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Corso di Laurea Triennale in Ingegneria Gestionale

# Analisi tecno-economica della produzione di idrogeno nell'ambito della transizione energetica italiana

## Techno-economic analysis of hydrogen production for the Italian energy transition

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# Abstract

In this thesis, the production of hydrogen with the lowest environmental impact is examined. The first chapter, it starts with a general description of hydrogen and its important characteristics to understand why this element is increasingly considered of great importance for the energy transition. It is also evident that hydrogen can be produced using various techniques that have different impacts on emissions but only one is really close to zero impact. This technique is based on the water electrolysis process that uses renewable electricity. It is precisely on this technique that the thesis will focus particularly as it is the only one that is really important for the development of the Italian energy transition. The second chapter explains how this process of electrolysis actually takes place and what technologies are currently available. These technologies are analyzed both from a technical and economic point of view, then explaining what are the main aspects that would lead to cost reduction and a technological efficiency. The second chapter deals with the major issues related to the generation of this hydrogen focusing attention on how the electricity that powers the electrolysis systems is produced and what are the main limits to be taken into consideration. To conclude, in the third chapter different scenarios of hydrogen generation from electrolysis are hypothesized which are analyzed from a techno-economic point of view. The technical and economic parameters considered refer to the Italian case.

# Riassunto dell’elaborato in lingua italiana

In questa tesi viene approfondita la produzione dell’idrogeno a più basso impatto ambientale. Nel primo capitolo, si inizia con una generale descrizione dell’idrogeno e delle sue importanti caratteristiche per comprende per quale motivo questo elemento è sempre più considerato di notevole importanza per la transizione energetica. Si evidenza anche che l’idrogeno può essere prodotto mediante varie tecniche che hanno differenti impatti sulle emissioni ma solo una è realmente a impatto prossimo allo zero. Questa tecnica è basata sul processo dell’elettrolisi dell’acqua che utilizza energia elettrica rinnovabile. E’ proprio su questa tecnica che l’elaborato si incentrerà particolarmente in quanto l’unica realmente importante per lo sviluppo della transizione energetica italiana. Nel secondo capitolo viene spiegato come effettivamente si svolge questo processo di elettrolisi e quali sono le tecnologie attualmente disponibili. Queste vengono analizzate sia da un punto di vista tecnico che economico, spiegando poi quali sono gli aspetti principali che porterebbero a una riduzione dei costi e ad un efficientamento tecnologico. Sempre nel secondo capitolo vengono affrontate le maggiori problematiche legate alla generazione di questo idrogeno concentrando l’attenzione su come l’energia elettrica che alimenta gli impianti di elettrolisi viene prodotta e quali sono i principali limiti da tenere in considerazione. Nel terzo capitolo invece vengono ipotizzati diversi scenari di generazione dell’idrogeno da elettrolisi che saranno analizzati da un punto di vista tecno-economico. I parametri tecnici ed economici considerati fanno riferimento al caso italiano.

# 1. Introduction

## 1.1. General description of hydrogen

Among various alternatives to replace conventional sources of energy, hydrogen is considered to be the major energy carrier to solve the issues of fossil fuels depletion and climate change [1]. Indeed, hydrogen can be used in most applications requiring fossil fuels and it has more than two-times energy density (140 MJ/kg) than conventional fuels (50 MJ/kg) [2][3]. It is the lightest element known with density of 0.0695 with respect to air and it is an odorless, tasteless and colorless gas [4].

This element has several key characteristics that make it a strategic option for enabling energy transition and allow a rapid acceleration of it in some sector [5]. Hydrogen is a clean fuel with no toxic emissions, its combustion generates water vapor and it does not release carbon dioxide or any significant pollutants.

However, even though it is one of the most common elements in nature, unfortunately it is not available in significant quantities in the pure state, but is found bound to other elements, such as in water (molecule of hydrogen and oxygen) or in hydrocarbons (hydrogen and carbon). To separate it from the other elements with which it is found on Earth, it is necessary to "extract" it by providing energy that favors the separation process and affording an economic and often environmental cost.

Since hydrogen is not found alone in nature and a contribution of another type of energy is necessary to produce it, hydrogen is considered as an energy carrier and not an energy source, as it is instead as solar or wind power [4][6].

The final uses of hydrogen are different, this element can be used in two ways: as a **feedstock** in some production processes; as an **energy carrier** to be transformed into electricity or thermal energy in strategic sectors to be decarbonised, including industry, transport and residential sector. These applications represent the real challenge for the future development of the hydrogen value chain.

To date, about 3/4 of the hydrogen produced globally is used as a feedstock in industrial processes [1] . Three main sectors in which hydrogen is used as raw material are: **chemicals**, in which it has the potential to reduce the environmental footprint of the production chain of ammonia and methanol; **refining**, in which it is used to produce greener fuel by reducing sulfur emissions; **steel-making**, in which it is used to reduce polluting emissions in blast furnaces.

As an energy carrier, hydrogen can be used to produce electricity through electrochemical technologies such as fuel cells. These technologies can achieve high electrical efficiency (over 60%), especially in the case of partial load, making them particularly suitable in loading operations due to their capacity. Alternatively, hydrogen can be used for the generation of electricity through thermal technologies such as turbines and suitably adapted internal combustion engines, which see hydrogen (or methane gas and hydrogen mixtures) as fuel [5]. Hydrogen, as an energy carrier, has many appealing characteristics, including a large storage capacity, high energy conversion, cleanliness and environmental friendliness, renewable production, vast specific energy, zero emissions, wide sources, reliability, and easy storage and regeneration. Thus, it is considered to be the cleanest and most promising energy resource of the 21st century [7].

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[1] Source: IEA, 2018.

## 1.2. The colors of hydrogen

“Not all hydrogen is the same”, it can be produced in various ways using different technologies. Since each of the different technologies has a different impact of emissions, different colors are adopted to define the way in which hydrogen is obtained [8].

In literature there are many colors used to distinguish the types of hydrogen but the most frequently faced are three: gray, blue and green.
**Gray hydrogen** is extracted from oil or methane through water vapor at a temperature of 800 degrees centigrade in the presence of a material that speeds up the process (catalyst). In this way the carbon is oxidized, and hydrogen is released from the molecule with the emission of carbon dioxide (CO2). Alternatively, hydrogen can be obtained from coal through the gasification process in which coal reacts with water vapor at 900 degrees centigrade and then at 500 degrees centigrade with another catalyst compound. Gray hydrogen is currently the most produced but its production process is the most polluted.
**Blue hydrogen** is produced according to the gray hydrogen process which the Carbon Capture and Storage technology is associated, that allows the carbon dioxide deriving from the hydrogen production process to be "captured", usually transported in liquid form and injected into suitable geological confinement sites where it can be contained for several years. Among the geological sites generally used for this purpose there are old hydrocarbon deposits.
The least polluting hydrogen production process of all is that relating to **green hydrogen**. This hydrogen is obtained from the electrolysis process which consists in the splitting of water through the use of electricity, with the simultaneous production of oxygen. In order to be defined carbon free, the electricity must come from renewable sources [5][9][10].

Green hydrogen is certainly the best environmental solution; however, its production techniques have not reached the same cost with those used for the production of gray and blue hydrogen yet. From the cost curves in Figure 1 it is shown how green hydrogen will become a convenient solution in Italy as early as

2030. Blue hydrogen, on the other hand, is assumed to be a more suitable medium-term solution [5].

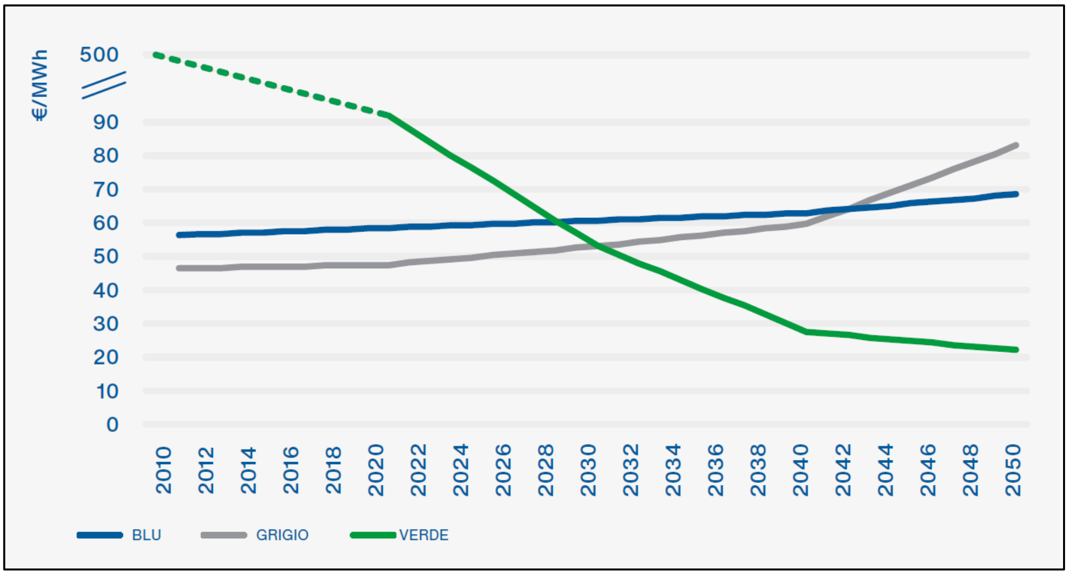

**Figure 1 - Hydrogen production costs by type (€ / MWh), 2010-2050 [5].**

## 1.3. Importance of low-carbon hydrogen for the Italian energy transition

Hydrogen supplied from fossil fuels generates a large amount of emissions, which is not environmentally or climate respectful. So, it is important to shift towards production of low-carbon hydrogen. Typically, low-carbon hydrogen means green hydrogen (produced from water and green electricity by an electrolyzer) and blue hydrogen (hydrogen from fossil fuels with reduced $CO_2$ emissions from the use of carbon capture, utilization and storage). However, between these two types of hydrogen, only the green one has a production process that can be defined as having zero emission.

There is a growing international consensus of opinion about the fact that low-carbon hydrogen will play an important role in the world's transition to a sustainable energy future [11].
This idea of hydrogen is strongly supported both by the scientific community and by several major companies such as the International Energy Agency (IEA). Despite the long and costly path of development towards utilizable and stable technology, hydrogen proved to be a risk-worth taking choice. For this reason, hydrogen today has an essential place in the sector of energy storage [12].

In Italy, hydrogen is going to have a great development potential by 2050. In line with international scenarios, in 2050 hydrogen could play a significant role, up to a potential penetration level of 23% of final energy demand, with a contribution of over 200 TWh. The use of hydrogen instead of fossil fuels would allow Italy to reduce emissions by 97.5 million tons of CO2eq, corresponding to a reduction of about 28% compared to Italian climate-altering emissions in 2018.
The sector that likely would benefit most from the introduction of hydrogen will be the transport sector, which is expected to cover 39% of the entire hydrogen demand by 2050 [5]. Another important factor not to be overlooked is that Italy has good potential to become a hydrogen hub. Italy has significant potential to use its solar and wind resources for the low-cost production of hydrogen. It also has gas infrastructure that connects it with North Africa and up to the North with

Europe. By putting "the solar panels where the sun shines" more, green hydrogen can be produced at a significantly lower cost, and transported using the existing natural gas pipelines to demand centers in Italy and further North to Europe, turning Italy into a hub for green hydrogen for Europe  [13].

A requirement for hydrogen to assure its place in the energy transition which also applies to any technology based on RES, is sufficient development of the technology itself. The potential for achieving a carbon-neutral society means little if efficiency, reliability, and scale of production are not adequate for the world's standards and needs. Therefore, decades of R&D of hydrogen technology seem to finally pay off. Hydrogen regarding efficiency can positively cope with concurrent technologies in most applications, and at the same time undoubtedly offer better commodities. Cost parity has not been reached yet in every aspect but learning from the experience of other RES-based technology development trend, it is to be expected. With the production scale increased, production costs will reach economical profitability [12].

In this regard, some italian companies decided to turn to European Commission expressing their interests in electrification using a european strategy based on green hydrogen. Just recently, Enel Italia CEO Carlo Tamburi illustrated (in the Chamber on Recovery Fund) the energy transition plans on which the company is working. He said: "We will create energies from renewables sources and we will give energy from hydrogen to Ilva in Taranto". Furthermore, Enel is working to create hybrid power plants composed of renewable plants (solar and wind) combined with electrolyzers, to produce green hydrogen, to be sold to customers for the decarbonisation of their processes [14].

# 2. Green hydrogen production

As already mentioned in the previous chapter, hydrogen can be produced from many different sources which can be renewable or non-renewable. These production processes have very variable costs and emissions. This chapter deals with the generation and distribution of so-called green hydrogen, which is considerable important for both the Italian and world energy transition. In addition to a technical description of the various technologies adopted for its production, the various costs are analyzed.

## 2.1. Electrolysis of hydrogen

The generation of green hydrogen involves the use of electrochemical devices called **electrolyzers** which, powered by electricity, allow in the presence of an electrolyte and a membrane to break water molecules by separating hydrogen from oxygen. To be truly defined as a green process, that is, without polluting emissions and without the consumption of precious natural resources, these electrolyzers should be powered by renewable sources such as wind or photovoltaic.

