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Review

Green Hydrogen Value Chain: Modelling of a PV Power Plant Integrated with H_2 Production for Industry Application

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Abstract: Based on the Sustainable Development Goals outlined in the 2030 agenda of the United Nations, affordable and clean energy is one of the most relevant goals to achieve the decarbonization targets and break down the global climate change effects. The use of renewable energy sources, namely, solar energy, is gaining attention and market share due to reductions in investment costs. Nevertheless, it is important to overcome the energy storage problems, mostly in industrial applications. The integration of photovoltaic power plants with hydrogen production and its storage for further conversion to usable electricity are an interesting option from both the technical and economic points of view. The main objective of this study is to analyse the potential for green hydrogen production and storage through PV production, based on technical data and operational considerations. We also present a conceptual model and the configuration of a PV power plant integrated with hydrogen production for industry supply. The proposed power plant configuration identifies different pathways to improve energy use: supply an industrial facility, supply the hydrogen production and storage unit, sell the energy surplus to the electrical grid and provide energy to a backup battery. One of the greatest challenges for the proposed model is the component sizing and water electrolysis process for hydrogen production due to the operational requirements and the technology costs.

Keywords: renewable energy; photovoltaic; green hydrogen production; value chain; energy storage; conceptual modelling; system sizing; water electrolysis

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1. Introduction

Energy is, nowadays, one of the most discussed topics due to its impact on economies worldwide. The energy demand will constantly increase to suppress the requirements of buildings, the industrial sector and mobility/transportation. The anticipated energy consumption by 2050 is projected to reach 500 EJ, indicating a notable increase of 13%, when compared to the energy consumption levels reported in 2022 [1].

According to the International Energy Agency (IEA), the final energy consumption in 2019, worldwide, was 418 EJ, and 66.3% of the total energy resources were directly obtained from fossil fuels. Furthermore, fossil fuel power plants accounted for 62% of the electricity consumed (82.3 EJ) [2]. Additionally, non-renewable fuel sources accounted for 85.9% of the world's energy supply. Regarding the industry sector, it is anticipated that the heat demand will increase by 1.7% annually until 2030 [3]. Thus, alternative and renewable energy options should be explored to reduce the use of fossil fuels and the consequent Greenhouse Gas (GHG) emissions. In addition to its impacts associated with climate change, GHG has an impact on human health [4]. Around the world, several regions register an average value of PM2.5 concentrations higher than recommended levels, and approximately 85% of the global population lives in those areas, which makes air pollution the fourth-leading cause of human life degradation [5]. Based on these facts and forecasts, most governmental and nongovernmental organizations around the world have promoted preventive measures and policies intending to reduce GHG emissions [6].

Following the concerns about climate change, 17 global Sustainable Development Goals (SDGs) were developed by the United Nations General Assembly. Goal 7 aims to ensure access to reliable, sustainable and clean energy for all. To achieve this, it is necessary to explore alternative, sustainable and environmentally friendly fuels, as well as to intensify the development and use of renewable energies. Goal 13 aims for countries to outline and implement power plans to reduce GHG emissions [7]. The Conference of the Parties (COP) is one of the primary recurring assemblies that specifically addresses these environmental issues. These meetings bring together countries that are signatories to the United Nations Framework Convention on Climate Change (UNFCCC). For instance, in 2015, during COP21, one of the most significant milestones in decarbonization was signed by 181 parties, the Paris Agreement [8]. Its purpose was to ensure that the global average temperature increase should be below 1.5 °C when compared to pre-industrial levels [9,10]. Since then, several measures have been defined to stay on track to accomplish the aforementioned agreement [11].

According to the Hydrogen Roadmap report, Europe aims to eliminate approximately 2800 Mton of carbon dioxide (CO_2) emissions by 2050 [12]. Around 60% of these emissions reductions is expected to come from the implementation of the Paris Agreement and energy efficiency measurements. However, additional efforts beyond the existing plans are required to address the remaining 1100 Mton of CO_2 emissions.

Furthermore, in 2020, the European Union designed a trajectory to follow in its battle against climate change. This is known as the "European Green Deal" [13], a sustainable investment plan worth EUR one trillion, focused on climate change mitigation and economic growth, combined with the sustainable management of energy resources. For this purpose, the European Commission has enhanced the environmental targets ambition for 2030, formulating climate, energy, transport and taxation policies that are suitable for achieving a reduction in net GHG emissions by at least 55% by 2030 [14]. In other words, there has been continuous investment to apply renewable energies, increasing energy efficiency, promoting decarbonization and achieving a reduction in fossil fuel consumption. With the "European Green Deal", European member states positioned themselves as extremely committed to decarbonization [7,15].

However, according to the Sustainable Development Goals Report [7], the current national undertakings made by countries are not enough to achieve the target of limiting global warming to 1.5 °C. Additionally, it highlights that if countries only adhere to their existing commitments, GHG emissions are projected to increase by nearly 14% in the next decade. To counteract this trend, it is imperative that new solutions emerge to reduce the dependency on fossil fuels [10].

In line with the "European Green Deal" [13], the shift towards achieving climate neutrality will not evolve only from renewable energies. Innovative technologies and infrastructure, including Carbon Capture, Utilization and Storage (CCUS), energy storage, smart grids, fuel cells and alternative fuels like hydrogen, are necessary for achieving the goals of decarbonization.

Renewable energy integration has been seen as a pillar of decarbonization. Solar and wind power are often characterized as intermittent renewable energy sources because their availability fluctuates based on natural factors such as weather patterns and seasonal variations. Unlike fossil fuels, which can provide constant power output when needed, renewable energy generation is subject to variability and unpredictability. Energy storage technologies, such as batteries, pumped hydro storage and thermal storage, play a crucial role in mitigating the intermittency of renewable energy sources by storing excess energy during periods of high generation and releasing it when needed during periods of low generation. Advances in energy storage technology are essential for maximizing the effectiveness and reliability of renewable energy integration [16,17].

In addition to these issues related to energy production, it is imperative to improve the integration of renewable energy plants with existing power planning systems. The fluctuations in renewable energy production not only require measures such as energy storage but also real-time measurements to balance supply and demand through flexible generation sources. This integration will enable solar, hydro and wind power to become grid-friendly, making it possible to achieve peak shaving. In other words, renewable power plants require the implementation of daily and seasonal balancing strategies [18]. This balance involves storing the surplus energy generated by renewable sources and using it when renewable sources alone are insufficient to meet the grid demand.

One of the solutions proposed is based on hydrogen. This type of system consists of storing clean energy so that intermittent production can be transformed into chemical energy and not be wasted [12,19]. Hydrogen can work as an energy storage medium from daily to seasonal periods. Subsequently, it can be converted into electricity or used as fuel for several applications, including vehicular mobility, supply heat demand and supporting industrial processes. This idea can be widely discussed since there are more efficient alternatives, such as batteries, but both hydrogen and batteries have their advantages and limitations as storage options for specific contexts. Generally, batteries have higher efficiency compared to hydrogen storage systems, because the process of converting electricity to hydrogen (electrolysis) and back again (fuel cells) involves energy losses at each step, whereas batteries store and release energy directly without intermediate conversion processes. However, for seasonal storage, hydrogen can represent a great option. While batteries are well suited for applications that require relatively small amounts of energy and where energy density by volume is important, hydrogen can be applied when large amounts of energy storage are required and for decentralized use, even with lower overall efficiencies of the PV–hydrogen–electricity conversion process. Examples include the long-range transportation of pressurized gas (e.g., trucks, ships) to supply fuelling stations and stationary power generation (e.g., backup power for remote areas and industrial processes) [20].

The decrease in solar and wind investment costs has amplified the possibility of incorporating hydrogen into the energy mix. For instance, in 2023, the photovoltaic (PV) capital costs are 75% lower than in 2010, which translates as a possible alternative to achieve cheaper electrolytic hydrogen production. This is a crucial factor in the energy transition and towards the hydrogen integration as a strategic vector [12]. Thus, the production of hydrogen through renewable power plants will allow us to use it as a storage method, being projected to reach a capacity of 2000 TWh by 2050. This will provide flexibility for the increased implementation of renewable energies, such as solar PV. Furthermore, it is expected that hydrogen and its byproducts, such as ammonia and methanol, will play a significant role in the overall final energy consumption, accounting for a share of approximately 12% by 2050. Consequently, nearly 30% of electricity consumption will be applied to the production of green hydrogen.

The main objective of this study is to analyse the potential for green hydrogen production and storage through PV production, based on technical data and operational considerations. The green hydrogen supply chain is also analysed, taking into account the production, transportation, storage, distribution and applications. Thus, we will identify and model all the components and systems of the installation. Regarding the hydrogen production, the research is focused on water electrolysis.

Section 2 presents and discusses the hydrogen supply chain, taking into consideration the centralized and decentralized production of hydrogen. The hydrogen supply chain can be divided into production, transportation, storage, distribution and application. In the Section 3, technical and economic data are discussed regarding the components' characterization from a PV power plant integrated with hydrogen production for industrial application. Finally, in the Section 4, the discussion and main conclusions from the research are presented.

2. Green Hydrogen Value Chain

There is huge pressure from the prevailing policies to change the energetic matrix by replacing non-renewable fuels with green power and achieving near- or even net-zero end-use emissions by 2050. One of the key paths is based on hydrogen as an energy carrier, which is becoming more and more attractive due to current pollution concerns [4]. The significant integration of renewable energy sources is leading to a substantial level of electricity curtailment, primarily resulting from a seasonal mismatch in electricity supply, particularly in large-scale systems [21]. Hence, by 2050, one of the most significant technical challenges in attaining carbon neutrality will be large-scale energy storage [22]. It appears to be a promising option for mitigating the seasonal electricity instability in the power system [22]. Hydrogen can enhance the power sector with the integration of renewable technologies through storage and later use [23]. The main goal of incorporating hydrogen into the energy system, especially in the electricity distribution network, is to improve the network stability by minimizing the energy loss factor [24].

