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Review

Green Hydrogen: Resources Consumption, Technological Maturity, and Regulatory Framework

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Abstract: Current climate crisis makes the need for reducing carbon emissions more than evident. For this reason, renewable energy sources are expected to play a fundamental role. However, these sources are not controllable, but depend on the weather conditions. Therefore, green hydrogen (hydrogen produced from water electrolysis using renewable energies) is emerging as the key energy carrier to solve this problem. Although different properties of hydrogen have been widely studied, some key aspects such as the water and energy footprint, as well as the technological development and the regulatory framework of green hydrogen in different parts of the world have not been analysed in depth. This work performs a data-driven analysis of these three pillars: water and energy footprint, technological maturity, and regulatory framework of green hydrogen technology. Results will allow the evaluation of green hydrogen deployment, both the current situation and expectations. Regarding the water footprint, this is lower than that of other fossil fuels and competitive with other types of hydrogen, while the energy footprint is higher than that of other fuels. Additionally, results show that technological and regulatory framework for hydrogen is not fully developed and there is a great inequality in green hydrogen legislation in different regions of the world.

Keywords: green hydrogen; water footprint; energy footprint; TRL of hydrogen technologies; green hydrogen regulatory framework; green hydrogen guarantees of origin

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1. Introduction: Scientific Background and Related Works

The climate emergency highlights the need to reduce carbon emissions in accordance with the commitments of the 2015 Paris Agreement [1] and to look for an alternative to fossil fuels [2,3]. In that sense, the implementation of systems based on renewable energy sources (RES) is essential to achieve this goal. However, the energy generation from RES (such as wind or solar energy) is not constant, but rather stochastic, so energy storage systems are required when renewable production is higher than energy demand and then use this stored energy when needed [4,5]. Then, the use of green hydrogen (produced from water and renewable sources) as energy carrier makes sense [4]. Furthermore, as a result of its high potential and chemical properties, hydrogen is expected to be a leading energy carrier and is considered to be decisive in reducing greenhouse gas emissions and helping to avoid raising the Earth's temperature above 1.5 °C [1,6,7].

Among the more than well-known properties that make hydrogen the most ideal candidate for decarbonising both the economy and the industry, the possibility of using hydrogen as a long-term storage option [8–10], thanks to its high lower heating value (LHV), which is 33.36 kWh/kg (much higher than that of the rest of fossil fuels) [8,9], can be highlighted. Hydrogen is a clean option, since it does not emit carbon dioxide during combustion. Moreover, in the case of green hydrogen, it is also sustainable, because it is obtained via renewable powered electrolysis [11–14].

The scientific literature has demonstrated that hydrogen has the chemical properties which make it the ideal candidate to be considered the fuel of the future [8–10] and that green hydrogen has well-known environmental benefits [11–13]. Now, it is time to evaluate green hydrogen from other points of view that help to understand the possibilities for large-scale deployment. Thus, resources consumption footprint, technology readiness level (TRL), and regulatory framework are three pillars that, properly analysed, will allow defining the necessary path that will lead to the correct and appropriate deployment of green hydrogen technology.

Different studies can be found in which the mentioned different aspects such as the hydrogen water footprint are considered: in [15], the water footprint of hydrogen obtained via steam methane reforming (SMR), glycerol reforming, and bioethanol reforming is presented; in [16], the water footprint of hydrogen obtained thanks to the conversion of municipal sludge into hydrogen by plasma gasification is calculated; in [17], the water footprint associated with hydrogen produced via water electrolysis with an energy input from the main grid on the one hand, from photovoltaic energy on the other hand, and finally from wind energy, is calculated for the case of Australia; while in [18], the water footprint associated with the different hydrogen production technologies, as well as the water footprint associated with different hydrogen production pathways are presented, and [19] explains that a green hydrogen economy would have lower water requirements than the current fossil fuel energy-based economy. However, in the analysed literature, no comparison of the water footprint of the different hydrogen production pathways with the water footprint associated with other energy sources, such as nuclear energy, oil, coal, etc. has been found.

On the other hand, regarding the energy footprint of hydrogen, in [18,20], the energy footprint of hydrogen production by different process (such as steam and methane reforming, water electrolysis, or biomass gasification, among others) is presented, while [21,22] present the energy footprint of different water electrolysis technologies. However, no comparison of the hydrogen energy footprint with the energy footprint of fossil fuels per unit of energy contained in the respective fuel, or what is equivalently called the inverse of the energy return on investment, EROI, for example, is found in the analysed literature.

From the point of view of the technological development of the different hydrogen technologies, various papers have made a study of the TRL of hydrogen production technologies (such as hydrogen obtained through SMR, water electrolysis, methane pyrolysis, etc.) [7,23–28]. Regarding storage and distribution, a study of the TRL of the different hydrogen storage technologies (metal hydrides storage, compressed hydrogen, liquid hydrogen, metal-organic frameworks, liquid organic hydrogen carriers, etc.) [28–33], and a study of the TRL of the hydrogen distribution process (which is carried out in the pipelines) [33], are presented. Moreover, it is possible to find studies which analyse the final uses that can be given to hydrogen (i.e., the iron and steel industry, the ammonia or methanol production, the use of hydrogen in refineries, in polymer exchange membrane fuel cells (PEM-FC), in solid oxide fuel cells (SOFC), etc.) from a TRL point of view [34–36]. However, none of the references consulted makes a study on the TRL including all the hydrogen technologies at each and every stage of the hydrogen supply chain, i.e., production, storage, distribution, and end use of hydrogen; moreover, in this last stage, almost no study explicitly analyses the TRL [37].

