuelling Stations Based on Different Hydrogen Sources and Plant Configurations. *Energies* **2022**, *15*, 541. [CrossRef]
24. Minutillo, M.; Perna, A.; Forcina, A.; Di Micco, S.; Jannelli, E. Analyzing the Levelized Cost of Hydrogen in Refueling Stations with On-Site Hydrogen Production via Water Electrolysis in the Italian Scenario. *Int. J. Hydrogen Energy* **2021**, *46*, 13667–13677. [CrossRef]
25. Ciancio, A.; De Santoli, L. Assessing the Levelized Cost of Hydrogen Production in a Renewable Hydrogen Community in South Italy. In Proceedings of the 2023 IEEE International Conference on Environment and Electrical Engineering and 2023 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe, Madrid, Spain, 6–9 June 2023; Institute of Electrical and Electronics Engineers Inc.: Piscataway, NJ, USA, 2023.
26. HyResponder, Lezione 3: Stoccaggio Dell'idrogeno. Available online: https://hyresponder.eu/wp-content/uploads/2023/03/L3_HyResponder_Livello3_ITA.pdf (accessed on 15 February 2024).
27. Coveri, M.; Ferraro, M.; Massaro, F.; Sanseverino, E.R.; Ruffino, S. The Sustainable Energy Development in Southern Italy through Green Hydrogen: A Cost Analysis. In Proceedings of the 2023 IEEE International Conference on Environment and Electrical Engineering and 2023 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Madrid, Spain, 6–9 June 2023; pp. 1–6. [CrossRef]
28. IEA. *Projected Costs of Generating Electricity*; IEA: Paris, France, 2020.
29. Clerici, A.; Furfari, S. Challenges for Green Hydrogen Development. In Proceedings of the 2021 AEIT International Annual Conference, AEIT 2021, Virtual, 4–8 October 2021. [CrossRef]
30. Terna. *Study on Reference Technologies for Electricity Storage*; Terna: Roma, Italy, 2023.
31. Tariffe Uso Commerciale—A.M.A.M. S.p.A. Available online: https://www.amam.it/portale-utenti/le-tariffe/uso-commerciale/ (accessed on 29 January 2024).
32. European Union Joint Research Centre (JRC). Photovoltaic Geographical Information System (PVGIS). European Union Joint Research Centre (JRC): Brussels, Belgium. Available online: https://joint-research-centre.ec.europa.eu/photovoltaic-geographical-information-system-pvgis_en (accessed on 27 June 2024).
33. Confindustria; ANIMA (Confindustria Meccanica Varia). *Modelli Di Business per l'utilizzo Dell'H2 e Lo Sviluppo Della Filiera in Italia*; Confindustria: Roma, Italy, 2024.
34. Zauner, A.; Böhm, H.; Rosenfeld, D.C.; Tichler, R. Innovative Large-Scale Energy Storage Technologies and Power-to-Gas Concepts after Optimization Analysis on Future Technology Options and on Techno-Economic Optimization; 2019.
35. Energy Sector Management Assistance Program (ESMAP). *Global Solar Atlas*; Energy Sector Management Assistance Program (ESMAP): Washington, DC, USA, 2020.
36. Technical University of Denmark (DTU). *Global Wind Atlas 3.0*; Technical University of Denmark (DTU): Lyngby, Denmark, 2024.
37. European Hydrogen Observatory. Available online: https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/end-use/hydrogen-demand (accessed on 22 May 2024).
38. GME (Gestore Mercati Energetici). Available online: https://mercatoelettrico.org/it/ (accessed on 25 March 2024).
39. Park, J.; Kang, S.; Kim, S.; Cho, H.S.; Heo, S.; Lee, J.H. Techno-Economic Analysis of Solar Powered Green Hydrogen System Based on Multi-Objective Optimization of Economics and Productivity. *Energy Convers. Manag.* **2024**, *299*, 117823. [CrossRef]

40. Statistics | Eurostat. Available online: https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_205__custom_10680922/default/table?lang=en (accessed on 4 April 2024).
41. Delegated Regulation—2023/1184—EN—EUR-Lex. Available online: https://eur-lex.europa.eu/eli/reg_del/2023/1184/oj (accessed on 11 April 2024).