The hydrogen supply chain can be divided into production, transportation, storage, distribution and application [23]. Regarding hydrogen production, there are a wide variety of methods for its production.

When it comes to hydrogen production, it can be achieved through a wide variety of feedstocks, specifically classified into two broad categories: fossil fuel-based, such as coal and hydrocarbons, and renewable energies [25]. In agreement with [26], in 2020, 96% of generated hydrogen used fossil fuels as feedstock: 48% originated from natural gas, 30% from heavy oils and naphtha and 18% from coal. The remaining 4% of hydrogen production was attributed to renewable energy sources, encompassing biomass, water and electricity derived from renewable power plants. In Figure 1, the general hydrogen production strategies are represented.

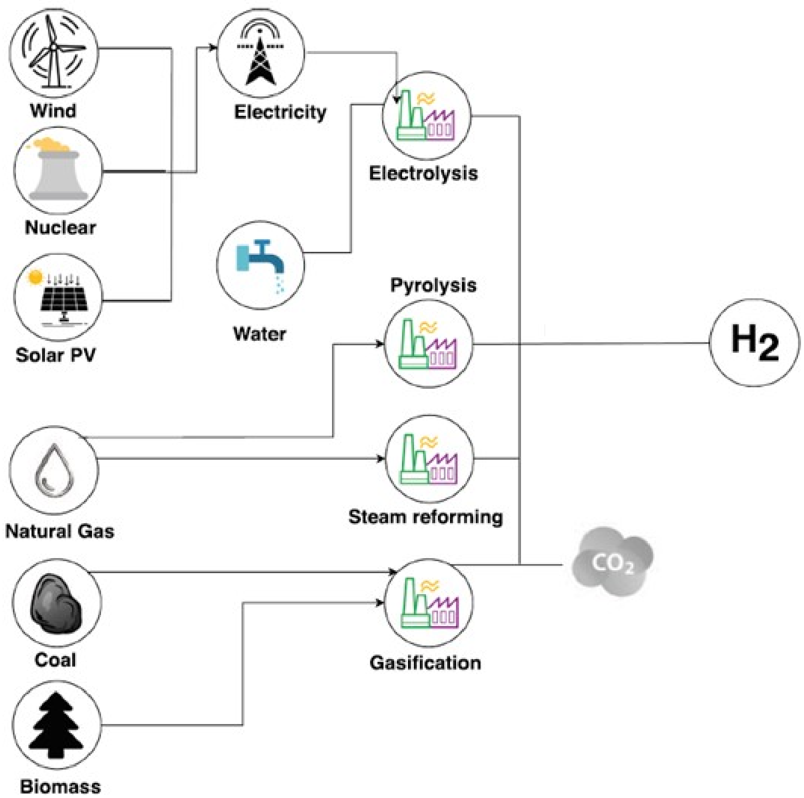

Figure 1. Hydrogen feedstocks and production processes. Reprinted with permission from Ref. [27]. Copyright (2024), with permission from Elsevier.

Hydrogen production pathways can be distinguished based on the energy source, catalyst and raw materials used. Gasification allows us to convert solid carbonaceous materials into carbon monoxide and hydrogen by reacting them with oxygen and/or steam. It can use a thermal source of energy based on fossil fuels or biomass. Reforming-based processes are reactions between carbon-based liquid or gaseous fuels with steam at high temperatures to produce carbon dioxide and hydrogen. It can also use fossil fuels or biofuels as the thermal heat source. Currently, 75% of the produced hydrogen is generated from steam reforming (SMR).

Thermolysis uses thermal energy to decompose water molecules at a very high temperature, approximately 2500 °C. Methane pyrolysis decomposes hydrocarbons into solid carbon and hydrogen at high temperatures, either thermally or catalytically, without the presence of oxygen [18]. Depending on which production method is used, byproducts can be generated, such as oxygen, carbon dioxide and other environmental gases, which represent the carbon footprint of the hydrogen production chain. Water electrolysis is based on water decomposition into oxygen and hydrogen by passing a direct current that drives electrochemical reactions [28].

Hydrogen production has been associated with a coloured system classification, which reflects the degree of sustainability in its production process [29]. However, hydrogen classified under the same colour may still be associated with different GHG emissions because of discrepancies in production parameters [30].

2.1. Hydrogen Production through Water Electrolysis

The process of water electrolysis requires a supply of electricity and water to continuously generate hydrogen and oxygen (green hydrogen). Moreover, the electricity required can be obtained from an electric grid or by a renewable power plant. When considering only renewable sources to produce electricity, the main sources include solar, hydro, wind and geothermal energies [31].

Furthermore, the cost of hydrogen generation is intrinsically connected to the price of the energy source [32]. In the literature, the renewable sources that are the most used in electrolyser production are solar and wind energy. Therefore, the behaviour of these sources as energy suppliers in the electrolysis process is studied in several articles [23].

According to [32], the levelized cost of hydrogen (LCOH) per kilogram, when produced with solar as the energy source, is approximately 41% to 55% more expensive than when it is produced with wind and nuclear sources, respectively. According to the literature, when considering the impact of renewable energy sources' unpredictability, it becomes evident that wind speed has a greater influence than the solar radiation on hydrogen production prices [32].

Table 1 presents the LCOH, for different energy sources, from the literature. Based on the data, reducing the fluctuation in the energy source leads to a decrease in the levelized cost of hydrogen. In other words, when combining PV and wind power plants, the power supply becomes less unstable, because it relies on two climate conditions instead of one. Consequently, the cost of hydrogen production decreases accordingly [32]. In the study [31], it is specified that the expense reductions vary from 30% to 63% when integrating multiple discontinuous energy sources, in contrast to systems that rely on a single dedicated renewable energy source. Regarding wind power, higher costs for wind electricity result in higher costs for producing hydrogen. In addition to that, there is an important correlation, known as the capacity factor of wind turbines. This correlation is represented by the ratio of generated wind power to the turbine capacity and is directly linked to hydrogen costs. Lower hydrogen costs are associated with higher-capacity factors [23,33].

It should be noted that there is a substantial difference between a renewable off-grid power plant and a renewable on-grid power plant when it comes to its role as an electricity supplier for electrolysis. According to [32], the LCOH production through electrolysis is twice as high connected to a standalone power plant when compared to a grid-tied plant.

Table 1. Electrolysis process feedstocks and the corresponding LCOH.

Input	Reference	Year	Nuclear Electrolysis	PV Electrolysis	Wind Electrolysis		PV + Wind Electrolysis
					Onshore	Offshore	
Electricity [kWh]	[23]	2023	54.2	54.2	54.2		-
Water [kg]	[23]	2019	10	10	10		-
LCOH [USD/kg or €/kg]	[23]	2019	4.3	9.49	5.6		-
	[32]	2020	-	(USD) 7.5	(USD) 4.4	(USD) 4.2	(€) 3.5

Additionally, it is important to mention that nuclear power and geothermal energy have the potential to produce cheaper green hydrogen, competing with grey (i.e., hydrogen from fossil fuels) hydrogen prices. An additional factor to consider is the availability of water. For wind and solar electrolysis, ten kilograms of water is required to produce one kilogram of hydrogen. Because of this, the use of water electrolysis technology is constrained in some geographic places.

To assess the least economically favourable type of hydrogen, researchers should conduct an economic evaluation covering several hydrogen types, as presented in [30]. Their assessment considered the LCOH and externalities, such as human health indicators, the monetized ecosystem quality and the monetized resource depletion. The conclusion reported that the gas reforming process combined with CCUS offers the most affordable option, with a final cost of 4.67 USD per kilogram of hydrogen produced [27]. However, CCUS may lead to a reduction of 5 to 14% in the energy efficiency of the steam methane reforming process.

Another issue is the social acceptance of processes involving the valorisation of CO_2 emissions [18]. In this case, the GHG is taken as a raw material for industrial processes rather than an undesirable byproduct, creating a market that undermines initiatives for green hydrogen production.

2.2. Hydrogen Storage

One of the foremost stages in the strategic analysis of the hydrogen value chain is related to the leakage of hydrogen at normal temperature and pressure (NTP) conditions (i.e., 20 °C and 1 bar). The low volumetric energy density of this energy carrier presents a significant challenge for its handling. Therefore, for any undertaking which incorporates hydrogen, a crucial aspect lies in determining the appropriate method to increase the volumetric energy density for its efficient storage [34].

Hydrogen storage serves two purposes. Firstly, it can address the intermittencies of renewable energy by enabling seasonal energy storage. Secondly, it should be noted that stockpiling has the potential to overcome the mismatch between renewable energy production and unsynchronized demand profiles [31]. In addition, in terms of mitigating the renewable energies' intermittency, hydrogen storage stands out positively due to its characteristics as an energy carrier. The versatility of ways that hydrogen can be stored for extended periods is a significant advantage over other storage technologies [22].

Generally speaking, hydrogen storage can be categorized into two wide classes: physical and material-based storage (Figure 2).

One way to achieve higher volumetric energy density is through hydrogen gas compression. However, storing hydrogen in the form of gas is a very complex task. One of the alternatives to attain a greater volumetric power density is to perform the liquefaction of hydrogen [35].