The last pillar to analyse is the regulatory framework from the point of view of guarantees of origin (GO). Papers [38,39] study the formal definitions of green hydrogen that can be found in the literature as well as the GOs that are being developed around the world based on the formal definitions under development, while [40] proposes a model to determine the so-called Hydrogen Cleanness Index (HCI), which can be considered for GO schemes. Furthermore, regarding GO certifications, there are already projects such as the Certifhy project, which has already proposed a European-wide GO to distinguish between low-carbon and renewable hydrogen [38,41]. However, among the references consulted, only [38] studies the state of the art of GO certifications around the world; nevertheless, this reference does not consider the current legal status of green hydrogen in different parts of the world, which is essential to later establish the GO certifications; in addition, only [39] partially studies green hydrogen regulation in the different National Hydrogen Strategies, giving green hydrogen definitions in the respective legislation when possible.

In summary, the authors' proposal presents a detailed analysis of the three key pillars upon which hydrogen technology is supported: resources consumption, technological development, and regulatory framework. For this purpose, Section 2 analyses the water footprint of green hydrogen, giving a practical example based on a real microgrid located at the "La Rábida Campus", University of Huelva (UHU), Spain, and comparing it with the water footprint of other types of hydrogen (i.e., hydrogen obtained by different chemical processes and/or with an energy input that comes from other energy sources).

Next, a study of the energy footprint of green hydrogen is conducted in Section 3, comparing it with that of other types of hydrogen and other fossil fuels (comparing the energy required to obtain that fuel per unit of energy contained in the respective fuel). Afterwards, a study of the TRLs of hydrogen technologies covering the entire hydrogen supply chain (i.e., production, storage, distribution, and final application) is made in Section 4. The legal status of green hydrogen in different parts of the world and, when applicable, the requirements needed to obtain a GO for green hydrogen are discussed in Section 5. The paper ends with the Discussions and Conclusions in Sections 6 and 7, respectively.

Table 1 emphasises the main novelties of this paper, compared to the analysed scientific literature.

Table 1. Main contributions of authors' proposal with respect to analysed scientific literature.

		[17]	[18]	[20]	[21,22]	[7,23–27]	[28]	[29–32]	[33]	[34–36]	[38]	[39]	[40]	Authors' Proposal
Water footprint	Green hydrogen	·	·											·
	Other types		·											·
Energy footprint	Green hydrogen (1)	·	·	·	·									·
	Other types	·	·	·										·
	Comparison with fossil fuels													·
TRL Hydrogen supply chain	Production					·	·				·			·
	Storage						·	·	·					·
	Distribution								·					·
	Final use									·				·
Regulatory frame-work	GO										·	·	· (2)	·
	Normative											·		·

(1) Water electrolysis technologies energy footprints are studied. (2) Ref. [40] proposes a model to determine the HCI.

2. Green Hydrogen Water Footprint

Atomic hydrogen, which is the most abundant element in the universe [42,43], cannot be found as a pure element on Earth. However, it can be found combined with other elements [44] (for example, oxygen, forming water, nitrogen, forming ammonia, or carbon, forming methane or other hydrocarbons). Depending on the chemical process carried out to extract the hydrogen and the type of energy used in the process, the hydrogen molecule can be classified into different categories labelled with different colours. These colours indicate, from green to black, the highest to lowest degree of renewability, respectively, of the process [45–47], Table 2.

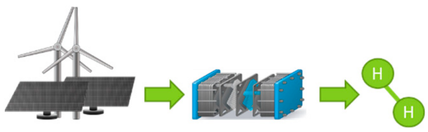
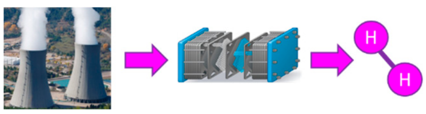
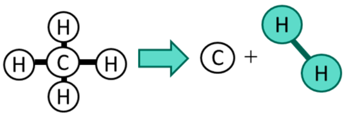
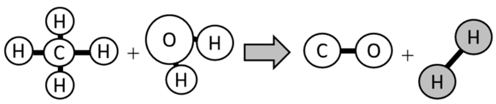
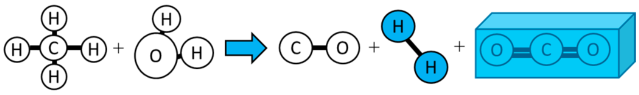
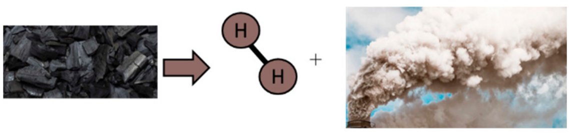
Among the different types of hydrogen that have been previously seen, green hydrogen (the only one that is obtained via renewable powered electrolysis), is produced from water. In this process, water molecule is separated into hydrogen and oxygen, Equation (1) [17,47]:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \quad (1)$$

From a simple operation, and taking into account the molar ratio to obtain hydrogen and oxygen from water, the molar mass of each molecule, and the volumetric density of water, the amount of water needed to produce 1 kg of hydrogen can be obtained from Equation (2).

$$1\ \mathrm{kg\ H_2} \cdot \frac{1\ \mathrm{mol\ H_2}}{0.002\ \mathrm{kg\ H_2}} \cdot \frac{1\ \mathrm{mol\ H_2O}}{1\ \mathrm{mol\ H_2}} \cdot \frac{0.018\ \mathrm{kg\ H_2O}}{1\ \mathrm{mol\ H_2O}} \cdot \frac{1\ \mathrm{L\ H_2O}}{1\ \mathrm{kg\ H_2O}} = 9\ \mathrm{L\ H_2O} \quad (2)$$

Table 2. Coloured labels used to classify the hydrogen molecule according to the production process and type of energy used in it.