Inside an electrolyzer, the generation of hydrogen takes place through the so-called electrolysis process, an established and well-known method, which is the most effective technique for splitting water [15][16]:

$$H_2O + Electricity\left(237.2\frac{kJ}{mol}\right) = Heat\left(48.6\frac{kJ}{mol}\right) + H_2 + \frac{1}{2}O_2$$

Typically, electrolyzers can be fragmented in three levels (see Figure 2):

- The **cell** is the core of the electrolyzer, and it is where the electrochemical process takes place. It is composed of the two electrodes (anode and cathode) immersed in a liquid electrolyte or adjacent to a solid electrolyte membrane, two porous transport layers (which facilitate the transport of reactants and removal of product), and the bipolar plates that provide mechanical support and distribute the flow.
- The **stack** has a broader scope, which includes multiple cells connected in series, spacers (insulating material between two opposite electrodes), seals, frames (mechanical support) and end plates (to avoid leaks and collect luids).
- The **system level** (or balance of plant) goes beyond the stack to include equipment for cooling, processing the hydrogen (e.g for purity and compression), converting the electricity input (e.g. transformer and rectifier), treating the water supply (e.g. deionization) and gas output (e.g. of oxygen).

Purified water is fed into the system using circulating pumps, or also by gravity. The water then reaches the electrodes by flowing through the bipolar plates and through the porous transport layers. At the electrode, the water is split into oxygen and hydrogen, with ions (typically $H^+$ or $OH^-$) crossing though a liquid or solid membrane electrolyte. The membrane or diaphragm between both electrodes is also responsible for keeping the produced gases (hydrogen and oxygen) separated and avoiding their mixture. This general principle has remained the same for centuries, but the technology has evolved since William Nicholson and Anthony Carlisle first developed it in 1800 [17].

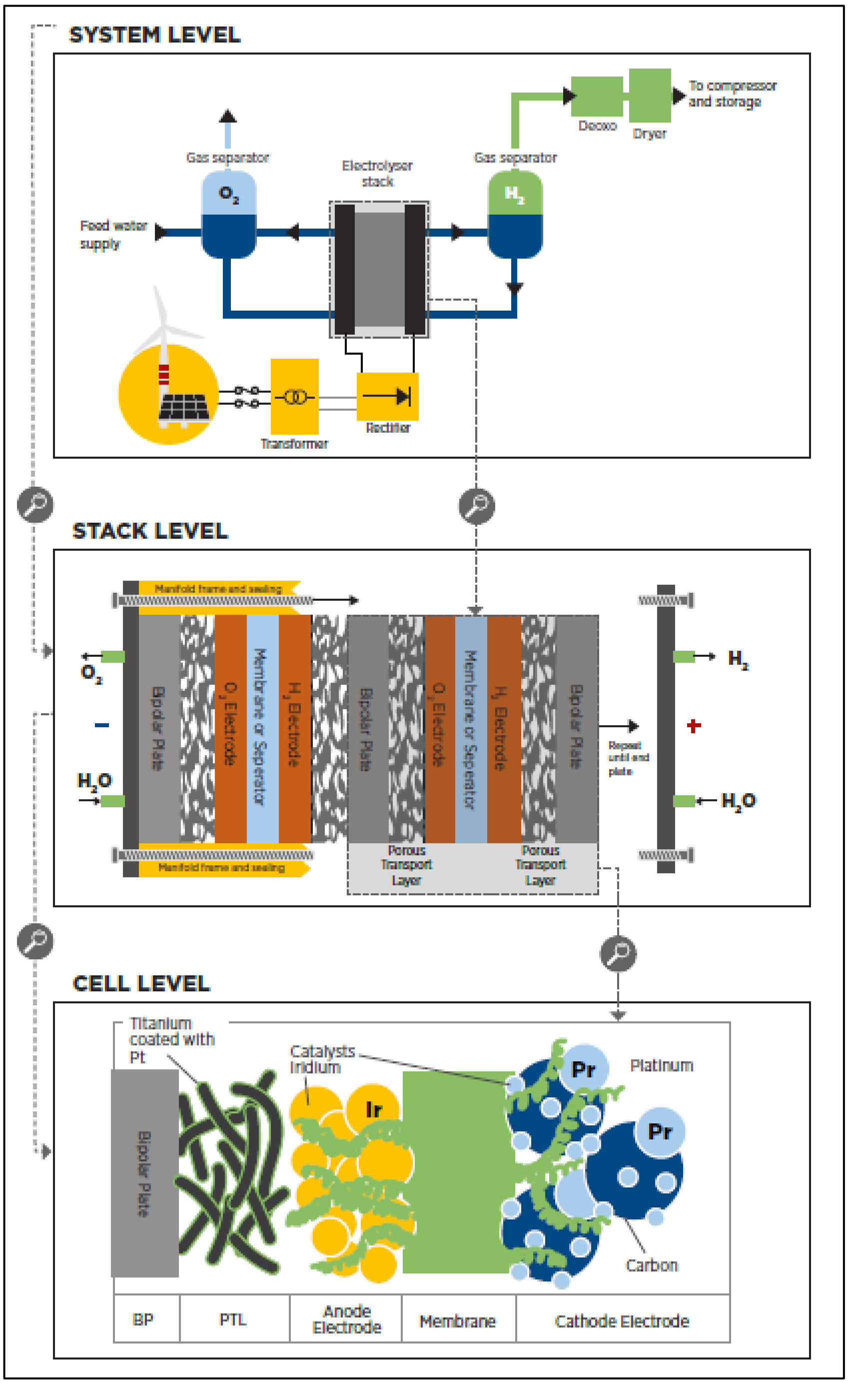

**Figure 2 - Basic components of water electrolyzers at different levels [17].**

Generally, when electric current is applied the water splits and hydrogen is produced at the cathode while oxygen develops on the anode side [15].

From a stoichiometric point of view, the $H_2$ production via water electrolysis consumes circa 9 kg of water per 1 kg of $H_2$. There are several types of electrolyzers with varying technological performance and thus, water consumption levels. Considering some of the electrolyzer manufacturers' specifications, slightly higher water needs per kg of $H_2$ are reported, varying among suppliers and electrolyzer type and ranging from 10.01 to 22.40 l per kg of $H_2$ [16].

Electrolyzers have been known for over two centuries. Although the fundamental technology has remained the same (see Figure 3), several trends have influenced its development, dividing the period into about five generations.

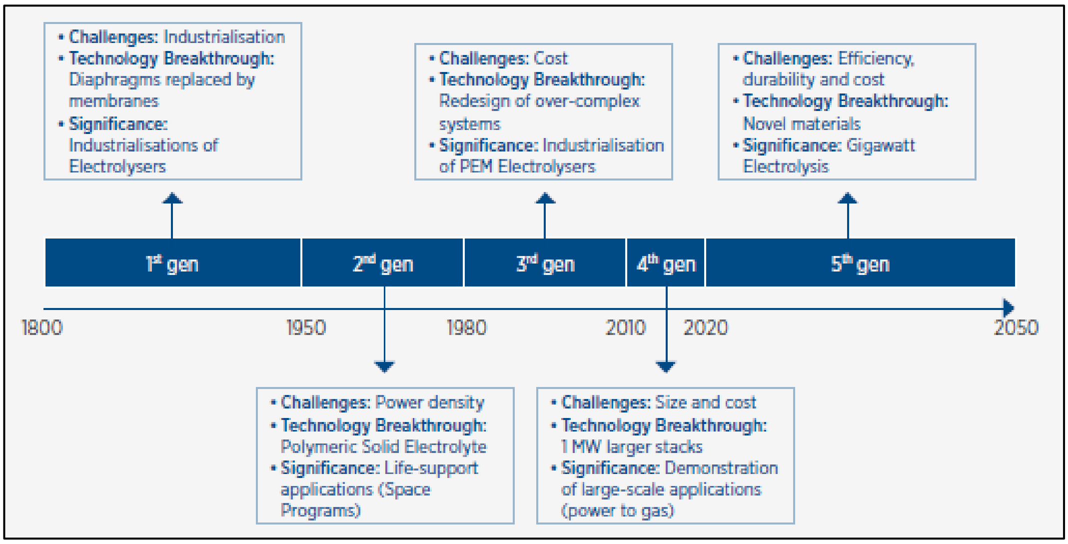

**Figure 3 - Challenges and technological breakthroughs for each of the generation of electrolyzers** [17].

### 2.1.1 Technical analysis of electrolyzer technologies

Electrolysis of water is a simple process but it allows the construction of different technological variants based on various physicalchemical and electrochemical aspects. Electrolyzers are generally divided into four main technologies: **Alkaline Electrolytic Cell (AEC)**, **Proton Exchange Membrane (PEM)**, **Anion Exchange Membrane (AEM)** and **Solid Oxide Electrolier Cell (SOEC)**. These can be distinguished by the type of electrolyte and temperature of operation that will guide the selection of different materials and components. The first two technologies have already achived a good ranking in the market and they have a stack (the plant cell where the water molecules are broken down into oxygen and hydrogen) with power in the order of MW. The other two have a stack size in the order of kW and with less duration, they could have good prospects for development, but they are not consolidated in the market yet [18].

The principles of all types of commercially available electrolysis cells are shown in Figure 4. There are many variations within each technology, with more radical differences related to the design of the cells, variations within the components and the degree of technological maturity.

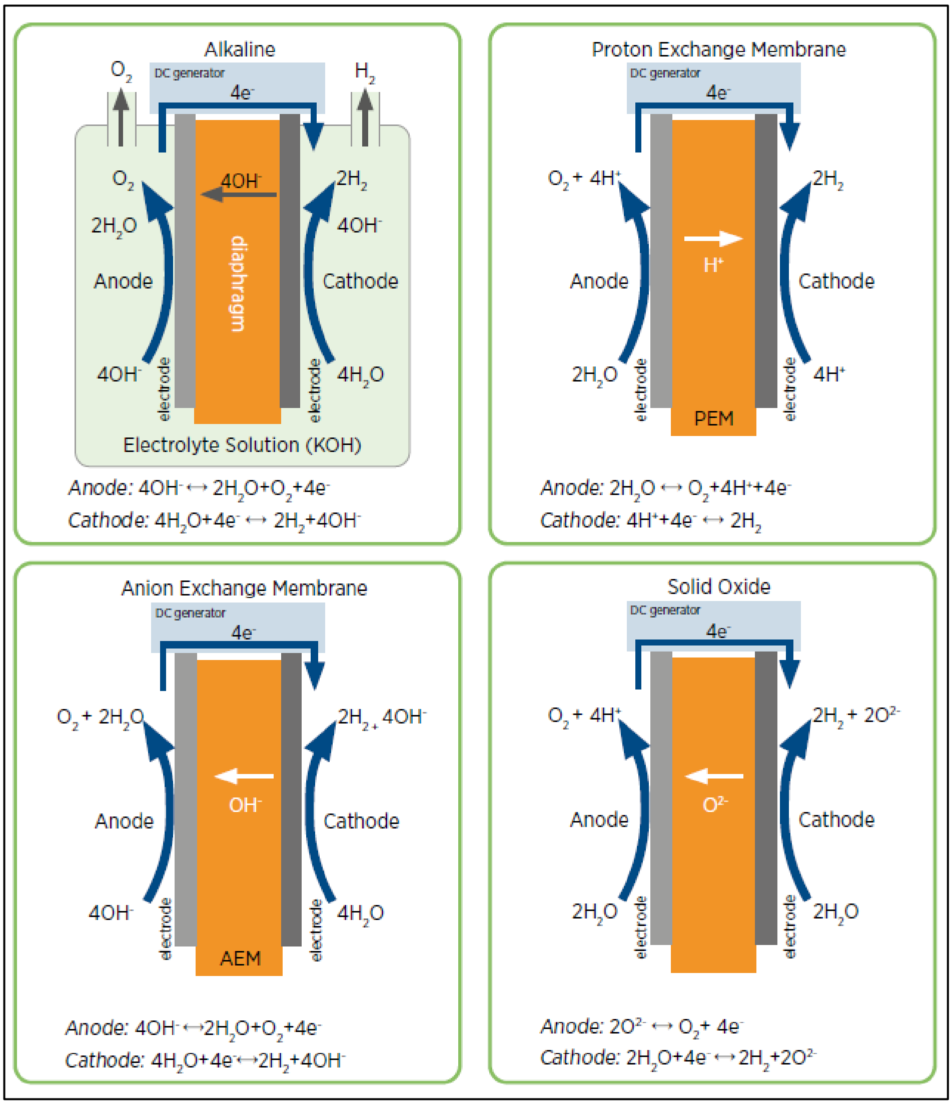

**Figure 4 - Different types of commercially available electrolysis technologies [17].**

Today AEC technology is the most widespread and widely used for large-scale industrial applications since 1920 [19]. Alkaline electrolyzers work by transporting hydroxide ions ($OH^-$) through the electrolyte from the cathode to the anode with the generation of hydrogen on the cathode side [20]. In this technology, alkaline water electrolysis operates at low temperature (60–80 °C), with KOH and/or NaOH aqueous solution as the electrolyte, the concentration of the electrolyte is approximately 20%–30%. In an alkaline electrolyzer, the diaphragm is asbestos, and nickel materials are used as the electrode. The purity of the generated hydrogen is approximately 99%; however, an alkali fog in the generated gas must be removed, for which desorption is typically used. The maximum operating current density of an alkaline electrolyzer is less than 400 $mA/cm^2$, and the power consumption for H2 production is approximately 4.5–5.5 $kWh/Nm^3$ with an efficiency of approximately 60%. To avoid hydrogen/oxygen penetrating the porous asbestos diaphragm resulting in an explosion risk, the pressure between the anode and cathode sides must be balanced. Moreover, alkaline electrolyzers cannot start up quickly, and have a slow loading response. Long start-up preparation makes it difficult to adapt alkaline electrolyzers to the variable nature of renewable energy sources. Therefore, alkaline electrolyzers are normally used with a steady power input [3]. Recent progress should nevertheless be observed, making AEC technology compatible for applications with grid services, on a short timescale. The lifetime of an AEC electrolyzer is usally twenty years and among the four technologies it is currently the cheapest with a lower cost of capital [21][16][18]. However, low current density and operating pressure negatively impact system size and hydrogen production costs. Also, dynamic operation (frequent start-ups and varying power input) is limited and can negatively affect system efficiency and gas purity. Therefore, development is focussed on increasing current density and operating pressure, as well as system design for dynamic operation to allow operation with intermittent renewable sources, for example. Previous analyses suggest that future cost reductions are most likely driven by economies of scale [19].