Typically, hydrogen is produced within a range of 1 to 30 bar pressure and 303 to 333 K temperature. Nevertheless, the liquid state of hydrogen can only be attained at temperatures ranging from below 20.37 K (at 1 bar) to 33.14 K (at 12.79 bar). Thus, a facility that employs cryogenic technology is required so the temperature can be lowered to ultra-low levels [22]. The process of transforming hydrogen into a liquid state involves four primary stages: (1) precompression performed in ambient conditions; (2) hydrogen temperature is decreased from ambient to around 80 K; (3) cryo-cooling with further temperature reduction from 80 K down to 30 K; and (4) liquefaction, achieved by reducing the temperature from 30 K to around 22.8 K or 20.37 K, depending on whether the hydrogen pressure is 2 bar or atmospheric pressure. The storage conditions for liquid hydrogen require a temperature of 20.15 K and a pressure of 4 bar [34]. Furthermore, during the process of liquefaction, a significant amount of energy is needed and consumed [36]. There exists a diversity of values in the literature that depict the amount of energy used in the process of liquefaction. For instance, according to [37], the energy consumed in this process is estimated to be 12 to 15 kWh per hour, whereas, for [38], the value is lower, about 11 kWh/kg. Conversely, a study [36] states that the energy consumption is about 25 to 45% of the hydrogen energy.

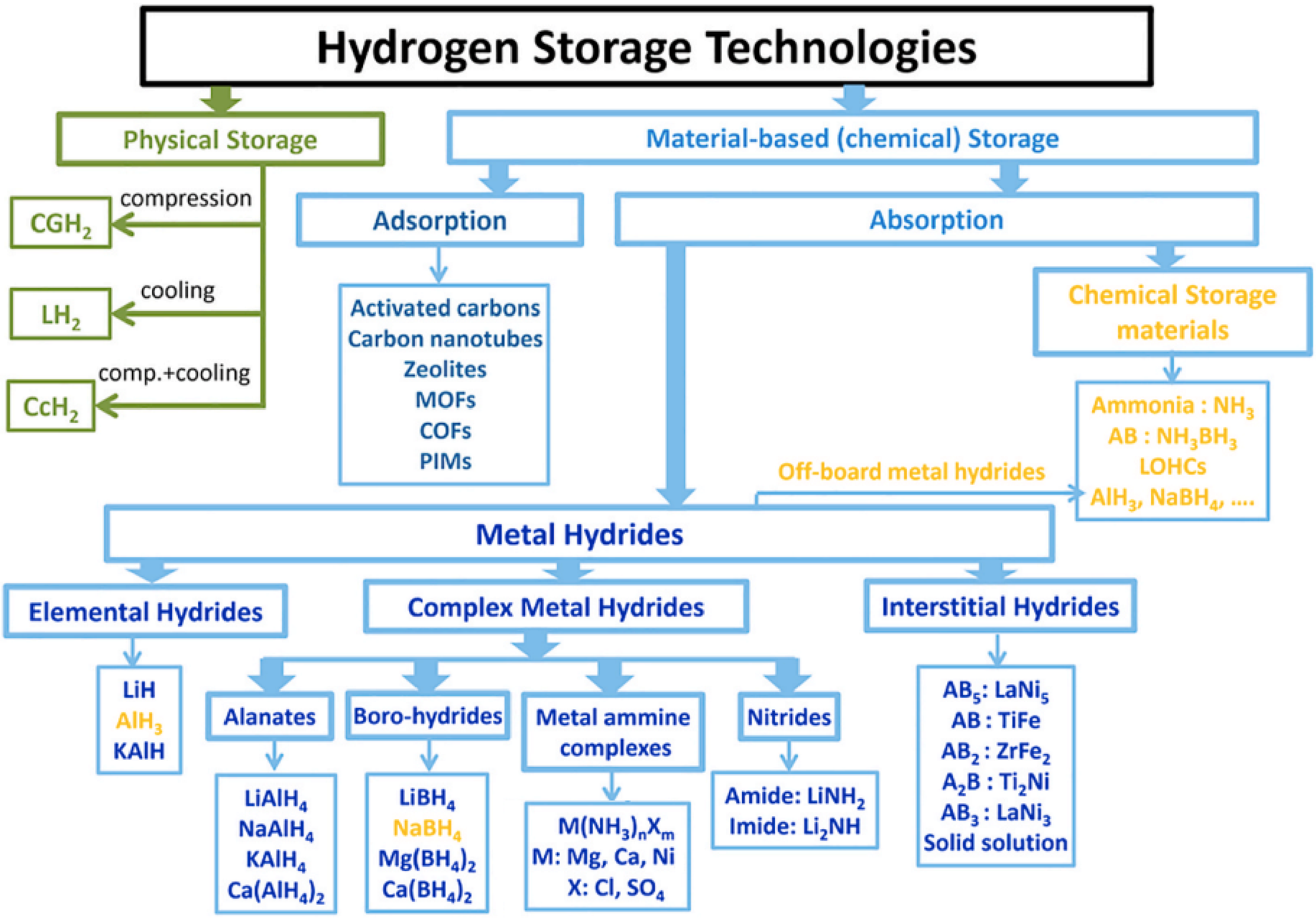

Figure 2. Hydrogen storage technologies. Reprinted with permission from Ref. [35]. Copyright (2024), with permission from Elsevier.

This represents a disadvantage when comparing liquefaction with the gasification of hydrogen. According to [35], the compression of hydrogen to 700 bar consumes approximately 10% of the gas energy content. Another downside of storing liquid hydrogen relates to its low heat of vaporization, which results in losses from the liquid hydrogen tank. Therefore, more energy is consumed to mitigate the loss of liquid hydrogen that may occur during long periods of storage.

In the literature, several publications are focused on the technical data of gaseous hydrogen storage. This type of storage can be divided into two categories based on pressure: low pressure and high pressure [39,40].

The low-pressure group has a maximum compression capacity of 200 bar, while the high-pressure group has a maximum compression capacity of 700 bar [39]. The pressure range in which the hydrogen can be compressed varies between 50 and 400 bar for stationary applications and up to 900 in mobility applications [22]. In [36], it is stated that storing hydrogen in standard steel cylinders, at a pressure of up to 206.65 bar, is the most straightforward approach, which enables approximately 16 kg of hydrogen to be stored in a one cubic meter tank. Similarly, [37] consider the same tank form, but the pressure threshold varies between 200 and 350 bar.

Regarding high-pressure storage, ref. [37] considers a range of 350 up to 700 bar. The research published in [41] studied the feasibility of offshore wind turbines coupled with hydrogen production. The authors consider storing hydrogen in a tank with compression ranging from 15 bar to 250 bar as the most conventional method. This narrow pressure range is also considered in [25]. Finally, ref. [42] takes into account a pressure range between 30 and 200 bar. Conversely, ref. [43] indicates a wider storage pressure range. Specifically, the authors state that hydrogen storage pressure can vary from 200 to 1000 bar. It also highlights that storage vessels designed for energy and transportation purposes typically have a tolerance for 700 bar pressure. To further explain, this high-pressure hydrogen storage, which ranges between 350 and 700 bar, is normally used to provide fuel for vehicles equipped with fuel cells [39,44].

Regarding the economics of hydrogen storage, there is not much information in the literature. In the considered works, the appropriate size of storage capacity is not calculated, and, frequently, an arbitrary quantity of storage is selected for cost calculations, without being properly sized or limited on the temporal hydrogen production. Thus, the adequacy of the chosen storage cost is not subjected to investigation, and, in certain scenarios, the storage cost is entirely disregarded. Also, the LCOH available does not make clear if the values correspond to the overall scenario, production or storage values.

Yet, regarding the storage cost, in [45], the capital costs for pressurized gas tanks (above-ground vessels) are analysed. According to this study, the specific capital cost can reach a value of 1040 EUR per kg of hydrogen stored.

An alternative approach for storing gaseous hydrogen involves underground storage. Subterranean retention can be achieved by using exhausted oil and gas fields, cavernously excavated from hard rock or salt deposits. This technique facilitates the storage of large quantities of hydrogen gas over substantial periods [39]. Based on [39] and considering only technical aspects, salt caverns are the preferred option for hydrogen storage. This is owing to the inertness of salt towards hydrogen, which, in turn, limits its diffusivity from the storage cave [34,44]. However, the availability of suitable geological formations for this kind of storage constitutes a significant obstacle [39].

According to [44], these underground tanks can also be produced with human intervention. For example, leaching salt reservoirs with a capacity of 750,000 cubic meters would cost between 20 and 30 Millions of EUR. Therefore, from an economic perspective, using this storage technique is more cost-effective when the quantity of hydrogen to be stored exceeds 20 tons. This is due to the specific investment involved, which can result in costs up to ten-times lower for a storage capacity of 100 tons of hydrogen, when compared to storing it in vessels [34]. Moreover, when considering economic aspects, another limitation of this storage method emerges. This limitation is related to the expensive transportation costs of hydrogen to and from these caverns, even in the case of reduced distances between the storage point and the production or application facilities [34].

The study of [46] provided the capital and levelized costs of hydrogen storage in depleted gas reservoirs, salt caverns and saline aquifers in the Intermountain-West region of EUA. The levelized costs range from approximately 1.3 USD to 3.4 USD per kg of hydrogen.

Regarding the technical parameters, the compression pressure thresholds for subterranean storage may fluctuate within a range of 20 to 180 bar [39]. In contrast, ref. [34] states that the pressure of hydrogen can achieve 200 bar in this type of storage. Also, the salt cavern storage can operate with hydrogen compressed between 60 and 150 bar [25]. On the other hand, ref. [44] states that for 500,000 cubic meters, hydrogen must be compressed to pressures that vary from 60 to 180 bar. Hence, underground tanks require lower pressure compared to above-ground storage. Table 2 presents a summary of compressed hydrogen storage technical data.

Table 2. Technical information on compressed hydrogen storage.