	Coloured Label for H_2	Chemical Process + Energy Input	Highlights
	Green	Renewable powered water electrolysis	Sustainable (no carbon emissions associated)
	Pink	Nuclear powered water electrolysis	Very low carbon emissions associated
	Turquoise	Methane pyrolysis	Generates solid carbon residues (neutral in carbon dioxide emissions)
	Grey	Steam and methane/gas natural reforming	Generates greenhouse gases emissions
	Blue	Hydrogen obtained from fossil fuels with carbon capture	Carbon dioxide emissions are significantly reduced
	Black/brown	Hydrogen obtained from gasification of coal	Large carbon emissions associated

Although theoretically only 9 litres of water are needed to obtain 1 kg of hydrogen, in practice, this rate is higher for the different water electrolysis technologies. This is due [48] to the need of a cooling load in the electrolysers (which may require up to 30–40 L of additional water per kg of hydrogen), as well as the associated water treatments, which imply a higher water usage. On the other hand, the water consumption to produce 1 kg of hydrogen is very different between the analysed studies and the commercially available electrolysers that provide water consumption data. For example, [18] estimates the water consumption at 18 L of water per kg of hydrogen produced for polymer exchange membrane (PEM) electrolysers and 9.1 L of water per kg of hydrogen produced for solid oxide electrolysers, while Siemens-Energy [49] claims that their PEM electrolyser (Silyzer 300) has a consumption of 10 L of water per kg of hydrogen produced and SinoHy Energy [50] claims that their alkaline electrolyser has a consumption of 10.1 L of water per kg of hydrogen produced (however, all of these rates are far below the study in [48], which puts the amount of water consumed in an electrolyser at 60–95 L of water per kg of hydrogen produced). Regarding the green hydrogen generation water footprint (i.e., considering the whole process of using renewable energy to produce hydrogen), [51] estimates the green hydrogen water footprint at 13.4 L of water per kg of green hydrogen produced via wind-powered electrolysis at a central electrolysis plant located in the US, while the study carried out in [17] estimates, in the case of Australia, a water footprint of 43 L of water per kg of green hydrogen produced via solar-powered electrolysis and a water footprint of 17 L of water per kg of green hydrogen produced via wind-powered electrolysis (this rate is considerably lower than the water footprint of hydrogen produced via grid-mix powered electrolysis, which is estimated to be 129 L of water per kg of hydrogen produced).

Due to this disparity of data and criteria, the authors present a real practical case to study the water footprint of green hydrogen produced in a microgrid. The microgrid is located at the "La Rábida Campus", University of Huelva, Spain. Based on [52], it is known that the global average water footprint of PV energy is 0–0.11 L of water per kWh (during the operational stage); however, this rate is subjected to wide variations depending on the location. To know the water footprint of PV energy in the region under consideration, firstly, the total amount of water needed in the world (so that PV plants can operate) can be estimated. For that purpose, the total amount of energy produced worldwide by PV energy is needed to be known before that of the total PV power installed worldwide. As the IRENA data show [53], this date is known to be 830,741 GWh for the year 2020, while the total PV power installed by the end of 2020 reached 710 GW globally. Assuming a lifetime of the photovoltaic panels of 25 to 30 years [54,55], the water footprint of PV power (during the whole lifetime of the panel) can be estimated, see Equation (3):

$$
\begin{aligned}
WF_{PV}\left(\frac{\text{L H}_2\text{O}}{\text{kW}}\right) &= \frac{WF_{PV\ world}\left(\frac{\text{L H}_2\text{O}}{\text{kWh}}\right)\cdot E_{a.PV\ world}\cdot T_{PV\ panel}}{P_{PV\ world}} \\
WF_{PV}\left(\frac{\text{L H}_2\text{O}}{\text{kW}}\right) &= \frac{0-0.11\frac{\text{L H}_2\text{O}}{\text{kWh}}\cdot 830741\frac{\text{GWh}}{\text{year}}\cdot\frac{10^6\text{kWh}}{1\text{GWh}}\cdot\frac{25-30\text{ years}}{\text{panel}}}{710\ GW\cdot\frac{10^6\text{kW}}{1\text{ GW}}} \\
WF_{PV}\left(\frac{\text{L H}_2\text{O}}{\text{kW}}\right) &\approx 0-3861\frac{\text{L H}_2\text{O}}{\text{kW}}
\end{aligned}
\tag{3}
$$

where

$WF_{PV}\left(\frac{\text{L H}_2\text{O}}{\text{kW}}\right)$: water footprint of PV power.

$WF_{PV\ world}\left(\frac{\text{L H}_2\text{O}}{\text{kWh}}\right)$: water footprint of PV energy worldwide (0–0.11 L H_2O/kWh).

$E_{a.\ PV\ world}$: PV energy generated annually worldwide (830741·10^6 kWh/year).

$T_{PV\ panel}$: average lifetime of a PV panel (25–30 years/panel).

$P_{PV\ world}$: total PV power installed worldwide (710·10^6 kW).

Taking this into account, now the water footprint of PV energy per kWh (during the whole lifetime of a PV panel) will be studied for the case of PV panels located at the renewable-based microgrid at the "La Rábida Campus" of the University of Huelva. For this purpose, the water footprint of PV power will be considered equal regardless of geographical location, but not the water footprint of PV energy, which will depend on the amount of energy produced by a panel of a given power, i.e., the water footprint of PV energy will be implicitly determined by the geographical location). From previous works [9], for the renewable-based microgrid located at Huelva, containing 15 kW of PV power (5 kW of mono-Si, 5 kW of poly-Si, and 5 kW of thin film technology), the energy generated during a whole year will be 22,590 kWh, see Figure 1.