The PEM technology uses a solid polymer electrolyte and works at a low temperature below 80 ° C, with the protons passing through a special membrane

[18][21][16]. PEM electrolysis is based on proton exchange membrane fuel cell technology. Proton exchange membranes replace asbestos, with protons conducted into the membrane. In particular, the gas permeability of a PEM is much lower than that of asbestos. Without an alkaline mist in the generated gas, PEM electrolyzers are more environmentally friendly. Introduced in the 1960s and marketed in the last decade, these systems tend to have a smaller footprint, they offer faster dynamic response and wider operating power ranges than the AEC, making them more suitable for intermittent powering [3][21][18]. The capital costs are higher than those of alkaline electrolyzers, platinum catalysts and fluorinated membrane materials are used which are more expensive. In addition, the system has a higher complexity due to high pressure operation and water purity requirements and the life of the cells must be improved [16][19]. However, rapid response, high efficiency, compact design and high output pressure make PEM electrolysis a promising technology for hydrogen production that it is rapidly gaining market share [3][21].

Anion Exchange Membrane (AEM) technology operates at low temperatures and have interesting development potential. The low cost of the materials used and the simple balancing of the system allow to efficiently build a 2.4 kW electrolyzer; the main purpose is to use it in a decentralized / distributed hydrogen production with standardized components that can be added as desired. So far only a few companies are active in this technology production but one of them has hundreds of small plants up to 20 kW currently in service in 36 countries [18].

SOEC is the least developed electrolysis technology. Unlike previous technologies, it operates at high temperature (from 650 to 1000 ° C) and uses solid ionic conduction ceramics as the electrolyte.
Potential benefits include high electrical efficiency, low material cost and options to operate in reverse mode as a fuel cell or co-electrolysis mode producing syngas ($CO + H_2$) from water vapor ($H_2O$) and carbon dioxide ($CO_2$) [19]. This technology offers a very high development potential but is still being tested with some prototypes, for this reason there are only a few companies with high prices [18]. A key challenge is the severe degradation of the material due to high

operating temperatures. Therefore, current research is focused on stabilizing existing component materials, developing new materials, and lowering the operating temperature to 500-700 °C (650 to 1000 °C) to enable commercialization of this technology [19].

### 2.1.2 Economic analysis of electrolyzer technologies

Despite their market availability and maturity, PEM and alkaline water electrolyzers are still considered very expensive from both a CAPEX [2] and OPEX [3] perspectives, compared to fossil fuel-based hydrogen production. PEM water electrolyzers are 50%-60% more expensive than alkaline and represent an additional barrier to market penetration. Both are still considered to have untapped potential for cost decrease when considering economies of scale, automation, an increase in availability of components from various OEMs [4] , massive market demand and deployment for energy storage (coupling of electrolyzers with underground storage or tanks).

For AEM and solid oxide electrolyzers, these cost considerations are much more challenging, as there are only a few companies responsible for their commercialisation. Moreover, many of their components are still lab-scale based, with no OEM responsible for their manufacturing and commercialisation. These are small stacks, and system size are only up to a few kilowatts. While these two technologies can still contribute to a low production cost of green hydrogen, they have a longer way to go compared to alkaline or PEM. For these reasons, only the cost breakdown for these two technologies is explored in more detail below. Significantly, AEM can use less expensive materials (in particular titanium, which can represent around half the stack cost for PEM) and therefore AEM has an advantage over PEM in cost-cutting potential.

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[2] CApital EXpenditure

[3] OPerational EXpenditure

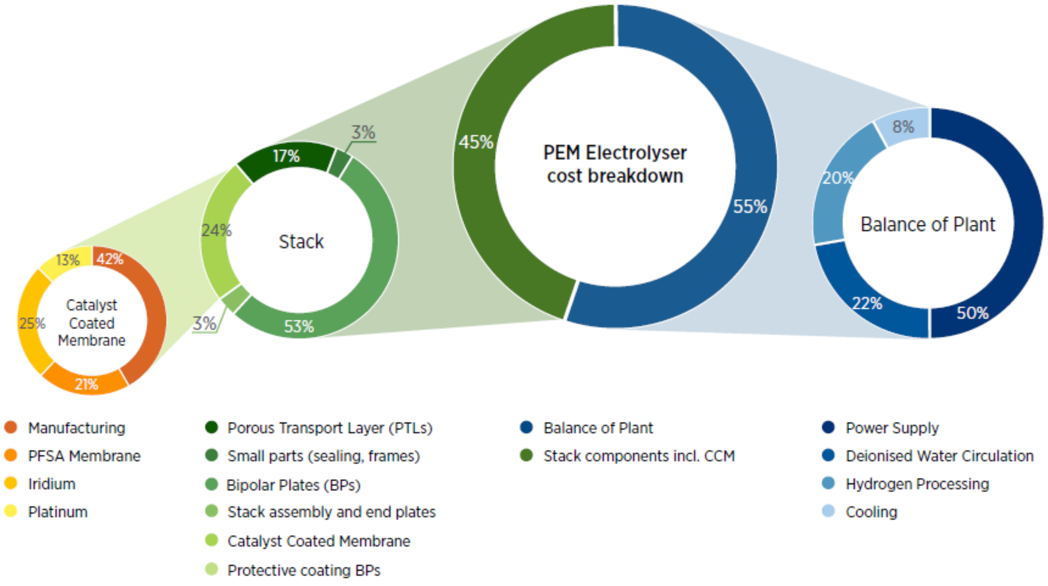
[4] Original equipment manufacturer

There are two main problems with cost estimates for electrolyzers. First, the availability of data, given its confidential nature and the retention of competitive advantage. Second, the boundaries for the cost estimates are not consistent (e.g. stack, balance of plant, full system) and, in many cases, not even specified, which makes the comparison across studies more difficult. For the second barrier (boundaries), different system scopes are analyzed for the cost estimates:

- The first level is a single cell unit. This is the core of the electrolyzer where the main electrochemical process takes place. This includes the catalyst coated membrane where the catalyst layers are coated directly as electrodes onto the membrane for the PEM type and the electrodes and diaphragms for the alkaline type, plus the manufacturing of these components which can represent a large share of the costs.
- The second level within stack costs includes the cells plus the PTLs, bipolar plates, end plates and other small parts such as spacers, seals, frames, bolts and others. This level usually represents about 40%-50% of the total.
- The third level is the system costs. The scope is all the balance of plant components and peripherals responsible for operating the electrolyzer, but excluding any component responsible for further gas compression and storage. The major components for the balance of plant cost models typically include rectifier, water purification unit, hydrogen gas processing (compression and storage) and cooling components. These items can constitute 50%-60% of the total cost.

Today, the main contributor to system costs is still the stack, which represents 40%-50% of the total, for both alkaline and PEM electrolyzers. This share greatly depends on design, manufacturing strategy, business case, and customer specifications. Cost breakdowns for AEMs and solid oxide systems are still not available, due to the limited number of systems that have been deployed commercially. titanium with cheaper materials, relying on the coating for its functional characteristics to remain unaffected, while reducing cost [17].

Figure 5 and Figure 6 show a breakdown of cost components for both PEM and alkaline electrolyzers.



Note: The specific breakdown varies by manufacturer, application and location, but values in the figure represent an average.

**Figure 5 - Cost breakdown for a 1 MW PEM electrolyzer, moving from full system, to stack, to CCM [17].**

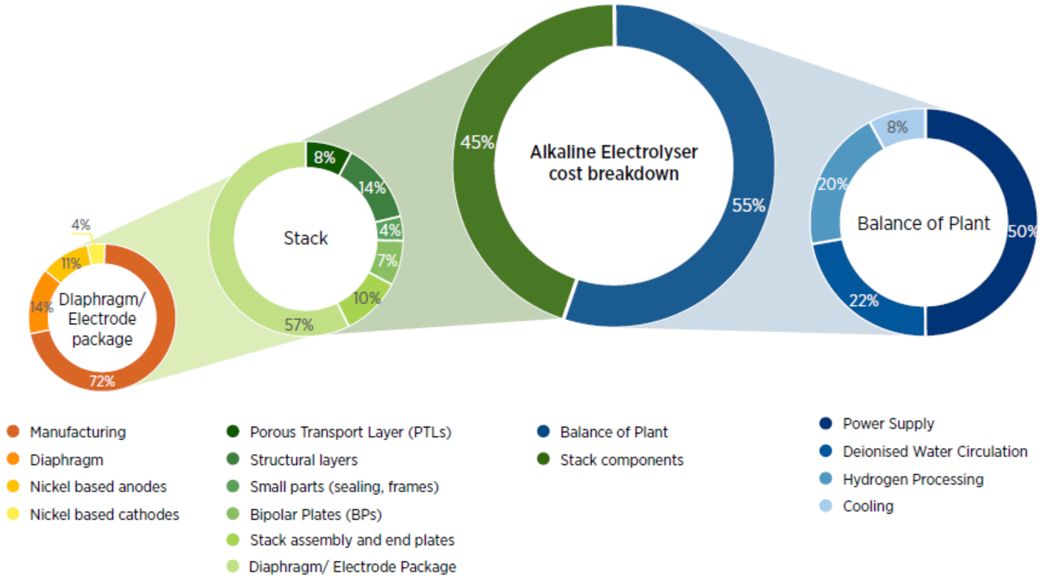


**Figure 6 - Cost breakdown for 1 MW alkaline electrolyzer, moving from full system, to stack, to membrane electrode assembly (MEA) [17].**

Although the precise cost estimation of the various technologies is not simple, some literature studies have been dedicated to summarizing both historical trends and short-term and long-term projections of investment costs (CAPEX) and performance data for two of the most common water electrolyzer technologies currently in use, AEC and PEM systems. However, such literature reports are often only able to generate a relative wide range of CAPEX data, depending on the exact performance (e.g. input power) of the system being considered. For instance, Fig. 7 summarizes CAPEX data from available literature reports examined in ref. [22]. It can be observed that the spread of the CAPEX estimations in the 1990s was in the range 870–2350 Euro/kW and 310–4750 Euro/kW for alkaline and PEM technology, respectively. At the same time, estimations for the future investment costs by the year 2030 are reported to be in the range 790–910 Euro/kW and 400–960 Euro/kW, respectively.