Reference	Type of Storage	Type of Compression		Geological Storage
		Low Pressure	High Pressure	
[39]	Pressure range [bar]	Up to 200	Up to 700	20 up to 180
	Type of vessel	Based on SA516 Grade 70 carbon steel	-	Salt caverns depleted oil and gas fields and aquifers
	Application	Stationary applications	Transportation fuel (refuelling stations)	Stationary applications
[22]	Pressure range [bar]	50 up to 400	Up to 900	-
	Type of vessel	-	Carbon fibre composite pressure vessels	-
	Application	Stationary applications	Mobility applications	-
[36]	Pressure range [bar]	Up to 206.65		-
	Type of vessel	Standard steel cylinders		-
	Application	-		-
[37]	Pressure range [bar]	200 up to 350	350 or 700	-
	Type of vessel	-		-
	Application	Stationary tube systems	Automotive applications (on-board hydrogen storage)	-
[43]	Pressure range [bar]	200 up to 1000		Up to 200
	Type of vessel	Composite shell associated with a permeation barrier		-
	Application	Transport applications (700 bar)		-
[25]	Pressure range [bar]	15 bar up to 250		60 up to 150
	Type of vessel	-		Salt cavern
	Application	-		-
[41]	Pressure range [bar]	15 bar up to 250 bar		-
	Type of vessel	-		-
	Application	-		-
[42]	Pressure range [bar]	30 to 200		-
	Type of vessel	-		-
	Application	-		-

Table 2. *Cont.*

Reference	Type of Storage	Type of Compression		Geological Storage
		Low Pressure	High Pressure	
[47]	Pressure range [bar]	-		-
	Type of vessel	Cylindrical or spherical pressure tanks		-
	Application	-		-
[44]	Pressure range [bar]	-	Up to 700	60 up to 180
	Type of vessel	Cylindrical or spherical tanks		-
	Application	-	Electrical energy production (through fuel cell devices)	Rock caverns, and coal or salt mines

Regarding storage vessels, there is a clear distinction between gaseous and liquid hydrogen. High-pressure containers consist of a metallic or polymeric layer that makes contact with the gas, functioning as a shield to prevent hydrogen permeation. Additionally, it is common to use a composite shell made of carbon or glass fibres embedded in resin to increase the mechanical strength [34]. This type of tank can be in the cylindrical or spherical form [44,47] and has higher costs than medium-pressure tanks [37].

Due to the need to use specialized tanks, storing liquid hydrogen has more stringent requirements than storing gaseous hydrogen at high pressures. In other words, the use of specialized tanks is what makes the storage of liquid hydrogen more complex.

The usual method of constructing these tanks is by placing several metal vessels within each other in a concentric way. Several methods, including high vacuum, vacuum-powder or multilayer technologies, are used between the inner and outer vessels to create an insulation barrier that minimizes heat transfer to the inner vessel [36].

The gaseous pressure vessels can be categorized based on different characteristics, resulting in four types of vessels, as shown in Figure 3 [35]. A cylinder type I, which is the most used, has a volume of 50 L. However, the energy storage capacity of these tanks falls significantly below the targets required for practical energy applications. Regarding pricing, this type of tank usually costs between EUR 100 to 200. The price variation is due to delivery, as the tanks are typically shipped in packs.

Vessels type II have higher pressure thresholds due to their reinforcement with carbon fibre. This composition is also associated with higher prices. Additionally, type III and type IV have a full composite overwrap, enabling them to achieve a higher gravimetric performance than the two previous tank types mentioned [35]. Furthermore, ref. [35] suggests that including composite filaments in these storage systems increases corrosion resistance, reduces weight and increases strength. Thus, these tanks can accelerate the commercialization of hydrogen in the automotive industry.

Industrial cylinders are manufactured to withstand pressure of 300 bar. Nevertheless, many cylinders in use still only accommodate a pressure of 200 bar, because they were designed according to the most popular pressure rating used in the past.

Type			I	II	III	IV	V
Schematic							
Components and related failures	Metallic	part	Fully metallic	Metallic enclosure	Metallic liner	Boss	-
		Failure	- Hydrogen Embrittlement, mechanical properties degradation and premature cracks. - Premature failure for fatigue for metal liner and liner damage. **Reason:** contact between metal and Hydrogen, surface impact.				
	Composite	part	Not applicable	Some fibre over-wrap	Full composite over-wrap		Fully composite
		failure		Fibber breaks, delamination and matrix cracking, composite thickness decrease. **Reason :** accidental mechanical impacts and subsequent pressure loads.			
	Polymer	part	not applicable			Polymer liner	Under consideration
		failure				Permeation, leakage **Reason :** contact between polymer and H_2, charge/discharge conditions	
Pressure limit			≤ 50 MPa	Not limited	≤ 45 MPa	≤ 100 MPa	
Vessel price			++	+	-	-	
Gravimetric capacity wt. % or tank mass			-	±	+	++	
Popularity & maturity			****	**	*	*	

Figure 3. Categorization of pressure vessels for hydrogen storage. Regarding the vessel price and the gravity capacity, the vessels' type is compared through a qualitative scale, being "++" the highest capacity value, "±" is undifferentiated capacity and "-" the lowest capacity. Regarding the comparison in terms of popularity, the highest mature technology was classified with four asterisks and lowest with only one. Reprinted with permission from Ref. [35]. Copyright (2024), with permission from Elsevier.

2.3. Hydrogen Transportation

Regarding transportation, two primary procedures are involved: transportation and distribution. The transportation process usually incorporates the transport of hydrogen over long distances, connecting the production facilities to the storage stations. This transportation can be long distance, crossing regions or even countries. Notwithstanding, the distribution is characterized by the transport of hydrogen from storage to the point of use [23]. To meet the need, multiple methods of hydrogen transported in large-scale production systems were developed. It is worth noting that certain studies describe hydrogen transportation as a form of mobile storage [38].

Nowadays, hydrogen can be transported either in a liquefied state or as a compressed gas. In the first scenario, the main approaches of transport are tanks mobilized through road vehicles, ships and trains. Hydrogen can also be transported via high-pressure pipelines, tube trailers or railway tube cars. Moreover, tube trailers, which have been widely studied in hydrogen supply chain models, are a commonly used mode for transporting smaller quantities of hydrogen. Alternative methods, such as pipelines and shipping vessels, may be more cost-effective for higher volumes of hydrogen [48].

Therefore, the selection of a hydrogen transportation method is substantially affected by investment and operation costs. Another crucial factor to take into account is the distribution of hydrogen demand, which determines the distance to be covered. For instance, a pipeline may be impractical or prohibitively expensive for transporting hydrogen across the ocean. Additionally, the transportation of hydrogen can be accomplished through the use of a hydrogen carrier, such as ammonia, liquid organic hydrogen carriers or metal hydrides [23,25,31,36,49].

Ammonia has been considered a potential alternative method for storing and transporting hydrogen because it has a higher volumetric energy density than pure hydrogen gas. However, there are several challenges associated with using ammonia as a hydrogen carrier. From an operational point of view, handling and storing ammonia require specialized equipment due to its corrosive properties, which can increase the cost of using it as a hydrogen carrier. Also, the infrastructure for handling and distributing ammonia for use as a hydrogen carrier is not well developed, requiring significant investment and adaptation. Converting ammonia back into hydrogen can be energy-intensive, reducing the overall efficiency of hydrogen storage [50]. In addition, the production of ammonia itself often comprises carbon dioxide emissions, unless it is produced using renewable energy sources or processes such as electrolysis. Moreover, both energy and financial costs for purifying and compressing the released hydrogen to feed fuel cells are substantial.

2.3.1. Gaseous Hydrogen Transportation

As previously mentioned, the transportation of hydrogen gas relies on trailers coupled with cylinders or bundled tubes, which have been extensively embraced for transporting small quantities over short distances, up to 200 km. Furthermore, the fraction of hydrogen dispatched through this mode of transportation is contingent upon the degree of compression imposed on the product. The pressure gradient oscillates between 220 and 500 bar, which corresponds to 420 and 1100 kg of hydrogen, respectively.

Technical data related to the transportation of gaseous hydrogen via trailers can be found in the literature. This fact highlights a considerable degree of diversity in this matter. In the literature, it is stated that hydrogen transported via trucks is generally performed under a pressure of 180 bar. This pressure value is lower in comparison to the pressure levels noted in stationary pressure vessels [38].

There are two distinct types of cylinder trailers [25]. One variation consists of a tube of steel that manages hydrogen at 162 bar, whereas the other category, which was previously disclosed by [35], comprises a tube trailer manufactured with composite materials, possessing the ability to transport and store up to 1100 kg of gaseous hydrogen under a pressure of 500 bar.

Both refs. [22,49] state that the prevalent technique employed to store and distribute hydrogen in modest amounts is gaseous compression. The pressure of compression varies depending on the final use of the product. According to [22], the range of this variation for mobility applications spans from 50 bar to 900 bar. In a study presented by [49], hydrogen compression up to 200 bar and transportation via trucks are mentioned. Moreover, ref. [35] specifies a spectrum of compression from 200 up to 500 bar, whereas the hydrogen is transported in cylinders or bundled tubes on tube trailers on trucks.

In accordance with [37], the economic costs incurred for the transportation of gaseous hydrogen via truck trailers solely depend on the distance traversed, as a result of the constrained capacity of each transported batch. Therefore, there is no consequential benefit to be derived from an escalation in demand. To be more precise, the expenditure of this transportation model can be calculated considering multiple factors, such as the velocity during transportation, the duration of the loading and unloading process and the fuel consumption of the truck. Additionally, the study also supports that composite tube trailers enable higher storage capacity when compared with steel-tube trailers. It is stated that the storage capability of this composite equipment reaches 1150 kg of hydrogen gas, despite the higher cost compared to steel tubes. It is also concluded that one of the viable options for gaseous transportation is a composite tube trailer capacity of 680 kg.

Regardless of the modest capital cost of traditional tube trailers, their storage capacity is not substantial. To illustrate this statement, the researcher presented a conventional tube trailer priced at USD 300,000 with a capacity of 300 kg of hydrogen [25].