With all this information, the water footprint of PV energy (L H_2O/kWh) for the studied case can be calculated, see Equation (4):

$$
\begin{aligned}
WF_{PV-Huelva}\left(\frac{\text{L H}_2\text{O}}{\text{kWh}}\right) &= \frac{P_{PV}\cdot WF_{PV}\left(\frac{\text{L H}_2\text{O}}{\text{kW}}\right)}{E_{a.\ PV\ microgrid}\cdot T_{PV\ panel}} \\
WF_{PV-Huelva}\left(\frac{\text{L H}_2\text{O}}{\text{kW}}\right) &= 15\text{ kW}\cdot 0-3861\frac{\text{L H}_2\text{O}}{\text{kW}}\cdot\frac{1\text{ year}}{22590\text{ kWh}}\cdot\frac{1\text{ panel}}{25-30\text{ years}} \\
WF_{PV-Huelva}\left(\frac{\text{L H}_2\text{O}}{\text{kW}}\right) &\approx 0-0.1\frac{\text{L H}_2\text{O}}{\text{kWh}}
\end{aligned}
\tag{4}
$$

where

$WF_{PV-Huelva}\left(\frac{L\ H_2O}{kWh}\right)$: water footprint of PV energy in the "La Rábida Campus" (Huelva).
P_{PV}: PV power installed in the considered location (15 kW).
$E_{a.\ PV\ microgrid}$: PV energy generated annually in the studied microgrid (22590 kWh).

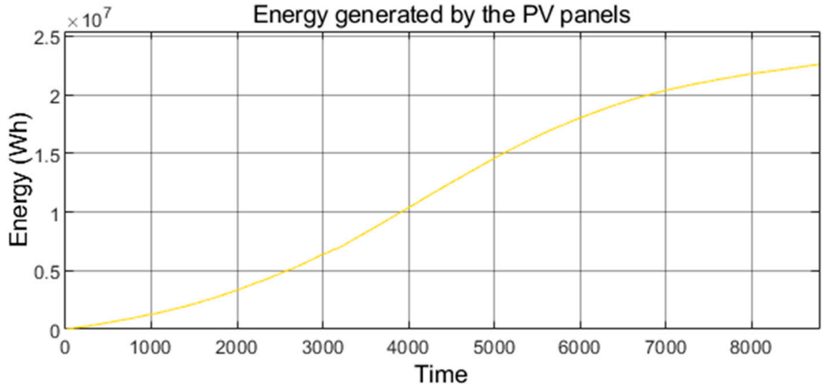


Figure 1. Energy generated by a 15 kW-PV array during a year at La Rábida campus.

That is, the water footprint of PV energy in Huelva is slightly lower than the global average water footprint for PV energy [52].

In case the renewable resource for producing hydrogen from electrolysis is wind energy, during the operational stage, its water footprint [52] is estimated to be 0 L/kWh for the case of the European Union; however, this rate rises to 0.64 L/kWh [52] over the life cycle of wind energy in the case of China. This takes into account that, according to Reuters [56], the wind power generation in China for the year 2022 was about 800 TWh, while the total installed wind power capacity was 278.353 GW as of January 2023. As the lifetime of a wind turbine is estimated to be around 20 years [57,58], then the water footprint of wind power (during the whole lifetime of a wind turbine, considering that the water footprint of wind power is, regardless of its location, similar to the water footprint of PV power) can be obtained, see Equation (5):

$$WF_{wind}\left(\frac{L\ H_2O}{kW}\right) = \frac{WF_{wind\ China}\left(\frac{L\ H_2O}{kWh}\right)\cdot E_{a.\ wind\ China}\cdot T_{WT}}{P_{wind\ China}}$$
$$WF_{wind}\left(\frac{L\ H_2O}{kW}\right) = \frac{0-0.64\ \frac{L\ H_2O}{kWh}\cdot 800\,\frac{TWh}{year}\cdot\frac{10^9 kWh}{1\ TWh}\cdot\frac{20\ years}{wind\ turbine}}{278.353\ GW\cdot\frac{10^6 kW}{1\ GW}} \quad (5)$$
$$WF_{wind}\left(\frac{L\ H_2O}{kW}\right) \approx 0-36788\,\frac{L\ H_2O}{kW}$$

where
$WF_{wind}\left(\frac{L\ H_2O}{kW}\right)$: water footprint of wind power.
$WF_{windChina}\left(\frac{L\ H_2O}{kWh}\right)$: water footprint of wind energy in China (0–0.64 L H_2O/kWh).
$E_{a.windChina}$: wind energy generated annually in China (800·10^9 kWh/year).
T_{WT} : average lifetime of a wind turbine (20 years/wind turbine).
$P_{windChina}$: total wind power installed in China (278.353·10^6 kW).

With this information, the water footprint of wind energy for the case of a wind turbine located at the "La Rábida Campus" of the University of Huelva can now be calculated. For this purpose, the annual wind energy generation needs to be known. From previous works [9], for a 3.4 kW wind turbine located at the aforementioned place, the annual energy generation result is 1087 kWh, see Figure 2.

Then, the water footprint (L H_2O/kWh) of wind energy for the studied case can be calculated thanks to Equation (6):

$$WF_{wind-Huelva}\left(\frac{\text{L H}_2\text{O}}{\text{kWh}}\right) = \frac{P_{wind}\cdot WF_{wind}\left(\frac{\text{L H}_2\text{O}}{\text{kW}}\right)}{E_{a.\ wind\ microgrid}\cdot T_{WT}}$$

$$WF_{wind-Huelva}\left(\frac{\text{L H}_2\text{O}}{\text{kWh}}\right) = 3.4\ \text{kW}\cdot 0 - 36788\frac{\text{L H}_2\text{O}}{\text{kW}}\cdot\frac{1\ \text{year}}{1087\ \text{kWh}}\cdot\frac{1\ \text{turbine}}{20\ \text{years}} \quad (6)$$

$$WF_{wind-Huelva}\left(\frac{\text{L H}_2\text{O}}{\text{kWh}}\right) \approx 0 - 5.75\frac{\text{L H}_2\text{O}}{\text{kWh}}$$

where
$WF_{wind-Huelva}\left(\frac{\text{L H}_2\text{O}}{\text{kWh}}\right)$: water footprint of wind energy in "La Rábida Campus" (Huelva).
P_{wind}: wind power in the considered location (3.4 kW).
$E_{a.\ wind\ microgrid}$: wind energy generated annually in the studied microgrid (1087 kWh).