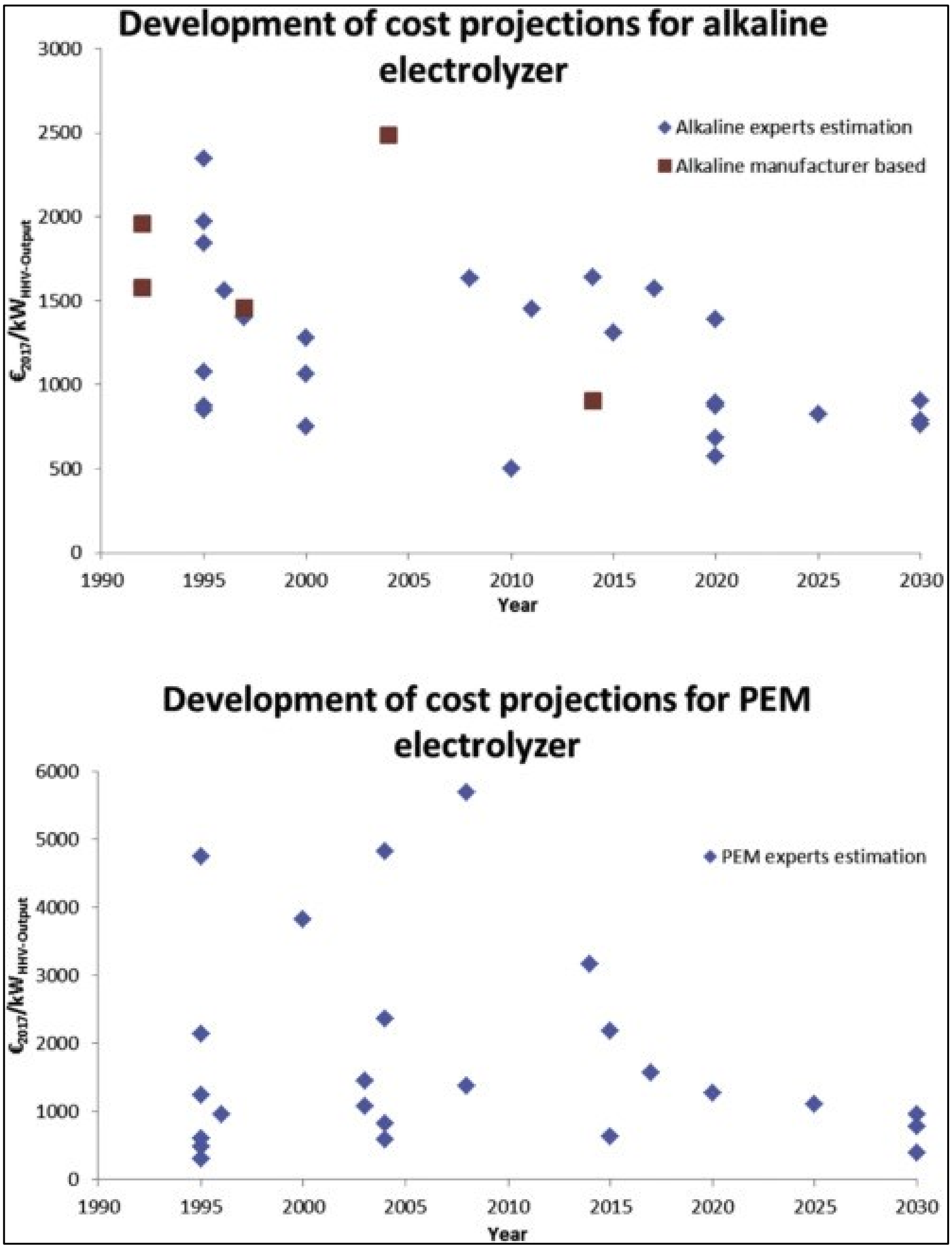


**Figure 7 - Compilation of past and expected alkaline (top) and PEM (bottom) electrolysis plant cost in Euro/kW, based on available literature studies [23].**

When it comes to the short- and long-term projections reported in the expert elicitation study on future cost and performance of water electrolyzers of ref. [19], capital costs by 2020 are predicted to lie between 800 and 1300 Euro/kW for alkaline, and between 1000 and 1950 Euro/kW for PEM systems (all 50th percentile estimates, at current R&D funding and without production scale-up). By 2030, these costs are estimated in the same report to be only slightly lower than in 2020, being in the range 700–1000 Euro/kW and 850–1650 Euro for alkaline and PEM, respectively [23].

In conclusion, each technology has its own strengths and weaknesses. There is no technology that is entirly better than the others. Competition and innovation research play an important role in lowering prices [18].

### 2.1.3 Strategies for cost reduction

The cost of production is a major obstacle for green hydrogen. Costs are decreasing, largely due to the decrease in renewable energy costs. However, green hydrogen is currently more expensive than blue hydrogen and gray hydrogen, so further cost reductions are needed.

The largest single cost component for on-site green hydrogen production is the one related to renewable electricity needed to power the electrolyzer. This makes the production of green hydrogen more expensive than blue hydrogen, regardless of the cost of the electrolyzer. A low cost of electricity is therefore a necessary condition for producing competitive green hydrogen.

However, the low cost of electricity is not enough for a competitive production of green hydrogen. Therefore, a reduction of the cost of electrolysis plants is also necessary. This is the second largest cost component of green hydrogen production. Appropriate strategies allow to reduce investment costs for electrolysis plants from 40% in the short term to 80% in the long term. These strategies range from the fundamental stack design (multiple cells combined) of the electrolyzer to larger system-level elements, including:

**Electrolyzer design and construction:** Increaseing module size and innovation with increased stack manufacturing have significant impacts on cost. Increasing plant size from 1 MW (typical in 2020) to 20 MW could reduce costs by over a third. Optimal system designs maximise efficiency and flexibility. Cost, however, is not the only factor affecting the size of the plant, as each technology has its own stack design, which also varies between manufacturers.

**Economies of scale:** Increasing stack production with automated processes in gigawatt-scale manufacturing facilities can achieve a step-change cost reduction. At slower production speeds, the stack represents approximately 45% of the total cost, but at higher production speeds it can drop to 30%. For PEM electrolyzers, the turning point appears to be around 1 000 units (from 1 MW) per year. This growth allows a cost reduction of almost 50% in stack manufacturing. The cost of the surrounding system is as important as the electrolyzer battery and savings can be achieved by standardizing the system components. Procurement of materials: Scarcity of materials can impede electrolyzer cost reduction and scale-up.

According to data (IRENA), up to 85% of green hydrogen production costs can be reduced in the long term thanks to a combination of cheaper electricity and investments in the electrolyzer. Important is also a greater efficiency and optimized operation of the electrolyzer. Design and operation of electrolysis systems can be optimized for specific applications in different industries. Moreover, an ambitious energy transition, aligned with key international climate goals, would drive rapid cost reduction for green hydrogen. It is stimated that the trajectory needed to limit global warming at 1.5oC could make electrolyzers 40% cheaper by 2030.

By analyzing the electrolyzer technology in more detail, it is possible to identify four strategies to achieve a lower cost. Two related to the stack level and two to the system level.
At the stack level, an **appropriate stack design and cell composition** using less critical materials would allow greater efficiency (i.e. lower electricity cost), higher durability (longer lifetime to distribute the investment) and increase the current density (higher production rate). Furthermore, **increasing the size of the module** could lead to economies of scale for some of the components of the plant's equilibrium. This strategy should consider a trade-off between a small module size that enables mass-manufacturing, standardisation and replication, and a large module size that achieves larger cost reduction in balance of plant components at the expense of fewer units deployed and less learning by deployment.

At the system level, **increasing the manufacturing scale of the plant** would reduce the cost contribution of each component by performing a high throughput, automated manufacturing operation. This includes, for example, rolltoroll manufacturing of the catalystcoated membrane (for PEM) and advanced coating processes for metal plates. The second strategy of the system level is a more theoretical strategy, it concerns the **learning-by-doing** referring to standardization, to the application of lessons learned from distribution and to the optimization of the installation of equipment through the execution of multiple projects. These two effects are not independent, since increasing the global cumulative deployment is expected to be linked to an increase in global manufacturing capacity. Nevertheless, applying both concepts separately allows us to draw different insights into the drivers of lower production costs [17].

The strategies described above are for a general approach to reducing the cost of electrolyzers. Each technology has different characteristics, so to be more precise it will also be necessary to find key factors that allow the reduction of costs for the individual technologies.

For example, production automation, new electrode coating methods and increased production rates are perceived as key drivers for AEC cost reductions. On the cell-level, experts envision increased current densities up to 0.6 A $cm^{-2}$ through better mixed metal oxide catalysts and more stable electrodes and electrolytes for potential high temperature operation by 2030, and perhaps, more radically, a move to zero gap configurations.

For PEMEC, a significant capital cost reduction driver seems to be component standardisation, which, combined with production scale-up, enables the shift to high volume production methods like laser cutting, plastic injection moulding or 3D-printing. In addition, further increased current density (>3A $cm^{-2}$) is investigated through better electrode design, catalyst coatings and thinner membranes. In parallel, the reduction of catalyst loading and replacement of titanium in bipolar plates with high-conductivity coatings on low-cost substrates like steel would reduce capital costs. Finally, more operational experience would enable the de-risking of system design to optimise and combine system components for better system integration and operation at optimised set points.

For SOEC systems, capital cost reductions would be based on reducing the electrode polarisation resistance to enable lower operating temperatures (~450°C) that then allow the employment of lower cost component materials like stainless steel. Similar to PEMEC, increased field experience could allow leaner system engineering and improved system integration. The mentioned manufacturing (high volume methods, reduced overhead costs) and supply chain improvements (higher volumes, more suppliers) apply to SOEC systems as well [19].

## 2.2. Electrolyzers powered by RES

The generation of green hydrogen by electrolyzer (explained in the previous chapter), to be really defined as a green process, that is without polluting emissions and consumption of valuable natural resources, assumes that the electricity supplying the electrolyzer comes from renewable sources. Various research points up towards wind and solar energy for hydrogen production since these two RESs are considered the best-suited energy sources for hydrogen production [12].

### 2.2.1 Variability and intermittence of wind and photovoltaic

A key problem to be addressed is the intermittency and variability in the production of electricity by wind and photovoltaic plants. The production of electricity from renewable sources is highly dependent on weather conditions and this leads to fluctuations that cause instability of the power systems. Furthermore, energy security is generally ensured when supply and demand are balanced at all times, instead there is a limited time coincidence of the renewable resources with demands. As a consequence, systems for storing energy are becoming increasingly significant. Among the various solutions that are being evaluated, hydrogen is currently considered to be one of the key enabling technologies allowing future large scale and long term green storage of renewable power to be combined, for instance, with the well-established pumped hydro storage [24].

A fundamental measure to understand intermittent renewables such as photovoltaic and wind power is the capacity factor which is the ratio between the electricity actually produced in a given period of time and the nominal generation power of the plant.

The capacity factor can be expressed in hours or as a percentage of the time of the specific period considered necessary for the nominal power of the plant to provide the total energy actually produced. A plant with a capacity factor of 100% means that it produces energy at all times. Equivalent hours (usually one year) are also used to produce the total energy actually produced at nominal power.

The capacity factor varies widely from energy source and technology. In the case of renewables such as wind and photovoltaic, there is also the necessity to consider that the capacity factor depends from place to place based on variables such as windiness, irradiation and hours of light.

These variables mean that the production of energy from wind and photovoltaics show strong variations not only during the year, but also in the month, in the day and even in a single hour and with appreciable differences even in different years. The hourly variations of energy input into the Italian electricity grid by all connected wind or solar plants and relating to Terna's preliminary data for 2020 are shown below. Subsequently, data on wind plant of approximately 100 MW located in Southern Italy are reported. and a 12.5 MW photovoltaic plant in Sicily. This type of data from which relevant information can be derived is not always easy to find.

Total production of wind power was 18,550 TWh with a global capacity in operation of 10.75 GW on 1/01/2020 and 10.82 GW on 31/12/2020, and a capacity factor of 1,720 hours / year. There are over 2,000 hours with power below 10% of the total connected power and over 5,000 hours with power below 20%.

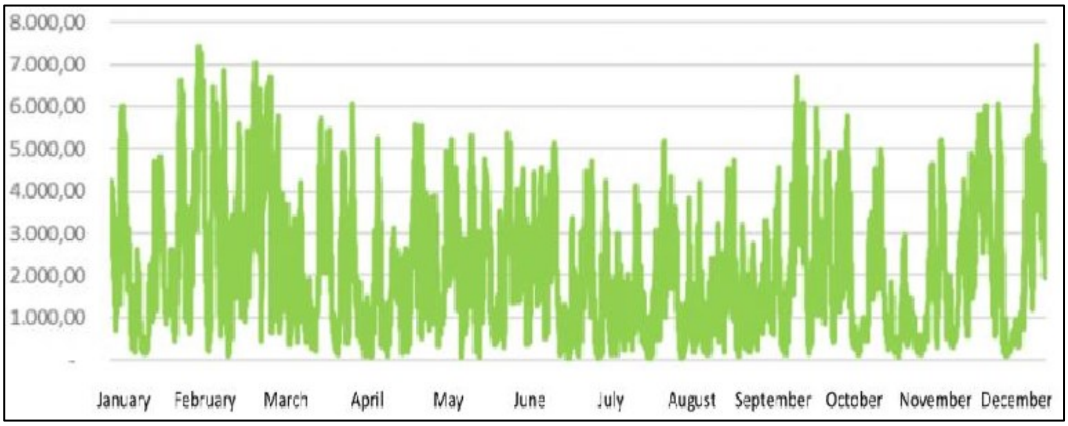


**Figure 8 - Annual variation of the power fed into the grid in MW by all connected Italian wind farms [25]**

As for solar, the total production was 25,550 TWh with a capacity in operation on 01/01/2020 of 20.85 GW and 21.2 GW on 31/12/2020 and a capacity factor of 1,215 hours / year. There are 4,500 hours in which no power has been fed into the grid.