Regarding pipeline transportation, the infrastructures assigned to the distribution of natural gas are widely dispersed. This fact, coupled with the fact that energy transmission through natural gas pipelines is more efficient and results in lower energy losses, encourages the use of these infrastructures for the distribution of hydrogen. Blending green hydrogen, which is generated from renewable energy sources, with natural gas in the pipelines creates hydrogen-enriched natural gas [39]. Furthermore, the admixture of hydrogen into natural gas at a maximum concentration of 10% would result in no remarkable impact on the pre-existing natural gas infrastructure or terminal equipment [39]. However, ref. [23] suggests a higher admissible flow of hydrogen. With lower than a 15% hydrogen concentration, this technology can be implemented with slight alterations. This means that, with minimal initial investment, the operation of pipelines can be carried out promptly.

Moreover, the production of hydrogen can be integrated into the natural gas grid, and the resulting hydrogen can be directly supplied to the grid or, in specific circumstances, stored in gas tanks. In this case, the main function of storage tanks is to guarantee the uninterrupted integration of the necessary volume of hydrogen into the natural gas pipeline, consequently matching the supply and demand [39,44].

Thus, this grid can perform two important roles, namely, storage and transportation, within the hydrogen supply chain, owing to its construction designed for the conveyance of substantial volumes. The operational mechanism of this versatile infrastructure is straightforward, i.e., hydrogen may be drained or injected into pipeline terminals, similarly to the procedure of storage charging or discharging [38]. For these reasons, the literature reveals the benefits of deploying pipeline transportation in the hydrogen supply chain. According to [38,39], this approach can satisfy the required energy storage capacity, avoiding the energy loss originated by renewable energy. The determination of the hydrogen flow rate can be predicated upon the maximum admissible concentration of hydrogen in natural gas, a threshold which has been established in the existing literature, depending on the application [39,44]. For instance, the region, the country policies and grid components' technical requirements are also constraints.

Despite the benefits and practicality of using gas grid pipelines for the transportation and storage of hydrogen, any potential project must take several constraints into account. These include pipeline lifespan and potential leakage. Given that many of the existing pipes are over 100 years old, they may pose safety risks, for instance, the possibility of ignition and explosion. Another concern is reflected in limitations in the permissible proportion of hydrogen in natural gas pipelines, which is associated with uncertain effects around end-point devices. If the permissible limits typically lie between 5% and 20% hydrogen concentration, higher hydrogen blending may result in additional costs for the final users. Furthermore, hydrogen blends exceeding a 40% threshold require the substitution of compressors, which represents a major drawback [23,39].

An alternative approach is based on the projection of a grid of pipelines solely for hydrogen rather than a mixture. This solution is currently in use, but the networks are still on a small scale. The United States currently has approximately 2600 km of pipelines intended for the transport of hydrogen, compared to the 300,000 km of transmission lines that make up its natural gas network [23]. According to [25], a pipeline that has a diameter of 20 cm can transfer up to 120 tons a day and costs around USD 285,000 per kilometre.

Regarding cost-effectiveness, pipeline transportation proves to be a more lucrative option than electricity transportation when the distance exceeds 1000 km. This is due to the significant initial capital investment required for pipeline transportation, which is offset by lower operational costs [35,37]. Apart from the considerable upfront capital costs, this technology requires a larger number of turbines and compressors compared to the natural gas pipeline grid. This is essential for delivering hydrogen at an appropriate volumetric flow that matches its volumetric energy density [23]. Therefore, an increase in equipment leads to a hydrogen transportation cost that is approximately 1.5- to 1.8-times higher than the cost of natural gas transportation.

2.3.2. Liquid Hydrogen Transportation

The transportation of liquid hydrogen over extensive distances can be accomplished via specialized tanks fitted onto truck trailers and semi-trailers. These tanks have a volumetric capacity ranging from 25 to 55 m^3 [36]. However, as stated in [35], the volumetric capacity can achieve values up to 60 m^3. Additionally, ref. [38] reports that the hydrogen-carrying capacity of commercially available liquid trucks is usually four tonnes, whereas ref. [37] states a wider range, which varies from 4.0 to 4.5 tons of hydrogen. These mass values correspond to 133 and 149 MWh of hydrogen, respectively. Therefore, the hydrogen liquid transportation via trucks exceeds the capacity of hydrogen gas trucks, which corresponds to 1.15 tons (38.3 MWh).

Thus, the transport of hydrogen in a liquid state is believed to be more effective for larger quantities or longer distances [35]. According to analyses from [37], liquid hydrogen is exclusively lucrative compared to gaseous hydrogen for transporting distances over 500 km (in other words, for remote transportation). Furthermore, the liquid hydrogen tanks operate at slightly elevated pressures compared to the atmospheric pressure to prevent air from infiltrating the hydrogen environment while in transit through rail or road transportation [36].

Despite the technical aspects of liquid hydrogen transportation, liquefaction itself represents a great challenge. Hydrogen liquefaction is a process that requires a temperature reduction from an ambient level, condensing at 20 K, which demands a substantial quantity of energy, approximately 30% of its lower heating value. According to [51], a share of this high energy needs is related to a change in the balance of hydrogen's nuclear spin isomers under cooling below about 200 K. Whereas in STP conditions, hydrogen comprises 25% parahydrogen and 75% orthohydrogen, in liquid conditions, it is almost 100% parahydrogen. Thus, when hydrogen is cooled to very low temperatures to liquefy it, there is a spontaneous conversion of orthohydrogen to parahydrogen due to the lower energy state of parahydrogen. This conversion process releases heat, which can lead to temperature fluctuations and make it difficult to maintain the low temperatures required for liquefaction. So, there is a challenge in reducing the heat released during the process and making it more efficient [52].

2.4. Hydrogen Applications

Nowadays, the application of hydrogen is essentially divided into two sectors, chemical and steel industries, specifically refining processes (in refineries) and industries, such as the chemical industry, with the production of chemical compounds, and the steel industry [53,54]. According to [53,55], the demand for hydrogen has been growing, with an increase of approximately 50% when comparing the data from 2000 to 2020. In addition to that, in 2021, there was a post-pandemic economic recovery that allowed for a 5% increase in hydrogen demand. Thus, the demand reached 94 Mton in 2021, whereas only 60 and 90 Mton were requested in 2000 and 2020, respectively.

Hydrogen is one of the main raw materials for the petrochemical industry, particularly in refinery operations. It is foreseen that by 2030, the consumption of hydrogen in this field will double when compared to the amount consumed in 2005 [53,56]. The main processes are hydrodesulfurization, hydro isomerization and hydrocracking [57,58].

Nowadays, the high demand for hydrogen in the aforementioned processes is met primarily by hydrogen derived from fossil fuels. This reliance on fossil fuel constitutes a big share of carbon emissions regarding refining processes. Therefore, by decarbonizing hydrogen, which means producing hydrogen without emitting carbon dioxide, it becomes possible to attain a substantial reduction in GHG emissions in the respective sector. For this reason, there is a wide and attractive market for green hydrogen in the refinery sector [56,57].

According to [53], the production of chemical compounds such as methanol and ammonia through the Haber–Bosch process consumed 15 and 34 Mton of hydrogen, respectively. In terms of percentage, methanol production corresponds to 10%, while the ammonia formation process accounts for 55% of the global hydrogen demand [58]. A significant share of the produced ammonia acts directly in food production through the fertilization of agricultural fields [57,59].

For this reason, several projects to reduce carbon emissions in ammonia production are under development. These initiatives focus on the adoption of CCUS systems, as well as water electrolysis as a productive method for hydrogen generation. Based on the study of [53], there was a 200% increase in water electrolysis projects and a 40% rise in CCUS projects in 2021, when compared to 2020.

Synthetic fuel methanol can be obtained via the reaction of CO_2 with hydrogen. This compound has a wide range of applications; for instance, it can be blended with diesel or gasoline, increasing its octane rating. As a result, the carbon emissions are reduced. Additionally, it can be used directly in fuel cells, specifically designed for this operation. Moreover, due to the lack of carbon emissions in its liquid state, methanol proves to be an excellent compound for storing and transporting the energy produced from renewable sources [54,57]. Therefore, methanol can be used for storing and transporting renewable energy. Methanol production from hydrogen and CO_2 is an excellent way to transport and store hydrogen produced from renewable energy since the methanol energy density, 5.53 kWh/kg, is higher than hydrogen's [54]. Notably, some projects of this character are being developed. As an example, the Chinese group Henan Shuncheng has initiated a project using emissions-to-liquids technology developed by the Icelandic company Carbon Recycling International (CRI). This project aims to hydrogenate one hundred thousand tons of carbon dioxide, resulting in methanol and other hydrocarbons as reaction products [54]. Similar to methanol, ammonia can also serve as an energy carrier for renewable power plants through green hydrogen. In this way, some challenges that are being experienced in the energy transition, imposed by decarbonization measures, can be solved [54,57].

Another important application of hydrogen is in the steel industry. This industry alone accounts for 7% of the total CO_2 emissions. Therefore, efforts have been made to transform it into a more sustainable production chain. One of the proposed solutions consists of the use of green hydrogen instead of fossil fuels [57,58,60].

Firstly, hydrogen can be used as an energy source for production processes through a fuel cell. Additionally, it can be used to facilitate iron reduction (H-DR). It is worth noting that the full or partial implementation of low-emission hydrogen in the steel production process is still in a developmental phase, and it is not even close to the same level of maturity as the conventional process, which uses coal and natural gas [54,57].

It is predicted that, by 2030, 1.8 Mton of environmentally friendly hydrogen will be available for the steel industry. Despite the environmental benefits associated with the hydrogen metallurgical industry, the final cost of steel might rise by 20% to 30%, making it economically less attractive [53,54].

Regarding the emerging applications of hydrogen, it is forecasted that hydrogen will play an important role in shifting the energy market, enabling a revolutionary transition. All the mentioned peculiarities are closely linked to the decarbonization path [57]. One of the main applications consists of the use of hydrogen as a storage medium for renewable energy power plants. The objective is to store the surplus energy generated by these intermittent power plants and utilize it during periods of non-production [39,60].