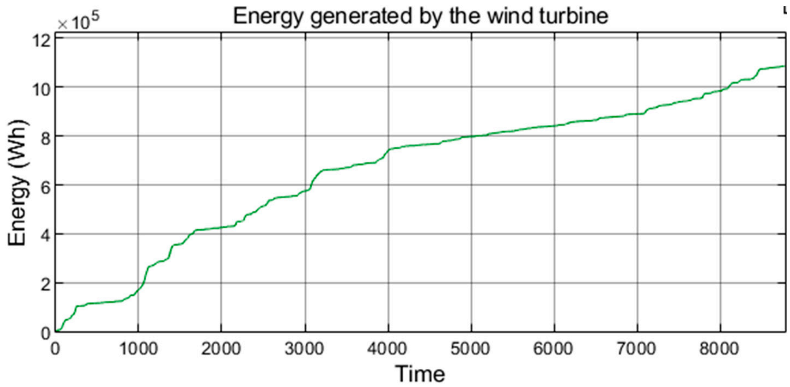


Figure 2. Energy generated by a 3.4 kW-rated power wind turbine during a full year at La Rábida Campus.

As result of the low wind energy production at the "La Rábida Campus", the water footprint of wind energy in this location is much higher than that of China. On the other hand, since the energy footprint of hydrogen obtained via water electrolysis (this will be further studied in the next section) is 36.14–54.6 kWh/kg [18], the water footprint of green hydrogen for the case studied will now be calculated for three cases: green hydrogen produced via solar-powered electrolysis, green hydrogen produced via wind-powered electrolysis, and green hydrogen produced via wind- and solar-powered electrolysis. For the first case, the water footprint will be shown in Equation (7):

$$WF_{Huelva\ H_2\ solar} = WF_{electrolyser} + E_{electrolysis}\cdot WF_{PV\ Huelva}\left(\frac{\text{L H}_2\text{O}}{\text{kWh}}\right)$$

$$WF_{Huelva\ H_2\ solar} = 9.1 - 18\frac{\text{L H}_2\text{O}}{\text{kgH}_2} + 0 - 0.10\frac{\text{L H}_2\text{O}}{\text{kWh}}\cdot 36.14 - 54.6\frac{\text{kWh}}{\text{kgH}_2} \quad (7)$$

$$WF_{Huelva\ H_2\ solar} = 9.1 - 23.46\frac{\text{L H}_2\text{O}}{\text{kgH}_2}$$

where
$WF_{Huelva\ H_2 solar}$: water footprint of green hydrogen produced via solar energy in Huelva (L H_2O/kg H_2).
$E_{electrolysis}$: energy required in the electrolyser so that the electrolysis takes place (36.14–54.6 kWh/kg H_2).
$WF_{electrolyser}$: water footprint of an electrolyser (9.1–18 L H_2O/kg H_2).

On the other hand, for the case of hydrogen obtained via wind-powered electrolysis at the "La Rábida Campus", the water footprint will be shown in Equation (8):

$$WF_{Huelva\ H_2\ wind} = WF_{electrolyser} + E_{electrolysis}\cdot WF_{wind\ Huelva}\left(\frac{\text{L H}_2\text{O}}{\text{kWh}}\right)$$

$$WF_{Huelva\ H_2 wind} = 9.1 - 18\frac{\text{L H}_2\text{O}}{\text{kgH}_2} + 0 - 5.75\frac{\text{L H}_2\text{O}}{\text{kWh}}\cdot 36.14 - 54.6\frac{\text{kWh}}{\text{kgH}_2} \quad (8)$$

$$WF_{Huelva\ H_2 wind} = 9.1 - 331.95\frac{\text{L H}_2\text{O}}{\text{kgH}_2}$$

where

$WF_{Huelva\ H_2\ wind}$: water footprint of green hydrogen produced via wind energy in Huelva (L H_2O/kg H_2).

Finally, for the case of green hydrogen obtained via solar- and wind-powered electrolysis at the aforementioned place, taking into account that the renewable-based microgrid placed there produces 22,590 kWh and 1087 kWh of solar and wind energy, respectively, the water footprint will be shown in Equation (9):

$$WF_{Huelva\ gr.\ H_2} = WF_{Huelva\ H_2\ solar} \cdot \frac{E_{a.PV\ microgrid}}{E_{a.\ PV\ microgrid} + E_{a.wind\ microgrid}} + WF_{Huelva\ H_2\ wind} \cdot \frac{E_{a.wind\ microgrid}}{E_{a.PV\ microgrid} + E_{a.wind\ microgrid}}$$
$$WF_{Huelva\ gr.\ H_2} = 9.1 - 37.6 \frac{L\ H_2O}{kgH_2} \quad (9)$$

where

$WF_{Huelva\ gr.\ H_2}$: water footprint of green hydrogen produced in Huelva (L H_2O/kg H_2).

To put into context the water footprint of green hydrogen, Table 3 shows a comparison of the water footprint (WF) of different types of hydrogen.

Table 3. Comparison of the water footprint of different hydrogen production processes.