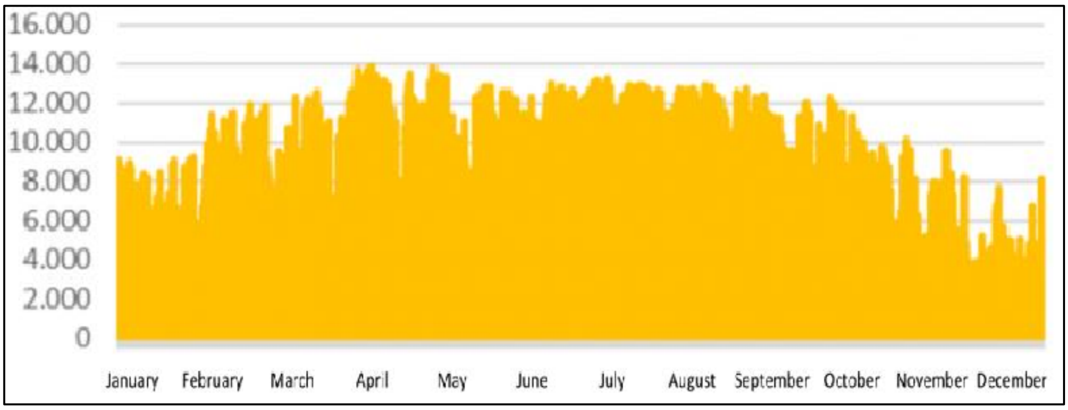


**Figure 9 - Total power fed into the grid by all connected photovoltaic systems [25]**

N.B.: The zero-power value during all nights is not visible from the diagram

An important analysis is to check whether it is possible to bridge the variability and intermittency of wind and photovoltaic by combining them. A simulation of the trend of the virtual combined power that can be produced by two adjacent 50 MW plants in March does not give totally positive results:

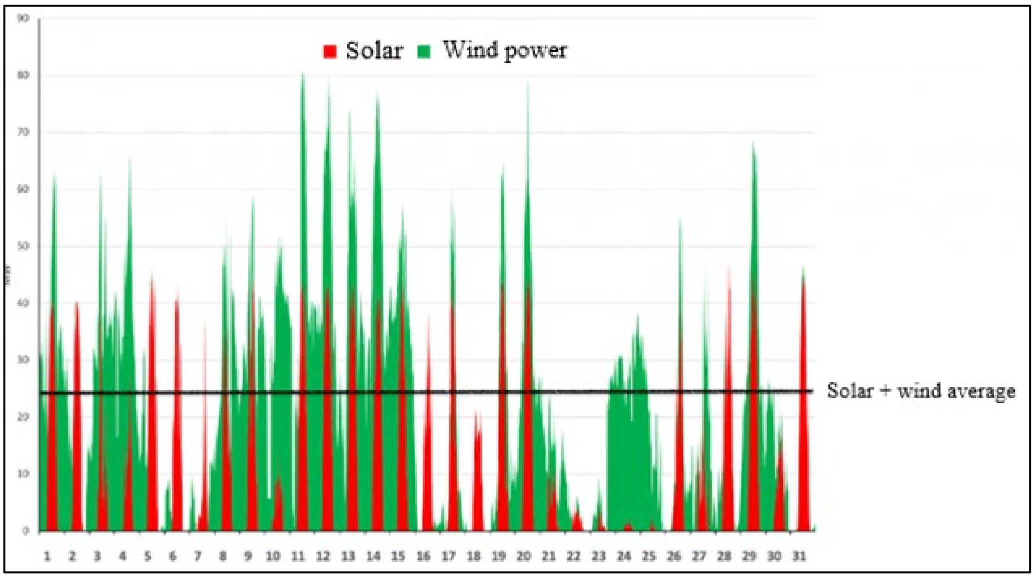


**Figure 10 - Trend of the virtual combined power that can be produced by two adjacent wind and photovoltaic plants, both of 50 MW in March [25].**

From this analysis it is clear that:

- the hours at zero power are reduced compared to a pure photovoltaic
- increases the capacity factor to about 2,100 hours, compared to 1,850 for wind power and 1,500 for photovoltaics
- but the variability is nevertheless considerable.

These technical observations are substantial in the debate on the prospects for the energy transition. The debate on hydrogen cannot ignore considerations on the relationship between electrolyzers and variable and intermittent production and the fundamental values that must be guaranteed for their efficient operation; furthermore, the actual technical and economic possibility of powering an electrolyzer from a dedicated wind or photovoltaic system in typical Italian conditions cannot be neglected [25].

Hydrogen may facilitate the large-scale integration of intermittent renewable electricity, offering solutions for both situations of electricity supply surplus and deficit: surplus electricity can be converted to hydrogen via water electrolysis, and re-electrification of hydrogen can be used to make up for deficit situations by enabling electricity time-shifts over extended timescales. Electrolysis may become an economically viable route for electricity storage in places with:

- electricity generation from intermittent renewables and surplus in the order of tens of TWhs over some 3000–4000 h annually,
- low electricity prices during a significant part of the year, and
- a favourable and sustained policy framework that also creates a market pull for clean hydrogen from sectors such as mobility or industry.

As a means of storing electricity, hydrogen competes with other flexibility measures to complement fluctuations in renewables, such as expanding interconnection capacity between electricity markets, demand management and various other storage options. To exploit its full potential, hydrogen must become an integral part of the energy system as a universal energy carrier alongside electricity [26].

### 2.2.2 Power supply mode of an electrolyzer system

There are basically two power options for producing "green" hydrogen:

- Electrolyzer connected to the existing electricity network. The necessary "green" electricity is purchased from the grid through power purchase agreements (PPAs).
- Electrolyzer powered by dedicated renewable plants such as wind and photovoltaic (and therefore disconnected from the grid).

The different implications of the two options are not irrelevant and contribute to defining the cost of hydrogen production [27][28].

About the first power mode, the amount of electricity consumed has to be equal to the amount of “green” electricity fed into the grid (i.e. from a balance sheet point of view 100% “green” electricity is used). Under these assumptions the electrolyzer can be operated with a constant supply of electricity resulting in a high utilization of the electrolyzer. The grid respectively the conventional and/or renewable power plants balance the fluctuations of the provided renewable “green” electricity. But under currently valid European legislation hydrogen from such a grid connected electrolyzer is not recognized as a renewable fuel; hydrogen counts as renewable if the conversion plant for “green” electricity and the electrolyzer are directly interconnected [27]. The disadvantage of this mode is the payment of transport cost and ancillary system services for renewable supplies estimated in Italy in some tens of €/MWh depending on the power and the amount of energy transported. This involves a higher electricity cost than the hypothesis of a dedicated renewable plant. However, the greatest benefit is precisely the possibility of overcoming the main criticality of the second power supply mode - an extremely variable electrical supply - thus maintaining the electrolyzer at a constant power supply without compromising its operation. As explained in the previous paragraph, wind and photovoltaic have the big limit of intermittence and variability. This problem affects the efficient use of the electrolyzer and its correct sizing. If the electrolysis plant is sized for the maximum summer power of the photovoltaic plant, there will be a maximum production of hydrogen in the year but a high investment for the electrolyzer and a load factor (equivalent to the capacity factor but for a plant that consumes energy) reduced per year. Conversely, if the electrolyzer system is sized for low winter power, the system will produce less hydrogen but will not use all the electricity available in the summer. A trade off only partially offset by a lower investment in the electrolyzer and a greater load factor [28].

To overcome the problem related to the fluctuation of electricity produced by RES, it is possible to apply an accumulation of electricity, for example batteries, to flatten the electricity supply (for example, electricity is stored if there is an overproduction while it is released if the electrolyzer capacity exceeds production). However, within certain limits, an electrolyzer can also operate with a fluctuating power supply [27].

An alternative solution to the previous problems addressed could be the combined use of both previously described power options and therefore the realization of an electrolyzer system powered by dedicated renewable plants and by an electricity grid. In periods with low production of electricity from RES, the electrolyzer is still guaranteed a constant level of electricity thanks to the grid. On the other hand, in periods in which there is an excess of electricity production by photovoltaic and wind power plants, the surplus of energy is not wasted but it is introduced into the grid through specific contracts.

If properly dimensioned, the electrolyzer system would make it possible to optimally exploit the wind and photovoltaic potential in their period of maximum electricity production.

Energy systems based on the production of hydrogen connected to renewable sources can thus become real enablers for different applications, for the storage of energy in the form of gas (power-to-gas), for storage and (re) conversion into energy through fuel cells or gas turbines (power-to-power), to cover requests such as heat (Power-to-Heat) or to cover requests such as fuel (Power-to-Fuel).
However, these facilities are currently associated with high costs, as they involve the installation of a complex multi-component system, with high investment costs and often with low demand for hydrogen at the end-user level [29][21][30].

# 3. Techno-economic analysis of different hydrogen production scenarios

In this third chapter, a techno-economic analysis of various hypothetical scenarios to produce green hydrogen from electrolysis is carried out. To perform this work, several scientific articles and reports from important international agencies such as the IEA (International Energy Agency) and IRENA (International Agency for Renewable Energy) were compared.

In all scenarios, the numerical values used take the Italian case as a reference, in particular Southern Italy.

Since this is a working hypothesis, it is not excluded that in the real production of hydrogen additional costs and parameters may emerge, but it can reasonably be considered that the parameters and costs identified are the most significant, also in light of the reference literature and which will be given information in the following.

## 3.1. Scenarios analyzed

The scenarios selected for this analysis are four and they are named as: scenario 1a, scenario 1b, scenario 2a and scenario 2b.

In each scenario, hydrogen is generated by means of an electrolyzer system based on alacaline technology (AEC) which, as explained in the previous chapter, is currently the most widespread and economical.

The substantial differences between these four scenarios concern to hydrogen production modes, continuity of production and final customers.

In the first scenario (1a) the alkaline electrolyzer is powered by electricity from a wind power plant, a photovoltaic system and, if necessary, from the national electricity grid. The energy from wind and photovoltaic fluctuates continuously during the year (for the reasons already set out in sub-paragraph 2.2.2) therefore in the periods in which these two plants produce less energy, the national electricity grid guarantees a constant power supply to the electrolyzer. In this mode it is possible to have a continuous production of hydrogen h24 7/7. Furthermore, a daily production of 192 kg of hydrogen is hypothesized, which are subsequently introduced into the national gas grid.

The second scenario (1b) is the only one of the four scenarios analyzed in which no connection to the national electricity grid is envisaged. In fact, the alkaline electrolyzer is powered by electricity produced only by wind and photovoltaic systems. Precisely for this reason, among the four scenarios it is the one that is most affected by the intermittency and variability of RES. Unlike the previous scenario, an on-demand production of 2400 kg of hydrogen per month is assumed to be sold to a fixed customer.

The third scenario (2a) and the fourth (2b) are more similar to each other than the previous two. In both, an electrolyzer powered by a wind power plant, a photovoltaic system and a national electricity grid is built. During the year, in particular every month, these three power sources guarantee the electrolyzer a fixed amount of electricity that allows it to produce 5200 kg of hydrogen per month and constantly to be fed into the national gas network. In some months of the year, the wind and photovoltaic systems produce electricity higher than the fixed quantity. This excess of electricity is used differently in the two scenarios. In scenario 2a the excess of electricity is used by the electrolyzer to produce hydrogen to be sold to a customer on-demand while in scenario 2b it is sold on the grid.