Several projects have been announced in the field of vehicles. As an example, Renault plans to launch a hydrogen-powered electric car by the end of 2024. Both Toyota and Hyundai already have vehicles available on the market. Additionally, Great Wall Motors is planning to develop a range of luxury cars equipped with fuel cell technology. Regarding buses, the West Midlands in the United Kingdom will deploy 124 new fuel cell buses [53]. The demand for hydrogen in the mobility sector is still insipient, accounting for only 0.003% of all energy consumed in transportation. Despite this fact, a growth of 60% in the requirement for this fuel was registered in 2021 compared to the previous year. As for the stock of fuel cell vehicles, it exceeded 59,000 units in June 2022, reflecting a 15% increase compared to the end of 2021. All the aforementioned data are in accordance with [53].

3. Modelling a PV Power Plant Integrated with H_2 Production for Industry

In an increasingly sustainable world, renewable energy generation from wind turbines or PV is gaining a relevant role in the energy market. Yet, establishing large-scale plants for storage batteries can be unfeasible due to their high costs and due to the inappropriateness of batteries for seasonal energy storage. As a result, these sources are intermittent and cannot consistently meet the electricity grid demands, which have consumption peaks, regardless of weather conditions [61].

Thus, one significant scenario that is gaining attention in industrial applications is the integration of PV power plants with hydrogen production and its storage for further use (when solar energy is not available). The outline of the PV plant integrated with the hydrogen production model is presented in Figure 4. According to the illustration, the system configuration aims to maximize the system's self-sufficiency, thereby avoiding energy purchasing from the electrical grid. Thus, the electricity generated by the power plant has three possible paths, whereas the energy from the PV system is distributed according to the order of significance of each application and their respective minimum and maximum limits of energy absorption.

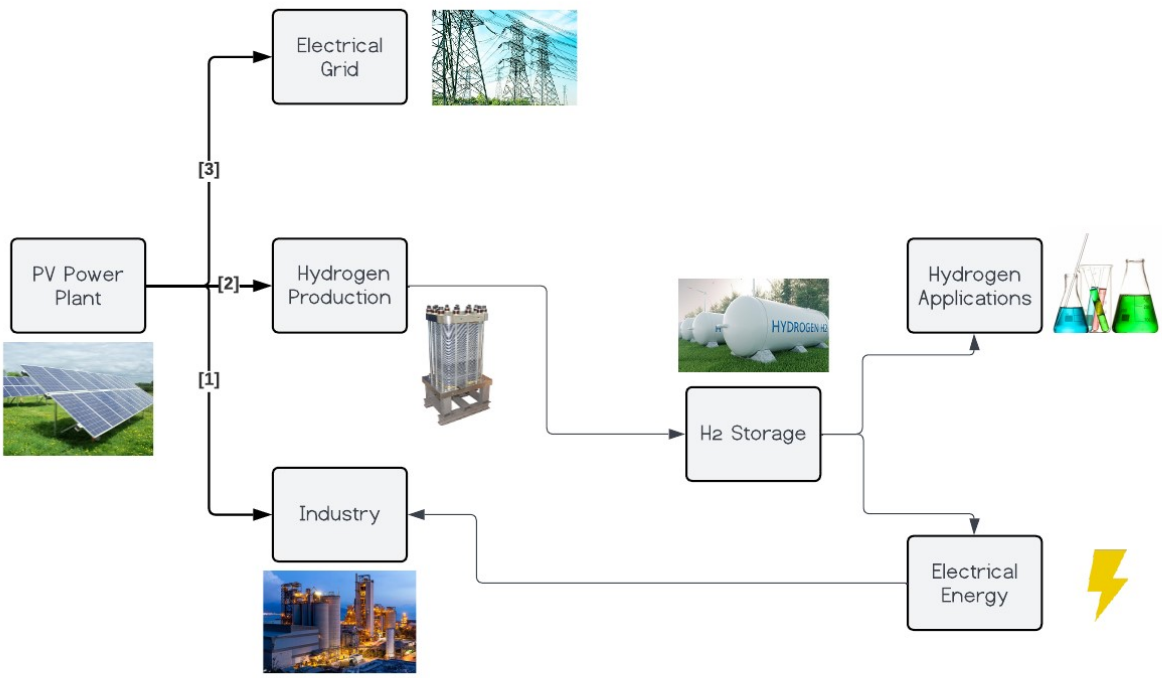

Figure 4. Outline of the PV plant integrated with the hydrogen production model.

The first path is the most important because it corresponds to the industry energy supply. The second path is the second most significant because it supplies the energy to the hydrogen production unit. The last path corresponds to the electricity sold to the grid. Thus, the priority of the system is to suppress the industry's electricity demand with renewable energy. In the case of excess energy production, after the primary need is fulfilled, the energy is directed to the electrolyser to proceed with hydrogen production. As hydrogen acts as an energy carrier, it allows energy to be stored for long periods, avoiding energy waste. If the surplus energy is higher than the maximum amount that the electrolyser can handle, the energy is sold to the grid to increase the cash revenues.

As hydrogen is produced, it can be stored at the same location of its production, namely a centralized water electrolysis facility. Furthermore, hydrogen can be stored for days to months. There are two main routes for storing hydrogen. One involves selling sustainable fuel for its applications, and the other potential route is taken when the energy generated by the PV power plant is not sufficient to meet the industry's energy demand. In this case, the hydrogen is converted into electricity and supplied to industries.

3.1. PV Power Production

A PV power production unit consists of a set of solar panels, an inverter that converts DC electricity to AC electricity and other components such as controllers and trackers. The most efficient systems are designed to optimize sunlight exposure for the PV panel by maximizing the amount of sunlight received and minimizing any potential shading effects. This is achieved with the use of a mechanism that rotates the axis, varying the tilt angle, to reduce the angle at which sunlight hits the plane of PV panels [62,63]. PV panel output power essentially depends on cell temperature, irradiance and load impedance [64]. The algorithm responsible for identifying and extracting the maximum power from a PV system is identified as the maximum power point tracker (MPPT). Its purpose is to optimize the power output of the PV panels, which oscillates with the variation in temperature and irradiance [65,66].

The string combiner box is an essential component placed between the PV modules and the inverter or DC converter since it can simplify the system by consolidating the multiple DC outputs of the PV panels in one output. Secondly, the combiner string box prevents the PV components from degrading drastically over its operation over the years.

3.2. Water Electrolyser

Although there are several methods for producing green hydrogen, the system modelling under scope was focused on water electrolysis, allowing for the use of renewable energy sources to generate electricity, which is then used to power an electrolyser that splits water into hydrogen and oxygen [30] and, therefore, avoiding the release of any GHG [34,67,68].

One of the most important aspects of green hydrogen production is the electrolyser selection, as it impacts the subsequent stages of hydrogen handling. Multiple devices are capable of conducting water electrolysis, which can be categorized into two major groups based on their operating temperature: low-temperature technologies and high-temperature technologies. The alkaline and Proton Exchange Membrane (PEM) electrolysis cells are the primary representatives of the low-temperature technologies, whereas solid oxide electrolysis cells (SOECs) correspond to high-temperature technologies [69]. To compare the different electrolysis technologies, Table 3 presents a summary.

Table 3. General characteristics of water electrolysis technologies [67,70].

Parameter	Alkaline	PEM	Solid Oxide
Electrolyte	KOH/NaOH (5 M)	Solid polymer electrolyte (PFSA)	Yttria stabilised Zirconia (YSZ)
Separator	Asbestos/Zirfon/Ni	Nafion	Solid electrolyte YSZ
Electrode/Catalyst (Hydrogen: side)	Nickel-coated perforated stainless steel	Iridium oxide	Ni/YSZ
Electrode/Catalyst (Oxygen side)	Nickel-coated perforated stainless steel	Platinum Carbon	Perovskites (LSCF, LSM) (La, Sr, Co, FE) (La, Sr, Mn)
Gas Diffusion layer	Nickel mesh	Titanium mesh/carbon cloth	Nickel mesh/foam
Bipolar Plates	Stainless steel/Nickel coated stainless steel	Platinum/Gold-coated Titanium or Titanium	Cobalt-coated stainless steel
Nominal current density	0.2–0.8 A/cm^2	1–2 A/cm^2	0.3–1 A/cm^2

Table 3. *Cont.*

Parameter	Alkaline	PEM	Solid Oxide
Voltage range (limits)	1.4–3 V	1.4–2.5 V	1.0–1.5 V
Operating temperature	70–90 °C	50–80 °C	700–850 °C
Cell pressure	<30 bar	<70 bar	1 bar
H_2 purity	99.5–99.9998%	99.9–99.9999%	99.9%
Efficiency	50–78%	50–83%	89% (laboratory)
Lifetime (stack)	60,000 h	50,000–80,000 h	20,000 h
Development status	Mature	Commercialised	R & D
Electrode area	10,000–30,000 cm^2	1500 cm^2	200 cm^2
Capital costs (stack) minimum 1 MW	270 USD/kW	400 USD/kW	>2000 USD/kW
Capital costs (stack) minimum 10 MW	500–1000 USD/kW	700–1400 USD/kW	Unknown
Stack specific costs	262–419 USD/kW	415–1158 USD/kW	1100–1300 USD/kW

Alkaline electrolysers have achieved a multi-megawatt scale in commercial applications worldwide. Part of the reason for their high market dominance is the elevated cost–benefit ratio when compared with other technologies. This is due to the utilization of affordable nickel-based metal electrodes, which are non-noble metals and usually have a prolonged lifespan and exhibit exceptional efficiency. Nonetheless, these types of devices are associated with several drawbacks. According to [71], these electrolysers are a piece of massive and bulky equipment, primarily due to their large size. These characteristics are related to the low electron density flux allowed in this type of electrolyser.