	Steam Methane Reforming (SMR)	Coal Gasification (CG)	Biomass Gasification (BG)	Biomass Reformation (BR)	Plasma Gasification (PG)	Green Hydrogen (GH)	
Water footprint (L H_2O)/kg H_2	21.87 [18]	2.91 [18]	305.5 [18]	30.96 [18]	11.56 [16]	13.4 (wind) [51] 43 (solar) [17] 17 (wind) [17] 129 (grid mix, no GH) [17]	
						UHU La Rábida Campus	9.1–23.46 (solar) 9.1–331.95 (wind) 9.1–37.6 (solar + wind)

Finally, if the LHV of hydrogen (33.36 kWh/kg) is taken into account [8,9], the water footprint of hydrogen per energy unit can be estimated, so that it can be compared with that of other fossil fuels and that of nuclear energy thanks to the data found in the analysed literature [59], see Table 4.

Table 4. Comparison of water footprint of hydrogen and other energy sources.

	Hydrogen	Coal	Conventional Oil	Natural Gas	Nuclear Energy
Water footprint (L H_2O/kWh)	0.656 (SMR) 0.087 (CG) 9.158 (BG) 0.928 (BR) 0.347 (PG) 0.272–1.289 (GH) (1)	0.284–7.56 [59]	0.77–4.284 [59]	0.274–4.464 [59]	0.065–4.464 [59] 1.514–2.725 [60]

(1) The WF of hydrogen obtained via grid mix powered electrolysis has not been considered in this case (it is not GH) and the WF of GH obtained via wind-powered electrolysis at the "La Rábida Campus" has not been considered (because wind energy production is very low in the mentioned place).

3. Green Hydrogen Energy Footprint

To obtain hydrogen from the raw materials, an energy input is necessary. In the case of green hydrogen, the energy footprint will be determined by the energy consumption that will take place in the water electrolysis process. To separate hydrogen from oxygen in the water molecule, it is necessary [47,61–63] to supply an energy equal to the enthalpy of formation of water (which is 284–286 kJ/mol [62], 285.84 kJ/mol [61]). However, it is not necessary to supply that amount of energy in the form of electricity; in fact, the minimum amount of energy of the enthalpy of formation of water that has to be applied as electrical energy is the free energy of reaction (Gibbs free energy) [63], which is related to the enthalpy of formation through Equation (10) [62,63]:

$$\Delta G = \Delta H - T\Delta S \quad (10)$$

where
ΔG : Gibbs free energy (kJ/mol).
ΔH : enthalpy of formation (kJ/mol).
T : temperature (K).
ΔS : entropy (kJ/(mol·K)).

On the other hand, ΔG can be obtained thanks to Equation (11) [61,62,64]:

$$\Delta G = zFU_0 \quad (11)$$

where
z : number of electrons converted per H_2 molecule (z = 2).
F : Faraday constant (96,485 C/mol).
U_0 : standard equilibrium voltage of the water electrolysis cell ($U_0 = 1.229$ V).

Gibbs free energy for the splitting of water into oxygen and hydrogen is $\Delta G = 237.2$ kJ/mol [47,61]. The rest of the energy needed for (1) to take place is taken from the environment in the form of heat (i.e., the term $T\Delta S$, which is 48.6 kJ/mol [47]). In summary, for water electrolysis, at least 237.2 kJ/mol of electrical energy or, equivalently, 2.94 kWh/Nm^3 H_2 are required [63,64]. For this reason, although different references [21,65,66] claim that the energy consumption of the solid oxide electrolyser (which is a promising electrolysis technology) is 2.5–3.5 kWh/Nm^3 H_2, the minimum value within this range that will be considered valid in this paper is 2.94 kWh/Nm^3 H_2. Taking this into account, Table 5 shows the information corresponding to the energy consumption to produce 1 Nm^3 of hydrogen according to the electrolysis technology used: i.e., alkaline water electrolysis (AWE), polymer exchange membrane water electrolysis (PEM-WE), solid oxide water electrolysis (SO-WE), or anion exchange membrane water electrolysis (AEM-WE).

Table 5. Electric energy consumption of different electrolysis technologies.

Electrolysis Technology	Energy Consumptions (kWh/Nm^3 H_2)
AWE	**Stack energy consumption:** 4.3–4.8 [23] 3.8–4.4 [47] (Nel A3880) 5.0–5.4 [47] (Cummins HySTAT®-100-10) 4.0–4.3 [47] (John Cockerill DQ-500) 4.5 [47] (McPhy MeLyzer 800-30) 4.7 [47] (Sunfire HyLink Alkaline) 4.6 [47] (Nuberg PERIC ZDQ-600) 4.4 [47] (TIANJIN Mainland FDQ800) 4.3 [47] (Green Hydrogen Systems HyProvide A-90) 4.2–5.9 [67] 4.46 [68] (Current state of the art) 4.29 [68] (Estimation for 2030) <3.75 [68] (Estimation for 2050) 4.5–5.5 [69] 4.2–4.8 [70] 4.2–5.89 (IRENA, 2020) [71] <3.75 (IRENA, 2050 target) [71] **System energy consumption:** 4.5–7.0 [21,70] 4.46–6.96 (IRENA, 2020) [71] 4.02 (IRENA, 2050 target) [71]