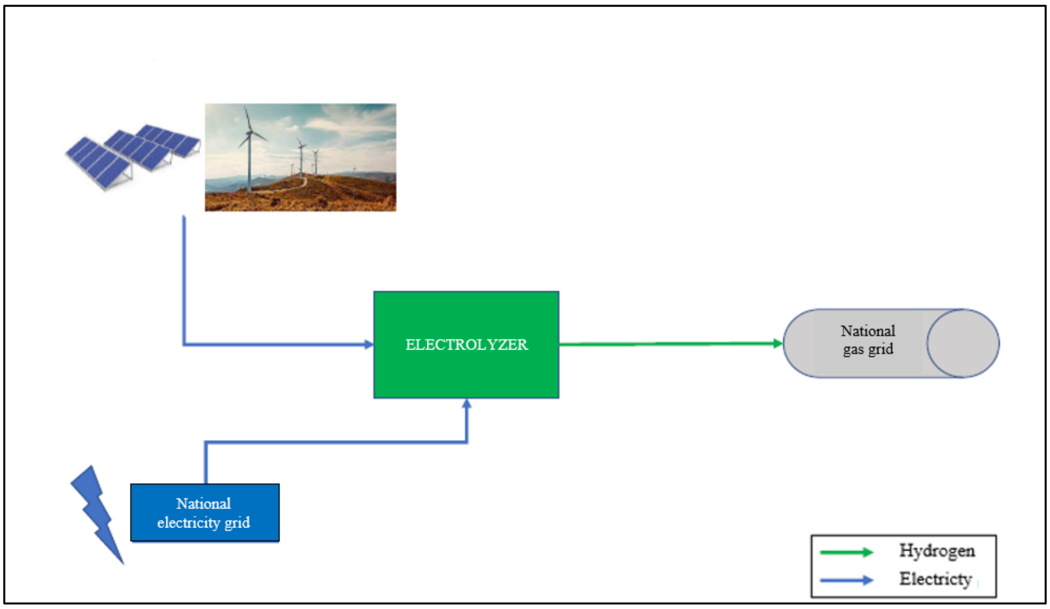


Figure 11 - Scenario 1a

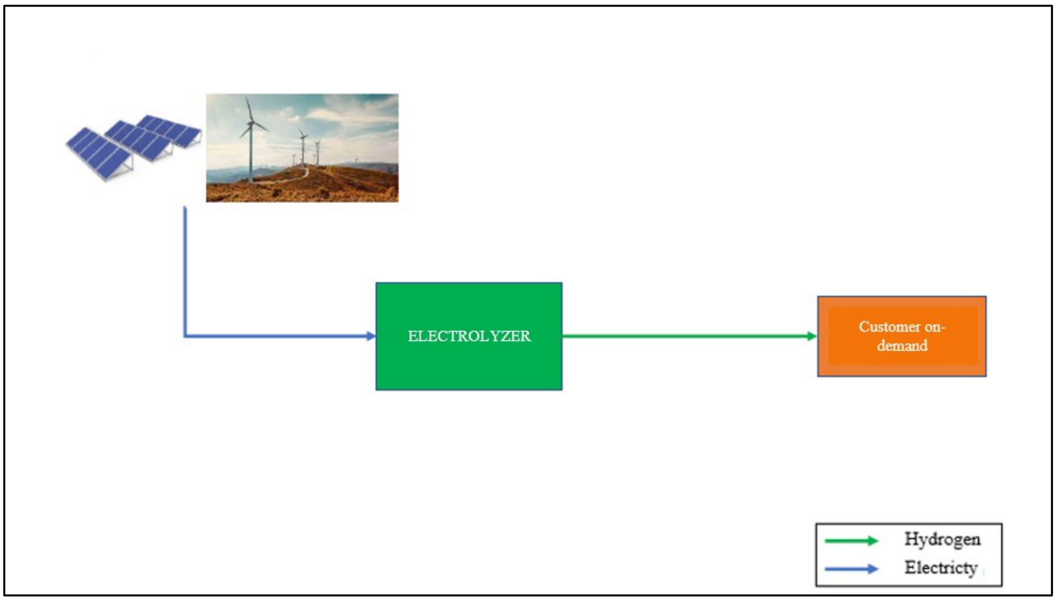


Figure 12 - Scenario 1b

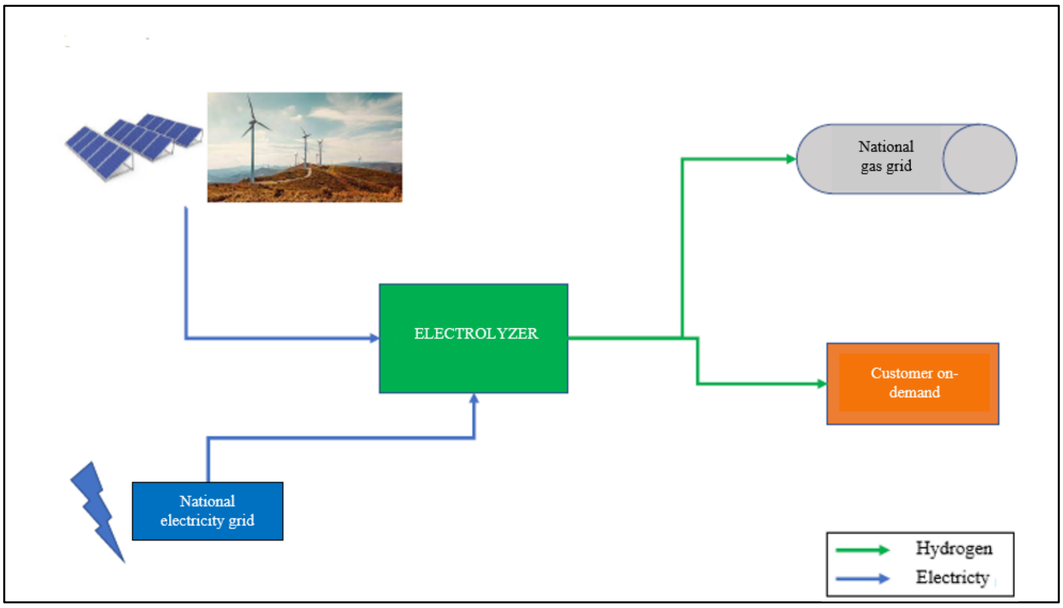


**Figure 13 - Scenario 2a**

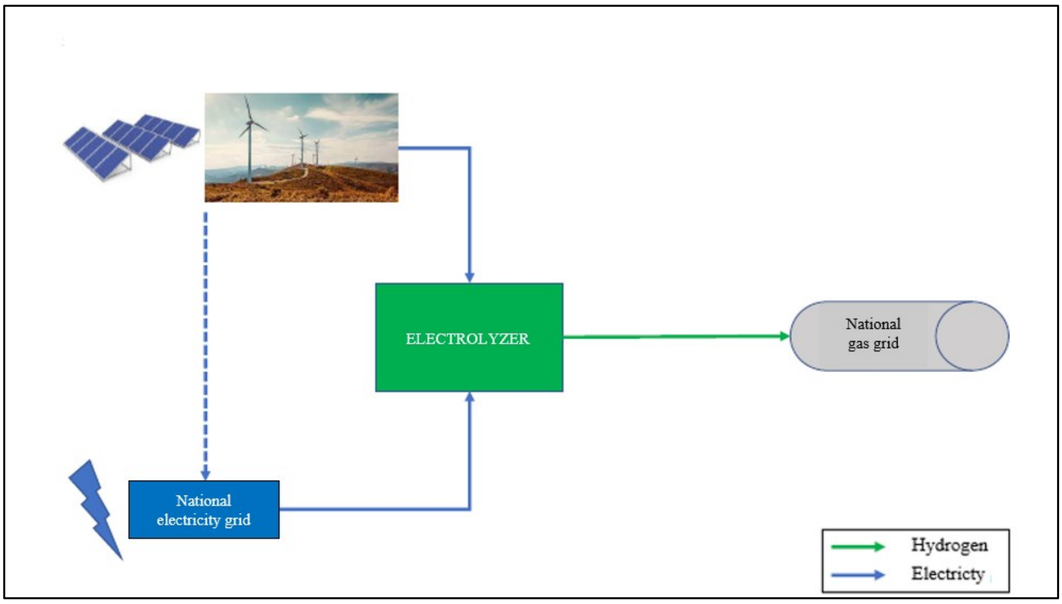


**Figure 14 - Scenario 2b**

Since the cost of hydrogen is the main factor that can favor the transition towards "hydrogen mobility", it is important to evaluate how this cost is influenced by the size, the technologies used as well as the energy management strategies related to its production [31].

## 3.2. Techno-economic parameters considered

After understanding the modalities of green hydrogen generation addressed in the literature, it was possible to carry out a detailed analysis of the scenarios previously described. In this analysis, various technical parameters were identified first and then economic ones.

With regard to technical analysis, the data research work was not easy as many of the analyzed data are closely linked to each other and some of these strongly depend on climatic conditions.

Furthermore, some of the data analyzed assume different values depending on the scenario considered. Therefore, to make this work more understandable to the reader, a scenario-by-scenario technical analysis is reported.

**SCENARIO 1a**

In this first scenario, the technical input parameters are as follows:

**Table 1**

| TECHNICAL PARAMETERS | UNIT | VALUE |
|---|---|---|
| Plant production capacity | kg/day | 200 |
| Hourly hydrogen production | kg/h | 8 |
| Daily hydrogen production | kg/day | 192 |
| Electrolyzer efficiency | % | 70 |
| Higher heating values of hydrogen | kWh/kg | 39,4 |
| Electrolyte rate [5] | kWh/kg | 56,3 |
| Water consumption [6] | l/kg | 11,2 |

- The maximum production capacity of the electrolyzer is 200 kg/day while the effective capacity is 192 kg/day. The latter value was calculated assuming a hydrogen production of 8 kg/hour continuously h24 7/7. Since the equivalent energy content of hydrogen is 39.4 kWh/kg, by assuming an efficiency of 70% for conventional alkaline electrolysis, the actual specific energy consumption is about 56.3 kWh/kg $H_2$. The water consumption of the electrolyzer is equal to 11.2 liters for each kg of hydrogen produced [21][31].

---

[5] Amount of electricity needed to convert water into hydrogen. At a mathematical level it is given by the ratio between the amount of electricity generated and the amount of hydrogen produced in the same period of time.

[6] Amount of water required for one kg of hydrogen.

The electrolyzer efficiency is related to the electrolytic rate by the following formulas [32]:

**Equation 1**

$$\frac{\text{Higher heating values of hydrogen}}{\text{Electrolyzer efficiency}} = \text{Electrolyte rate}\,.$$

From the parameters shown in table 1 it was possible to calculate the following electricity and water needs per year:

**Table 2**

| | UNIT | VALUE |
|---|---|---|
| Electricity used by the electrolyzer per year | kWh/year | 3945503 |
| Annual water need | l/year | 784896 |

It is assumed that during the year the lack of electricity from the photovoltaic system and the wind power plant are always compensated by the presence of the connection to the electricity grid and that the quantity of electricity used by the electrolyzer is suitably satisfied by the following *electricity mix* [7] :

**Table 3**

| ELECTRICITY MIX | UNIT | VALUE |
|---|---|---|
| Electricity produced by photovoltaic | kWh/year | 1577801,1 |
| Electricity produced by wind | kWh/year | 1972251,4 |
| Electricity purchased from the grid | kWh/year | 394550,3 |

---

[7] The share between the electricity supplied by the electricity grid and that supplied by the photovoltaic and wind power plant

- Wind energy has a higher RES share than to photovoltaic energy. The national grid provides the residual share, necessary for the electrolyzer system [29].

Once the electrical mix was defined, referring to the data reported in the selected articles [21][31][29][33], the following sizing of the electrolyzer, the photovoltaic system and the wind system was performed.

**Table 4**

| SIZES | UNIT | VALUE |
|---|---|---|
| Electrolyzer size | kW | 472 |
| Photovoltaic system size | kWp | 1214 |
| Wind power plant size | kWp | 935 |

**SCENARIO 1b**

In this second scenario, the technical input parameters are as follows:

**Table 5**

| TECHNICAL PARAMETERS | UNIT | VALUE |
|---|---|---|
| Plant production capacity | kg/day | 100 |
| Monthly hydrogen production | kg/month | 2400 |
| Electrolyzer efficiency | % | 70 |
| Higher heating values of hydrogen | kWh/kg | 39,4 |
| Electrolyte rate | kWh/kg | 56,3 |
| Water consumption | l/kg | 11,2 |

- Unlike the first scenario, the maximum production capacity of the electrolyzer is 100 kg of hydrogen per day. The effective electrolyzer capacity is considered on a monthly basis and it is equal to 2400 kg of hydrogen. This choice was made because the production plant is isolated from the national electricity grid, therefore - since the electrolyzer is powered exclusively by variable and intermittent electricity (produced by photovoltaic and wind) - it cannot be estimated per hour or daily production of hydrogen in a precise manner. Furthermore, considering that in this scenario it has opted for a production on demand that cannot be satisfied daily due to the technical problem described above, it was preferred to define a production on a monthly basis.

  As regards the remaining parameters indicated in the table, the same values of the first scenario were taken into consideration [21][31].

From the parameters shown in table 5 it was possible to calculate the needs for electricity and water per year:

**Table 6**

| | UNIT | VALUE |
|---|---|---|
| Electricity used by the electrolyzer per year | kWh/year | 1621029 |
| Annual water need | l/year | 322560 |

It is assumed that the amount of electricity used by the electrolyzer is suitably satisfied by the following electrical mix:

**Table 7**

| ELECTRICITY MIX | UNIT | VALUE |
|---|---|---|
| Electricity produced by photovoltaic | kWh/year | 698411 |
| Electricity produced by wind | kWh/year | 1022617 |

- ➢ Wind energy has a higher RES share than photovoltaic energy [29].
- ➢ To make this scenario more realistic, an excess production of 50,000 kWh/year of electricity for both wind and photovoltaics was also assumed. This excess is already included in the two values shown in the table. Excess electricity is produced whenever the power generation system produces more electricity than necessary. It is not possible to reduce excess electricity by decreasing the size of the power generation system because this will reduce the reliability of the electricity supply to a level below the load requirements of the electrolyzer [26].

Once the electrical mix was defined, referring to the data reported in the selected articles [21][31][29][33], the following sizing of the electrolyzer, the photovoltaic system and the wind system was performed.

**Table 8**

| SIZES | UNIT | VALUE |
|---|---|---|
| Electrolyzer size | kW | 236 |
| Photovoltaic system size | kWp | 538 |
| Wind power plant size | kWp | 485 |

**SCENARIO 2a**

In this third scenario, the technical input parameters are as follows:

**Table 9**

| TECHNICAL PARAMETERS | UNIT | VALUE |
|---|---|---|
| Plant production capacity | kg/day | 200 |
| Electrolyzer efficiency | % | 70 |
| Higher heating values of hydrogen | kWh/kg | 39,4 |
| Electrolyte rate | kWh/kg | 56,3 |
| Water consumption | l/kg | 11,2 |

- These parameters are the same as shown in table 1 of the input parameters of the first scenario, albeit in part [21][31].