PEM water electrolyser cells, unlike alkaline devices, accommodate higher current density and have a more compact system design, leading to the production of purer hydrogen. The process in the device involves the decomposition of water on the anode side, resulting in the generation of hydrogen ions, oxygen and electrons. Subsequently, the polymeric membrane permits the passage of hydrogen ions while acting as a barrier to electrons, which travel through the external circuit. On the cathode side, the hydrogen ions combine with the electrons to form hydrogen. It should be noted that hydrogen ions have higher mobility compared to hydroxide ions in the alkaline. This characteristic is one of the reasons why these PEM electrolysers can be more compact and capable of accommodating higher current density.

Low-temperature electrolysis typically requires a significant amount of electrical energy to split water molecules into hydrogen and oxygen. This energy needs can lead to lower efficiencies when compared to other methods of hydrogen production. Also, some electrolysis methods require specific catalyst materials, such as platinum, which are expensive and resource-intensive to produce. Finding alternative catalysts that are more abundant and cost-effective is an ongoing area of research [72].

When it comes to high-temperature electrolysis, SOECs are not widely adopted in industry due to the specific operating conditions, lack of long-term stability and because they are presently in developmental stages. SOECs require operation temperatures ranging from 700 to 1000 °C. Therefore, a continuous supply of heat is required to achieve these working temperatures. For this reason, this technology is economically viable only if there is access to a cost-effective or free available source of steam for heating purposes.

When using renewable energy sources for water electrolysis, it is important to consider the fluctuation in the power supply as a crucial factor. The electricity input must be within the working thresholds of the electrolyser, so it can work. As an illustration, alkaline electrolysers have several limitations that must be overcome. For instance, the minimum load required is usually between 10% and 40% of the nominal load, and the supply of electricity must be with a current density of 0.2 up to 0.4 A/cm^2 [71].

The process of water electrolysis with unstable input energy causes a much wider range of operating parameters compared to using electricity from the grid. Therefore, it is important to list the main variables and understand the trend of the rate of energy supply [61]. The operating temperature of the electrolyser increases with an increase in the power supplied from renewable energy sources and decreases with a decrease in the power provided [61]. In addition, when the outlet flux of the electrolyser is low due to a limited supply of renewable power, the purity of hydrogen decreases. Thus, low load capacities can be problematic when fuel cells are the end destination of the output, as they require high-purity hydrogen. Consequently, coupling the electrolysers with intermittent renewable electricity presents numerous hurdles [71].

Another important aspect to consider when providing renewable energy to electrolysers is the cyclic start-up and shutdown, which can lead to device degradation. In [72], the three significant states that an electrolyser can assume are highlighted: idle, standby and production mode. In standby mode, only a few systems, such as monitoring and anti-freezing units, are functioning. Therefore, this state is recognized for its lower energy consumption. On the other hand, in the standby state, the electrolyser stands at pressure and temperature that allows for a prompt transition, within seconds, to the production state. It should be noted that this transition consumes specific energy. Lastly, the production state is the only one that can generate hydrogen through the supply of water and electricity. To conclude, the dynamic nature of the electrolyser allows for the transition between different states, resulting in energy and time consumption.

Moreover, these state options can make an installation more profitable and flexible. For instance, in cases where the demand for hydrogen is under the capacity of the electrolyser, it can be advantageous to maintain the electrolyser in a standby state during periods of high electricity prices and produce hydrogen when prices are low. By keeping the electrolyser on standby, the need for frequent cold starts is reduced, which helps prevent the degradation of the system over its lifetime. However, there may also be instances where it is preferable to shut down the unit once the hydrogen demand for a specific period has been fulfilled to avoid the electricity consumption associated with hot standby [73]. As a result of the potential challenges and disadvantages associated with pairing electrolysers with intermittent renewable energy sources, several studies have been carried out to assess the feasibility. Some researchers have researched the capability of electrolysers to respond to short-term, one and three hours, fluctuations in renewable energy supply. Their findings suggest that these systems can adapt to large power fluctuations without requiring start-and-stop operations. The experimental results showed that cell voltage remained stable throughout the test periods, indicating that the electrolysers could maintain a consistent level of performance, even when energy inputs change [61].

Thus, for the best possible use of alkaline electrolysers, they should be associated with large-scale PV power plants, since they have a greater capacity to supply enough energy to prevent recurrent stoppages and restarts [61].

3.3. Compressor

The compressor serves as the primary element in gaseous hydrogen storage, being responsible for rising gas density through a pressure increase. The two main types of compressors applied in the present context are the so-called dynamic compressors and positive displacement compressors. Positive displacement compressors operate by reducing the volume of a gas within a confined space, while dynamic compressors operate by continuously increasing the velocity of a gas as it passes through them, without relying on a confined space.

There are a wide variety of sub-categories; however, due to the specific hydrogen compression requirements, not all of them can be used [74]. An important characteristic is the pressure ratio of the compressor. If the hydrogen electrolyser output pressure is 20 bar, then the maximum pressure ratio required is 12.5:1.

Additionally, another factor that impacts the selection of the compressor is the requirement for high-purity hydrogen for fuel cells. According to [47], a PEM fuel cell requires a minimum purity of 99.95% hydrogen, although 99.99% is recommended. Consequently, the risk of contamination must be mitigated as much as possible. In this regard, the preeminent alternative is to employ oil-free compressors.

Two distinct solutions are proposed in the literature [22]: diaphragm compressors and hydraulically driven dry-running reciprocating compressors. The authors' recommendation was based on operational criteria, which can be either continuous or discontinuous. This parameter has distinct consequences on the compressors' longevity. Compressors equipped with a diaphragm enjoy a prolonged lifespan under conditions of uninterrupted operation, as frequent starts and stops have a negative impact on their temporal endurance. The dry-running reciprocated compressors are comparatively less susceptible to the influence of intermittent operational modes.

Therefore, due to the inherent volatility in the production of renewable energies, the most practical option is to use a dry-running piston reciprocated compressor. This type of compressor allows for longer operation times without the need for frequent equipment replacements [22].

3.4. Fuel Cell

Fuel cells have a lot of similarities with electrolysers, being practically manufactured with the same components though working reversibly, i.e., the hydrogen (fuel) reacts with the oxygen contained in air and generates work water and heat. Fuel cells are a power-to-power technology that enables the conversion of chemical energy into electricity [75]. It is characterized by a wide variety of fuels, including hydrogen, natural gas, methanol and several hydrocarbon fuels [39,47]. When it comes to hydrogen conversion, it is devoid of GHG. For this reason, this device plays an important role in the seasonal storage of energy produced in renewable power plants. In other words, the fuel cells become a tool that can be used in the construction of a more sustainable world [76–78]. According to [77], there has been a growing demand for renewable and low-emission power generation solutions. Because of this, significant advancements in hydrogen and fuel cell technologies have been observed, accompanied by notable market trends. These developments have had a profound impact on the field, driving it to progress and innovate.

Similar to electrolysers, fuel cells have an equivalent categorisation of devices with identical designations. The most commonly discussed types in the literature include alkaline fuel cells, PEM fuel cells, solid oxide fuel cells and phosphoric acid fuel cells. This categorization is based on variations in the components that compose each fuel cell, including the electrolyte, as well as the operational configuration of each device [34].

3.5. Definition of Conceptual Model Configuration

The PV panels can be straightly connected with the electrolyser, or a DC-DC converter can be placed between these two units [79]. The installation with a direct connection, without a DC-DC converter, is a simpler installation with lower energy losses and lower costs when compared with the indirect connection. However, since the PV system is directly linked to the electrolysis device, the output voltage and current of the combiner string box are the same as the electricity that enters the hydrogen production unit. This results in a lack of flexibility due to the strong dependence of the electrolyser operating on the current–voltage parameters of the PV panels.

To achieve a higher coupling factor, which is the energy transfer efficiency, it is necessary to position the load line of the electrolyser as near as possible to the maximum power line. Another advantage of integrating the DC-DC converter in the installation is reflected in higher operational flexibility since the component can provide power regulation. This component also reduces the voltage and current output ripple, which is crucial for enhancing the efficiency of the electrolyser. Notwithstanding, this implementation increases installation investment costs [80–82]. A connection with a converter allows for the maximum point tracking of the PV system over time and ensures that the energy produced can be supplied to the electrolyser. As a consequence, the solar energy is efficiently captured by the PV and transported to the electrolyser [83]. Thus, it was decided to model the PV system, which powers an electrolysis device, by incorporating two DC-DC converters. The first converter works as maximum power point tracking, and the second controls the electrolyser operation voltage and current. Based on the technical data previously described and discussed, the resultant configuration of the PV power plant integrated with hydrogen production and storage can be analysed in Figure 5. The presented configuration is capable of maximizing the use of the produced renewable energy while suppressing the electricity needs of an industrial facility.