Table 5. *Cont.*

Electrolysis Technology	Energy Consumptions (kWh/Nm^3 H_2)
PEM-WE	**Stack energy consumption:** 4.6–5.3 [23] 4.5 [47] (Nel M5000) 4.3 [47] (HyLyzer®-4000-30) 5.2 [47] (Plug Power GenFuel 5 MW) 4.9 [47] (Elogen ELYTE 260) 4.2–5.5 [67] 4.91 [68] (Current state of the art) 4.29 [68] (Estimation for 2030) <3.75 [68] (Estimation for 2050) 3.84 (2020 US DOE target) [69] 4.4–5.0 [70] 4.2–5.89 (IRENA, 2020) [71] <3.75 (IRENA, 2050 target) [71] 4.88 [18] **System energy consumption:** 3.93 (2020 US DOE target) [69] 4.5–7.5 [65,70] 4.5–7.0 [21] 4.46–7.41 (IRENA, 2020) [71] 4.02 (IRENA, 2050 target) [71]
SO-WE	**Stack energy consumption:** 3.23 [18] 3.6 [47] (SunFire HyLink SOEC) 3.0–3.3 [67] 2.94–3.5 * [21,65,66] 3.13–4.46 (IRENA, 2020) [71] <3.13 (IRENA, 2050 target) [71] **System energy consumption:** 3.57–4.46 (IRENA, 2020) [71] <3.57 (IRENA, 2050 target) [71]
AEM-WE	**Stack energy consumption:** 4.8 [47] (Enapter AEM Multicore) 4.91 [68] (Current state of the art) 4.29 [68] (Estimation for 2030) <3.75 [68] (Estimation for 2050) 4.8 [65] 4.8–6.9 [70] 4.6–5.89 (IRENA, 2020) [71] <3.75 (IRENA, 2050 target) [71] **System energy consumption:** 5.09–6.16 (IRENA, 2020) [71] <4.02 (IRENA, 2050 target) [71]

*: Energy consumptions below 2.94 kWh/Nm^3 have not been considered because it is impossible to produce that quantity of hydrogen with that amount of energy.

On the other hand, the energy footprint of water electrolysis technologies can be compared to the energy footprint of other hydrogen production routes, as shown in Table 6.

However, these data need to be put in context with the energy footprint associated with other energy compounds, such as that of some fossil fuels. Thus, Table 7 shows a comparison of the energy footprint of different fuels in terms of energy required to obtain 1 kg of fuel (in kWh) per energy contained in 1 kg of the corresponding fuel (also expressed in kWh).

Table 6. Energy consumption of different hydrogen production technologies.

	AWE	PEM-WE	SO-WE	AEM-WE	SMR	CG
Energy consumption (kWh/Nm^3 H_2)	3.8–5.4 (stack) 4.46–7.0 (system)	3.84–5.89 (stack) 3.93–7.5 (system)	2.94–4.46 (stack) 3.57–4.46 (system)	4.6–5.89 (stack) 5.09–6.16 (system)	0.10 [18] (electricity) 2.04 [72,73] *	0.15 [18] (electricity) 0.55 [74] *

*: It refers to the amount of energy that is consumed in the hydrogen production process. In the case of water electrolysis technologies, the amount of energy that is consumed is considered to be electrical energy.

Table 7. Energy consumption of different fuels per energy contained in the corresponding fuel.

	Hydrogen	Coal	Oil
Energy consumption [(1)] ($kWh_{prod.}/kWh_{fuel}$)	1–2 (electrolysis, stack) 1.2–2.5 (electrolysis, system) 0.7 (SMR) 0.18 (CG)	0.0047 [75] 0.017 (China, 2018) [76] 0.013 (US, 2000) [77] 0.017 (US, 2007) [77]	19.83 (DEM) [(2)] [78] 4.96 (AAEM) [(3)] [78] 0.025–0.048 (Norway, 2008) [77] 0.022 (Mexico, 2009) [77] 0.1 (China, 2010) [77] 0.067 (China, 2018) [(4)] [76]

[(1)] To obtain the energy consumption (in terms of $kWh_{production}/kWh_{fuel}$), the lower heating values have been extracted from [79]. [(2)] DEM: Dry Extraction Method. [(3)] AAEM: Acid-assisted Extraction Method. [(4)] The huge differences between the energy consumption in [78] and the rest of the analysed literature are due to the derisory amount of oil extracted in [78], which causes the energy consumed per unit of energy to be extracted to skyrocket.

Finally, Figure 3 provides a comparative chart of water and energy footprint of green hydrogen, with other types of hydrogen (i.e., that produced via different hydrogen production pathways) and other fuels.

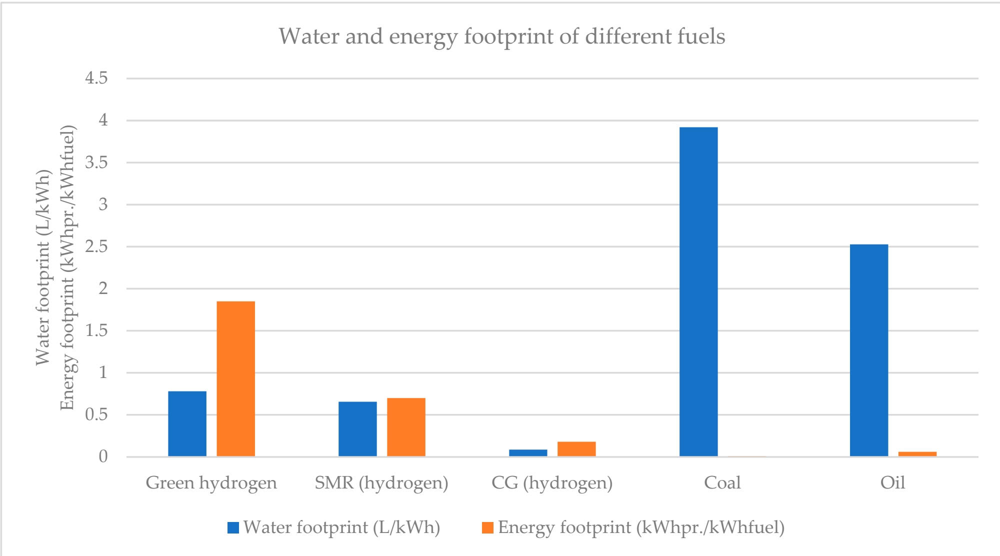


Figure 3. Water and energy footprint of different fuels.