Table 9 does not show the actual production capacity of the electrolyzer but it shows only the maximum capacity. In fact, for reasons that will be understood below, the determination of the effective capacity was preceded by the analysis of a hypothetical production of electricity.
This analysis hypothesis has been schematically represented in the following graph:

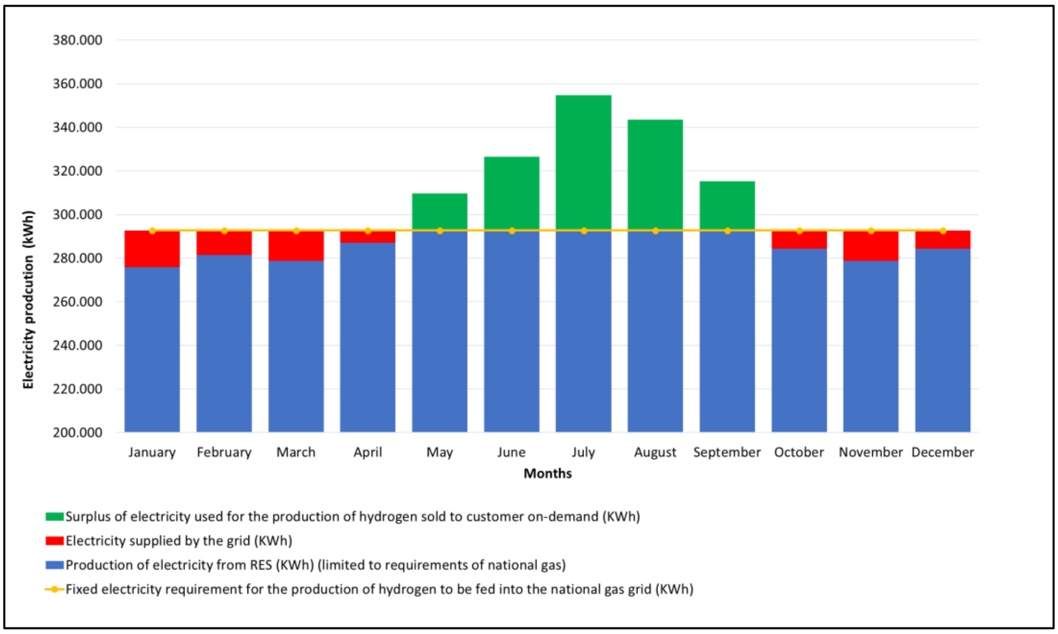


**Figure 15 - Analysis of a hypothetical production of electricity scenario 2a**

This graph represents the total amount of electricity used. The photovoltaic system, the wind power plant and the national electricity grid must guarantee the electrolyzer a certain fixed amount of electricity each month which is represented by the yellow line in the figure 15 and it is equal to 292760 kWh. This quantity, referring to the electrolytic rate reported in the table of input parameters, allows a monthly production of 5200 kg of hydrogen destined to be introduced into the national gas grid.

In some periods it occurs that the wind power plant and the photovoltaic system produce a quantity of electricity higher than the fixed quantity. This suprlus of electricity is used by the electrolyzer to produce hydrogen for a total of 3300 kg/year which will then be sold to a customer on demand.

In relation to the hypothesis of electricity production shown in the graph, it was possible to calculate the following needs for electricity and water per year:

**Table 10**

| | UNIT | VALUE |
|---|---|---|
| Electricity used by the electrolyzer per year | kWh/year | 3698910 |
| Annual water need | l/year | 736027 |

And on an annual basis, the following electrical mix was hypothesized:

**Table 11**

| ELECTRICITY MIX | UNIT | VALUE |
|---|---|---|
| Electricity produced by photovoltaic | KWh/year | 1448036 |
| Electricity produced by wind | KWh/year | 2172054 |
| Electricity purchased from the grid | KWh/year | 78820 |

Then, referring to the data reported in the selected articles [21][31][29][33], the following sizing of the electrolyzer, the photovoltaic system and the wind system was performed.

**Table 12**

| SIZES | UNIT | VALUE |
|---|---|---|
| Electrolyzer size | kW | 472 |
| Photovoltaic system size | kWp | 1114 |
| Wind power plant size | kWp | 1030 |

## SCENARIO 2b

In this fourth scenario, the technical input parameters are as follows:

**Table 13**

| TECHNICAL PARAMETERS | UNIT | VALUE |
|---|---|---|
| Plant production capacity | kg/day | 200 |
| Electrolyzer efficiency | % | 70 |
| Higher heating values of hydrogen | kWh/kg | 39,4 |
| Electrolyte rate | kWh/kg | 56,3 |
| Water consumption | l/Kg | 11,2 |

- These parameters are the same as in the table 9 [21][31].

Also in this scenario, the determination of the effective capacity was preceded by the analysis of a hypothesis of electricity production:

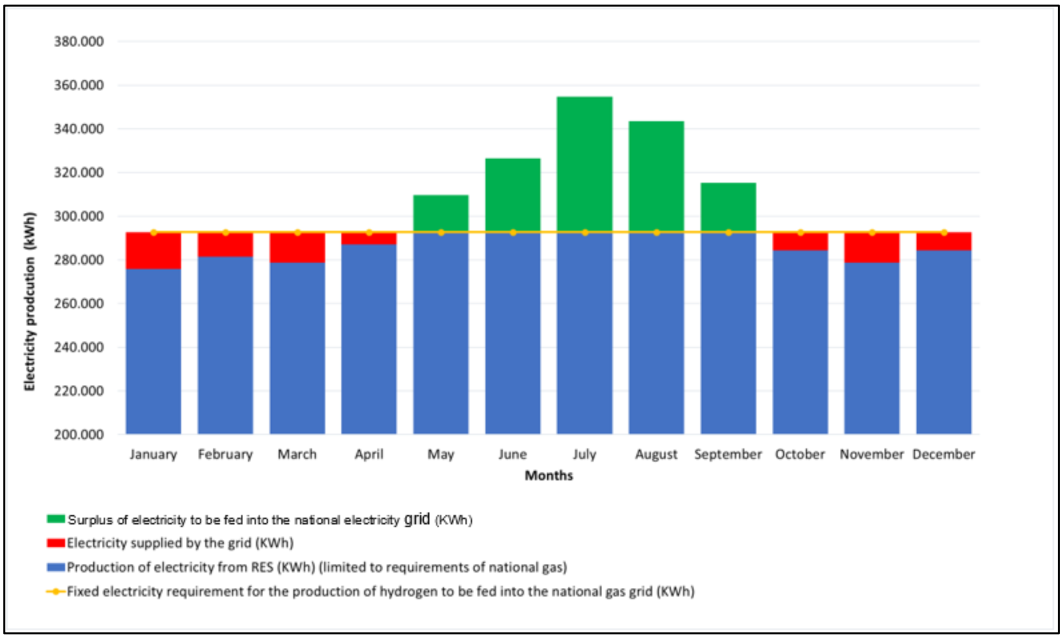


**Figure 16 - Analysis of a hypothetical production of electricity scenario 2b**

The quantities of electricity represented in this graph are the same as in the third scenario, the difference, albeit subtle, only concerns the description of the green color in the legend. In fact, in this scenario the surplus electricity produced from May to September, unlike the other scenario, it is not used to produce hydrogen but it is destined to be fed into the national electricity grid for a total of 185790 kWh / year (by means of special contracts).

In relation to the hypothesis of electricity production shown in the graph, it was possible to calculate the following needs for electricity and water per year:

**Table 14**

| | UNIT | VALUE |
|---|---|---|
| Electricity used by the electrolyzer per year | kWh/year | 3513120 |
| Annual water need | l/year | 699057 |

And on an annual basis, the following electrical mix was hypothesized:

**Table 15**

| ELECTRICITY MIX | UNIT | VALUE |
|---|---|---|
| Electricity produced by photovoltaic | KWh/year | 1448036 |
| Electricity produced by wind | KWh/year | 2172054 |
| Electricity purchased from the grid | KWh/year | 78820 |

Then, referring to the data reported in the selected articles [21][31][29][33], the following sizing of the electrolyzer, the photovoltaic system and the wind system was performed.

**Table 16**

| SIZES | UNIT | VALUE |
|---|---|---|
| Electrolyzer size | kW | 472 |
| Photovoltaic system size | kWp | 1114 |
| Wind power plant size | kWp | 1030 |

Once the technical analysis was completed, it moved on to an economic analysis in which it tried to best identify all the costs and various factors that affect the overall cost of producing green hydrogen.

In order of research, the cost factors selected are capital expenses, operating expenses, costs related to water consumption, purchase electricity costs and also pre-investment costs.

The CApital EXpenditure (CAPEX) and the OPerational EXpenditure (OPEX) respectively represent the initial investment costs and the future operating costs of the plants to be built. Consequently, assuming the realization of the previously described scenarios, there are CAPEX and OPEX for both the electrolyzer, the photovoltaic system and the wind system. The CAPEX of the electrolyzer was considered equal to 1100 €/kw, that of photovoltaics at 950 €/kw and that of wind power at 1500 €/kw [31][33][27].

On the other hand, as regards the OPEX of the electrolyzer, photovoltaic and wind power, the following values were taken respectively: 1.58% of the CAPEX of the electrolyzer, 2% of the CAPEX of the photovoltaic and 2.5% of the CAPEX of the wind power.

For the assessment of the cost (calculated as operating costs) due to the consumption of water, tariffs defined by the Italian Society ABC (based in Naples) were considered. Based on these data, this cost consists of a fixed annual cost (€/year) and a variable cost based on water consumption (€/$m^3$). The first term is equal to 18.12 €/year, the second term is equal to 1,006 € for each cubic meter of water consumed ($m^3$). In some scenarios, a fixed tariff of 129 € / MWh must be considered for the consumption of electricity purchased from the national electricity grid and / or a revenue relating to the excess energy produced to be fed into the grid equal to 50 €/MWh [31].

The preliminary investment costs such as choice of location, obtaining various permits, land purchase, feasibility studies and preliminary engineering of the plant, etc. they were assumed equal to 15% of the CAPEX (optimistic for many Italian situations, especially for plants that are not huge).

**Table 17**

| ECONOMIC PARAMETRS | UNIT | VALUE |
|---|---|---|
| Electrolyzer CAPEX | €/kW | 1100 |
| Photovoltaic CAPEX | €/kW | 950 |
| Wind power plant CAPEX | €/kW | 1500 |
| Electrolyzer OPEX | % CAPEX electrolyzer | 1,58 |
| Photovoltaic OPEX | % CAPEX photovoltaic | 2 |
| wind power plant OPEX | % CAPEX wind power plant | 2,5 |
| Fixed annual water cost | €/year | 18,12 |
| Variable cost of water | €/$m^3$ | 1,006 |
| Cost of electricity purchased from the grid | €/MWh | 129 |
| Revenues from electricity fed into the grid | €/MWh | 50 |
| Preliminary costs for the investment of the plant | % CAPEX electrolyzer | 15 |

All the data illustrated in this chapter have been entered in Excel and suitably linked together by means of mathematical operations.

## 3.3. Results

The work done in the previous paragraphs made it possible to carry out a global cost analysis in each scenario. Furthermore, to make the analysis more interesting, the levelised cost of hydrogen (LCOH) was calculated, which is the most important indicator among the economic evaluation indices.

LCOH is the average minimum price at which the green hydrogen generated by the electrolyzer must be sold to offset the total production costs over its lifetime. The calculation of the LCOH allows to evaluate the overall economic performance of the hypothesized plant configurations and therefore the one that corresponds to the lowest cost of hydrogen production during its life. From this definition it is evident that the lower the cost price of hydrogen from a given renewable source, the greater the leeway to enter the market competitively.

In this work the levelised cost of hydrogen was calculated as follows:

**Equation 2**

$$LCOH = \frac{\sum_{t=0}^{n} \frac{(Total\ Cost\ (€) - Electrical\ Revenue\ (€))_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{(H_2\ Annual\ Production\ (kg))_t}{(1+r)^t}}$$

Where n is the number of operating years considered equal to 20 years and r is the discount rate set at 8%.

This LCOH calculation does not include additional factors that are specific to the region and application, such as storage, compression and transmission costs, which are required if the hydrogen is not self-consumed [35][31][36][37][32][1].