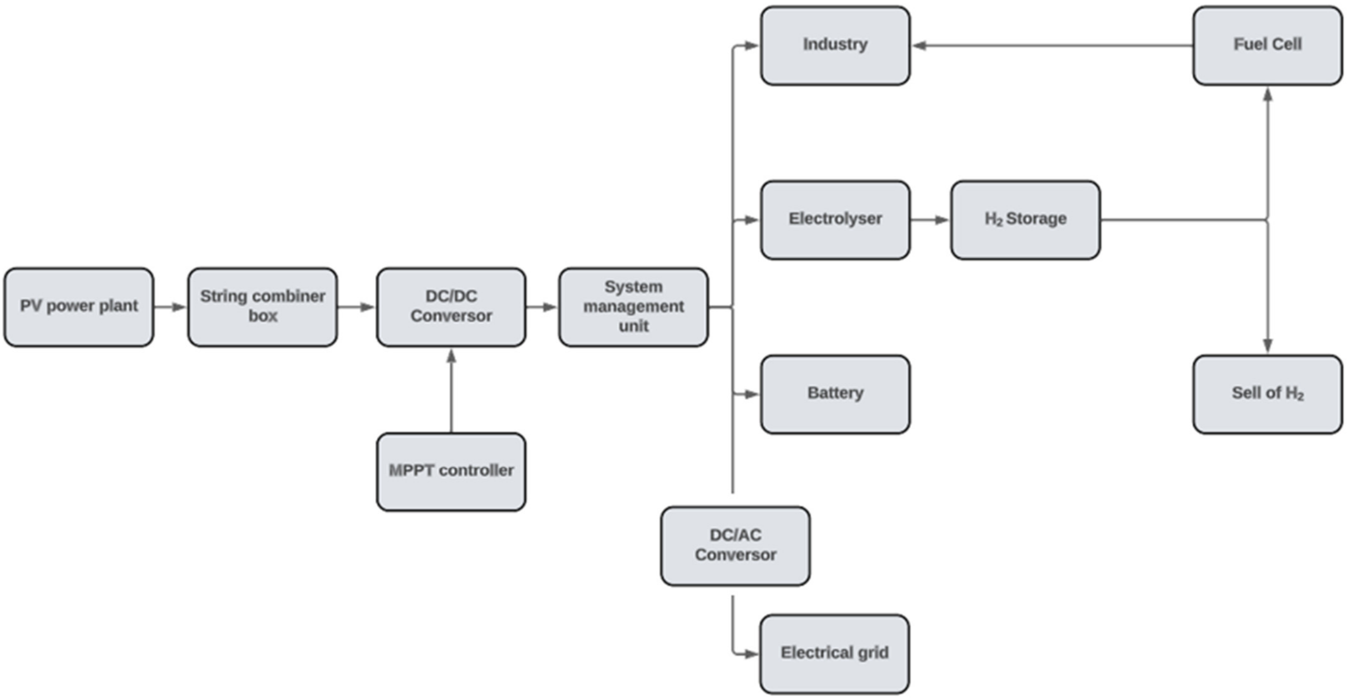

Figure 5. Model configuration of the PV power plant integrated with H_2 production for industry application.

The pivotal subsystem of this model is the PV power plant. This unit captures the solar energy and produces electricity. The PV power plant must incorporate at least one string box and the DC-DC controller. The monitoring system is responsible for receiving data corresponding to the energy produced by the PV panels and making decisions, based on specific criteria, about the distribution of this energy.

The proposed power plant configuration, in addition to the pathways to supply the industrial facility, the hydrogen production and storage unit or selling the energy surplus to the electrical grid, provides energy to a backup battery. The electrolyser should be selected considering the PV energy output, the energy required to supply the industrial factory facility and the excess energy on sunny days with the assurance that the device is not oversized. Therefore, it was necessary to estimate how much energy is produced during the days of abundant solar radiation.

Due to the inherent intermittency of the PV power plant, the compressor must be adaptable for intermittent operation. Therefore, as previously stated, the dry-running piston reciprocated compressor is the most suitable option for this kind of application. Also, as previously analysed, the PEM electrolysers have the most dynamic operation capacities and, therefore, are the best option for this application.

Regarding hydrogen storage, the selected method was to compress hydrogen gas until it achieved a satisfactory energy density, which is required for its storage. This pathway was chosen due to the higher technology maturity and lower cost. The second possibility is to use the stored hydrogen in a fuel cell to generate electrical power. In this case, another component must be considered, which is the fuel cell. Regarding the battery, this component has the role of storing part of the excess of the PV energy to fulfil the energy needs of the electrolyser and compressor, if necessary.

4. Discussion and Conclusions

The current work aimed to model the green hydrogen value chain and present the conceptual model of a PV power plant integrated with hydrogen production and storage, whereas the objective was to maximize the use of renewable energy produced while suppressing the electricity needs of an industrial facility.

European countries are implementing numerous protocols regarding sustainability. Notably, the European Green Deal stands as a substantial plan, backed by an EUR one trillion investment to combat climate change to stimulate economic growth and establish sustainable energy resource management. This steadfast commitment is demonstrated by investments in renewable energy, improved energy efficiency, decarbonization and reduced dependency on fossil fuels, positioning Europe at the forefront of sustainable development initiatives. To implement and achieve these sustainable objectives and policies, it is necessary to address the harnessing of renewable energy and mitigate its volatility. In this context, hydrogen emerges as a promising solution to address renewable instability since it can work as an energy storage medium, adaptable for daily to seasonal energy demands, and mitigate electricity instability and renewable energy integration.

Hydrogen use is expanding into more sectors of society, such as transportation and as a final energy supplier in industrial processes and steel manufacturing. The main goal is to promote decarbonization in these sectors through sustainable hydrogen supply chains. The combination of hydrogen-related technologies with primary energy sources, such as solar and wind, promotes energy storage and enhances its utility.

The integration of water electrolysis into the renewable energy power plant allows for the production of hydrogen using renewable energy during periods of low consumption and high renewable energy production. Consequently, energy is stored and not wasted. In addition, the chemical energy stored as hydrogen can be converted back into electricity and be used during periods of higher energy demand, such as peak consumption. As a result, it is possible to mitigate peaks in electricity demand and minimize the overall expenses associated with energy consumption [42].

A clean solution to convert chemical energy stored as hydrogen back into electricity is a fuel cell. Its operating principle is based on the conversion of chemical energy into electricity, with water and heat as a byproduct, representing a way to use hydrogen as a sustainable fuel. Despite its high investment cost, this technology reveals numerous qualities, such as its high efficiency that can exceed 90% when considering the recovery of 30% to 40% of emitted heat; its low operating cost; its high reliability with a degradation lower than 0.1% in a thousand hours of operation; and its silent operation. Furthermore, its abundant range of power ratings, from a few watts to several gigawatts, allows for its application in distinct environments. If the hydrogen supplied to the fuel cell has been produced from renewable energy sources, the direct emissions associated with the entire process will be approximately zero [84].

In sum, green hydrogen has one of the lowest environmental impacts, but its production is still costly compared to the remaining alternatives. In 2021, approximately 120 Mton of hydrogen was produced, and less than 1% of this amount was obtained through water electrolysis using renewable energy sources [18]. Therefore, research in the field of green hydrogen is focused not only on technical development but also on the economic aspect, aiming to achieve a cost-effective production method.

As explored in Section 2, several countries are exploring the possibility of integrating water desalination with renewable power systems. This integration aims to reduce the overall system cost while increasing the energy supply flexibility between the applications and economic sectors. Yet, some considerations should not be disregarded. For instance, ignoring the water supply can lead to misleading cost estimations, making the production appear cheaper than it is. Furthermore, choosing a production method without considering the local conditions of a particular region may result in an unsuitable approach for that specific area. Overall, structuring a hydrogen supply chain sourcing plan must consider two primary hurdles. The first hurdle concerns the availability, quality, location and accessibility of different energy sources and their cost concerning the energy market and long-term supplier agreements. The second hurdle involves the unpredictable nature of renewable sources. Also, one of the most challenging aspects of the proposed model is powerplant component sizing and the use of water electrolysis for hydrogen production, mostly due to the operational requirements and technology costs. As published in [85], for hydrogen production from solar energy sources, Portugal should be the location with the lowest LCOH production by 2030 (EUR 2.66 per kg). This represents a good perspective when compared with the estimated values from Hydrogen Europe to 2021, a cost from EUR 2.90 to 3.50 per kg.

The conceptual model of a PV power plant integrated with hydrogen production and storage requires the selection and sizing of all the system components. Taking into consideration the trade-off between energy generation and investment costs, it has been considered that the solar panels should be assembled in a single-axis solar tracker. The consideration is based on the fact that this single-axis solar tracker is the most balanced in terms of solar capture and investment costs. To be specific, the single-axis solar tracker has better solar capture than the fixed tracker and lower CAPEX and OPEX than the two-axis tracker. Additionally, the two-axis tracker is associated with lower reliability and a larger occupied area. The PV must incorporate controllers and a monitoring unit, responsible for receiving data corresponding to the energy produced by the PV panels and making decisions, based on specific criteria, about the distribution of this energy (four possible pathways for the energy—the industrial sector, hydrogen facilities, battery or the grid). The number of solar panels should be defined taking into account the energy output of the industry (main energy use pathway). Regarding the hydrogen production energy unit, this should be sized taking into account the PV energy output and industry energy demand (variation). As previously analysed, the PEM electrolyser has the most dynamic operation capacities and, therefore, is the best option for this application. Several factors were evaluated to select the most suitable compressor: the contamination of hydrogen because a high level of hydrogen purity is required; the compressor must be adaptable for intermittent operation due to the solar energy source; the need for sealing the compressor, avoiding hydrogen leakage. It is necessary to consider the fact that the compressor operation is related to the electrolyser output. Since it is extremely difficult to perfectly match the optimal operating point of each device over time, one of them has to be oversized. In this case, the compressor might need to have an oversized capacity because all the hydrogen generated must be compressed before its storage. Therefore, there is no point in having the electrolyser produce more hydrogen than the compressor can compress. Conversely, if the compressor is oversized, all the hydrogen produced can be compressed and stored. Regarding hydrogen storage, the selected method is to compress hydrogen gas due to the higher technology maturity and lower cost. Given that liquid hydrogen attains higher levels of energy density, which is more relevant for transportation than for stationary storage, there are no advantages in selecting liquid storage from this perspective.

After the definition of this conceptual model, and as future work, we propose the development of a thermo-economic model regarding the presented conceptual system to simulate energy production, taking into account the four paths for energy used. The mathematical model should be developed to optimize energy use from the PV power plant, whereas the primary objective is to maximize energy use with hydrogen production and storage.

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