## SCENARIO 1a

**Table 18**

| **Year** | **0** | **1, 2, …, 20** |
|---|---|---|
| Preliminary costs for the investment of the plant - € | 77880 | |
| Electrolyzer CAPEX - € | 519200 | |
| Photovoltaic investment CAPEX - € | 1153300 | |
| Wind power plant CAPEX - € | 1402500 | |
| Electrolyzer OPEX - € | | 8203,4 |
| Photovoltaic OPEX - € | | 23085 |
| Wind power plant OPEX - € | | 35062,5 |
| Cost of electricity purchased from the grid - € | | 50884,1 |
| Water expenses - € | | 807,7 |
| Revenues from electricity fed into the grid - € | | -- |
| Total - € | 3152880 | 118024,6 |
| Quantity of hydrogen produced - Kg | | 70080 |

LCOH = 6,27 € / kg

## SCENARIO 1b

**Table 19**

| **Year** | **0** | **1, 2, …, 20** |
|---|---|---|
| Preliminary costs for the investment of the plant - € | 38940 | |
| Electrolyzer CAPEX - € | 259600 | |
| Photovoltaic investment CAPEX - € | 511100 | |
| Wind power plant CAPEX - € | 727500 | |
| Electrolyzer OPEX - € | | 4101,68 |
| Photovoltaic OPEX - € | | 10222 |
| Wind power plant OPEX - € | | 18187,5 |
| Cost of electricity purchased from the grid - € | | -- |
| Water expenses - € | | 342,6 |
| Revenues from electricity fed into the grid - € | | -- |
| Total - € | 1537140 | 32853,8 |
| Quantity of hydrogen produced - Kg | | 28800 |

LCOH = 6,58 € / kg

## SCENARIO 2a

**Table 20**

| **Year** | **0** | **1, 2, …, 20** |
|---|---|---|
| Preliminary costs for the investment of the plant - € | 77880 | |
| Electrolyzer CAPEX - € | 519200 | |
| Photovoltaic investment CAPEX - € | 1058300 | |
| Wind power plant CAPEX - € | 1545000 | |
| Electrolyzer OPEX - € | | 8203,4 |
| Photovoltaic OPEX - € | | 21166 |
| Wind power plant OPEX - € | | 38625 |
| Cost of electricity purchased from the grid - € | | 10167,8 |
| Water expenses - € | | 758,6 |
| Revenues from electricity fed into the grid - € | | -- |
| Total - € | 3200380 | 78920,7 |
| Quantity of hydrogen produced - Kg | | 65716,7 |

LCOH = 6,16 € / kg

## SCENARIO 2b

**Table 21**

| Year | 0 | 1, 2, …, 20 |
|---|---|---|
| Preliminary costs for the investment of the plant - € | 77880 | |
| Electrolyzer CAPEX - € | 519200 | |
| Photovoltaic investment CAPEX - € | 1058300 | |
| Wind power plant CAPEX - € | 1545000 | |
| Electrolyzer OPEX - € | | 8203,4 |
| Photovoltaic OPEX - € | | 21166 |
| Wind power plant OPEX - € | | 38625 |
| Cost of electricity purchased from the grid - € | | 10167,8 |
| Water expenses - € | | 721,4 |
| Revenues from electricity fed into the grid - € | | 9289,5 |
| Total - € | 3200380 | 67160,33 |
| Quantity of hydrogen produced - Kg | | 62415,8 |

LCOH = 6,34 € / kg

## 3.4. Discussion

From an economic point of view, by setting the technology used, the main design parameters that affect the total costs of the plant are the hydrogen production capacity and the electrical mix. In fact, the hydrogen production capacity directly determines the size of the hydrogen production plant and the demand for electricity, while the electricity mix defines the size of the photovoltaic system.

Analyzing the previous results, it is noted that the levelised cost of hydrogen assumes values between 6.58 and 6.16 €/kg. The scenario with the highest LCOH is scenario 1b while the one with the lowest LCOH is scenario 2a.

The most interesting comparisons are those between sceraio 1a and 1b, and those between scenario 2a and 2b.

In fact, the first comparison shows that the connection of the electrolyzer to the national electricity grid brings an advantage to the plant in economic terms compared to a plant isolated from the grid. However, this does not in itself prove that the stand-alone configuration can ever cost less than connecting to the network. The optimal configuration for each situation will depend on the specific circumstances of that case. In fact, even if it is not economically convenient in the cases addressed, the stand-alone operating modes can be an advantageous solution to allow the installation of large plants in remote locations that do not have a connection to the high-power grid and which would therefore require investments too high to build a new grid.

In the second comparison, it is interesting to note that, following the assumptions made, scenario 2a is economically advantageous compared to scenario 2b. From this it can deduce that in circumstances similar to those described, converting excess electricity into hydrogen for sale it is a more advantageous option than that of feeding the same energy into the grid. Mathematically, this economic advantage is strongly influenced by the selling price of the electricity chosen (50 €/MWh). An increase in this value, of course, involves a lowering of the LCOH in the fourth scenario while in the others it remains unchanged (not having the sale of excess electricity on the grid).

LCOH is influenced not only by the capital costs of the plant to be built and the costs related to its management, but also by the use of the electrolyzer and its efficiency.

The high utilization of the electrolyzer reduces the specific share of the electrolyzer's capital cost in the hydrogen production costs; on the other hand, greater use increases the need for electricity and therefore higher costs related to the realization/management of the photovoltaic system and the wind power plant, and increases in costs for electricity purchased from the grid. Therefore, in order to minimize hydrogen costs, the use of the electrolyzer must be balanced with the size of the wind power plant, the photovoltaic system and the price of electricity.

An improvement in efficiency, on the other hand, results in greater hydrogen production per year without particular variations in costs, and therefore a reduction in LCOH.

As already written previously, all the data of this analysis work were opportunely inserted in Excel and linked together, so it was possible to show how variations in the efficiency of the electrolyzer lead to variations in the LCOH:

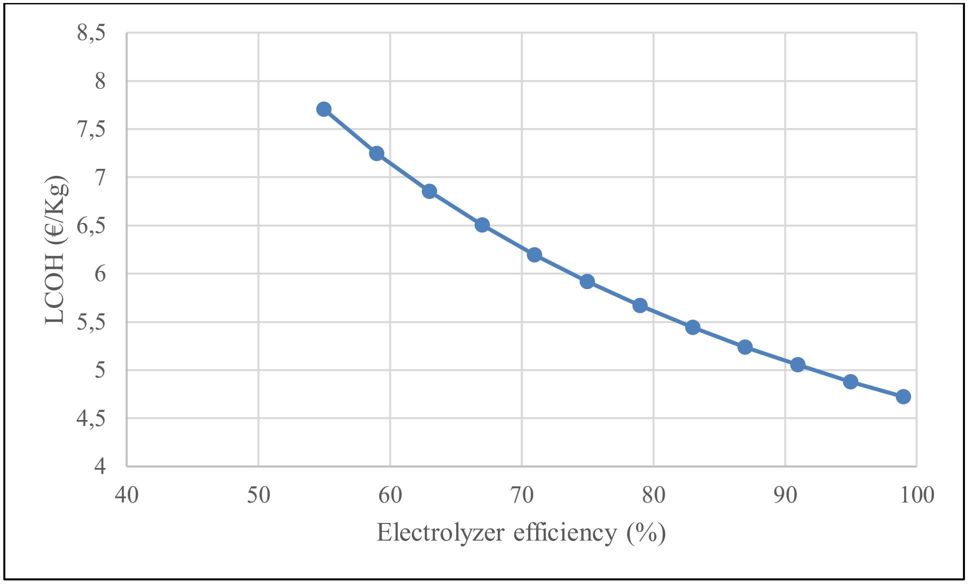


Figure 17 - Scenario 1a

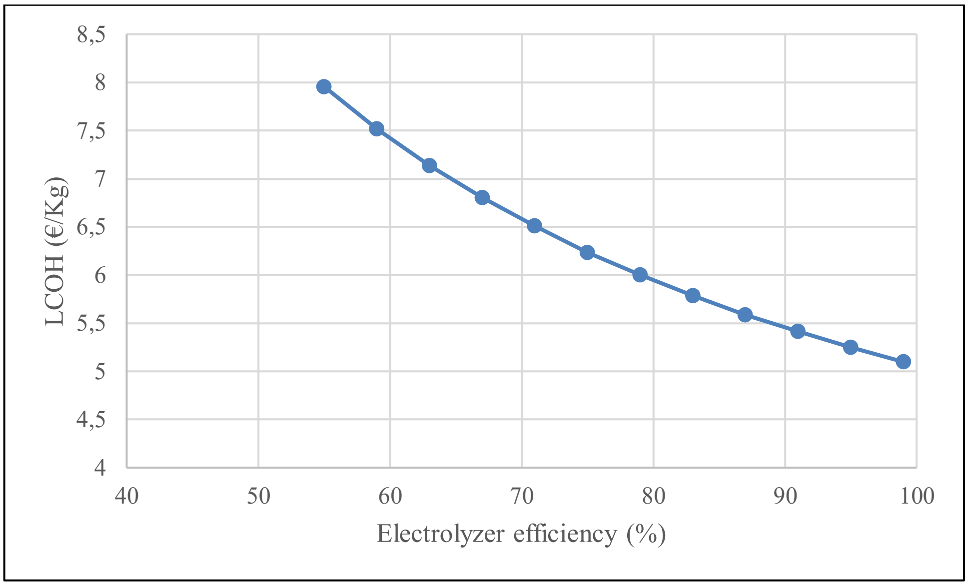


Figure 18 - Scenario 1b

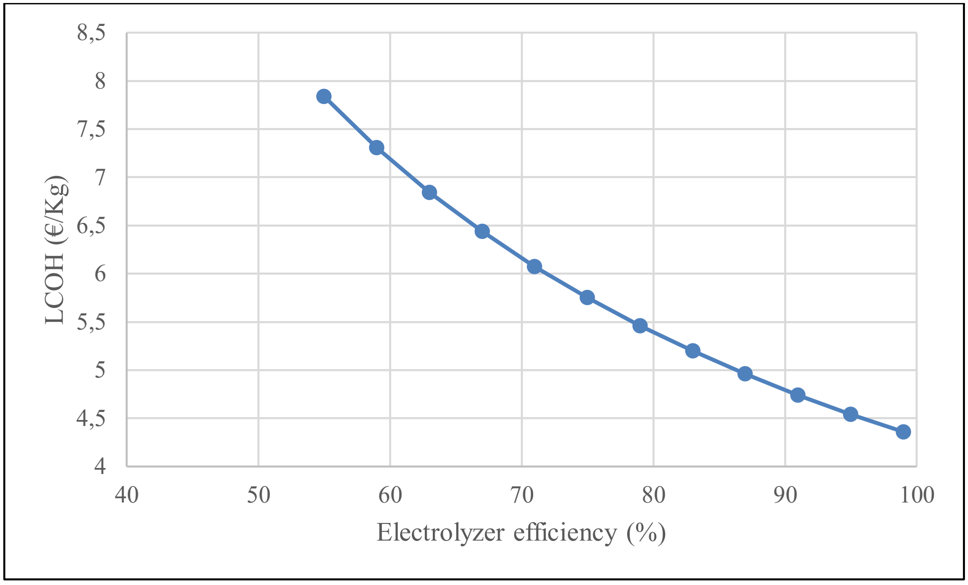


**Figure 19 - Scenario 2a**

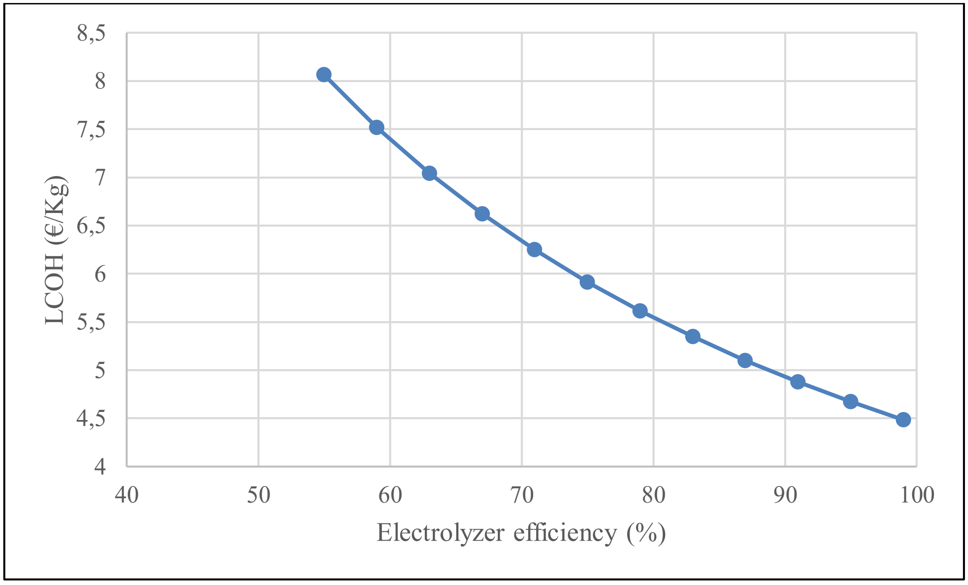


**Figure 20 - Scenario 2b**

As such, this is a key area for research to improve not only with alkaline electrolysis, but also with PEM and high temperature electrolysis, which can have higher theoretical efficiencies, albeit with higher CAPEX.

# Conclusion

Hydrogen plays an important role in the Italian energy transition as well as in other parts of the world. Many associations and various governments, including the Italian one, are increasingly striving to promote the concept of the hydrogen economy at all levels of society. The financial, social and political effort will be considerable but it will certainly be worth it.

Companies are geared towards a future where renewables are a dominant figure in the energy sector, energy storage and its use are becoming key factors in reaching the next step. It has become obvious that without incorporating hydrogen technology into energy transition strategies, there will not be enough potential to fully immerse ourselves in a zero-emissions future. The advancement and development of hydrogen technology is already at a satisfactory level for its full involvement in national strategies. Currently, the number of research and development projects underway is a record, with estimates forecast to increase even more rapidly in the near future.

As explained in the initial part of this work, the hydrogen to which more attention must be paid is that obtained by the electrolysis of water using renewable energy, especially in an international context of decarbonization aimed at building a carbon-neutral society.

At present, the main obstacle is the financial aspect where the key role in R & D remains in reducing production costs. However, even if the economic aspect of this technology achieves excellent results, this may probably not be enough. The main challenges are not only costs and the efficiency of the plants, but society and users must also be prepared for the presence of hydrogen in normal application and life. According to the strategies and forecasts of several governments, hydrogen-based systems and applications could, in a relatively short time, significantly expand their presence in the market, from the occasional cutting-edge technologies of the future to everyday events.

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