4. TRL of Hydrogen Technologies

In the hydrogen supply chain, the next steps after production are storage, transport and distribution, to drive hydrogen to its final use [80,81]. However, different hydrogen supply chains including different hydrogen technologies can be found [82,83]. On the other hand, not all hydrogen technologies used in the hydrogen supply chain have the same level of maturity. Thus, the technology readiness level (TRL) measures the degree of maturity of a technology [84]. Although the original definition of TRL [84] involved seven stages of development, the current one (which has been adopted by NASA and the European Union) has nine levels, which are explained in more detail in Table 8.

Table 8. Levels of TRL [84].

Level	Degree of Maturity
TRL 1	Basic principles observed and reported
TRL 2	Technology concept or application formulated
TRL 3	Concept or application proven through analysis and experimentation
TRL 4	Basic prototype validated in laboratory environment
TRL 5	Basic prototype validated in relevant environment
TRL 6	System or subsystem model or prototype demonstrated in a relevant environment
TRL 7	System prototype demonstrated in an operational environment
TRL 8	Actual system completed and qualified through test and demonstration
TRL 9	Actual system proven through successful operation

As previously said, not all hydrogen technologies have the same level of maturity, i.e., they will not have the same TRL. Furthermore, at each of the different stages of the hydrogen supply chain, different technologies (with different TRLs) can be found. For example, for the hydrogen production process, several techniques (with different levels of maturity) [85,86] can be found: from fossil fuels (which can be coupled with a carbon capture process), for example, from coal gasification, steam and natural gas reforming, light oil conversion to hydrogen, heavy oil oxidation to hydrogen, etc.; from water electrolysis, in which the alkaline electrolysis and the PEM electrolysis technologies can be highlighted; or from biomass, which allows hydrogen to be obtained from biological methods (water photolysis, photo-fermentation or dark-fermentation, among others) or from chemical methods (biomass gasification, pyrolysis reforming, among others). Among the different hydrogen production technologies available, water electrolysis technologies are those used for the production of green hydrogen (which is discussed in depth throughout this manuscript). However, these technologies present risks that need to be taken into account, such as gas cross-permeation effects. These effects are so important that they may create an explosive atmosphere. In addition to the above, the corrosive environment created in the electrolyte, which can be acidic or basic depending on the electrolysis technology, must also be taken into account [87]. Table 9 provides the TRLs of different hydrogen production technologies.

Table 9. TRLs of different hydrogen production technologies.

Source of Hydrogen Production	Technology	TRL
Water electrolysis	AWE	8–9 [23,27,88] 9 [7,24,28,89,90]
	PEM-WE	7–8 [7,23] 6–8 [24,89] 8–9 [27,90,91] 6–9 [28] 6–7 [88]
	SO-WE	3–5 [7] 5 [24,89] 7 [27] 5–6 [90] 4–5 [92] 6–7 [93] 2–5 [88]
	AEM-WE	3 [91] 2–3 [94,95]

Table 9. *Cont.*

Source of Hydrogen Production	Technology	TRL
Fossil fuels	Steam and methane reforming (SMR)	9 [24,88,89,96–98] 7–8 (with carbon capture and storage, CCS) [98] 5 (with CCS) [99] 9 (with CCS) [88]
	Coal gasification (CG)	9 [96–98] 8–9 [88] 6–7 (with CCS) [98] 8–9 (with CCS) [88]
	Autothermal reforming (ATR)	9 [26] 5 (with CCS) [99]
	Methane pyrolysis (MP)	3–6 [93] 3–5 [98]
Bio-hydrogen (biological and chemical methods to obtain hydrogen from biomass)	Dark-fermentation (DF)	5 [96] 2–4 [100]
	Photo-fermentation (PF)	4 [96] 2–4 [100]
	Biogas reforming (BR)	6–7 [100]
	Biowaste pyrogasification (BPG)	8–9 [100]
	Photocatalysis (PC)	<4 [101]

Regarding hydrogen storage technology, due to the low volumetric density and energy density of hydrogen at normal conditions of pressure and temperature, 0.0899 g/L [102,103] and 0.003 kWh/L [103], respectively, the hydrogen storage techniques focus on increasing these two aspects. Among these techniques, compressed hydrogen storage, liquid hydrogen storage, metal hydrides storage, physisorption, complex hydrides, cryocompressed hydrogen storage, or liquid organic hydrogen carriers (LOHC) technologies can be highlighted [102,103]. As each of these techniques have different levels of maturity (i.e., they will present different TRLs), Table 10 presents the TRLs of different hydrogen storage technologies (although TRLs higher than 9 have been found in some references [99,104], these TRLs have been considered to be 9 in this paper).

Table 10. TRLs of hydrogen storage technologies.

	Technology	TRL
Physical storage methods	Compressed hydrogen (CH_2)	9 [29,30,104] 7–9 [32] 8–9 [105,106]
	Liquid hydrogen (LH_2)	7 [32] 4–6 [104] 6–7 [105] 6–9 [106]
	Cryocompressed hydrogen (CcH_2)	7 [32] 4–6 [104] 4–5 [105]

Table 10. *Cont.*

Technology			TRL
Material-based (chemical) storage methods	Metal hydrides (MH)		4–6 [104] 4–5 [105] 7–9 [106]
	Complex hydrides (CH)		4–6 [106]
	Physisorption (PH)	Carbon fibres (CF) and nanotubes (CN), and activated carbon (AC)	7–8 [106]
		Graphene	5–6 [106]
		Aerogel (AEG) and templated carbon (TC)	2–4 [106]
		Metal-organic frameworks (MOFs)	2–4 [106]
	LOHC		4–6 [104] 6–7 [105] 4–7 [106]

Following with the hydrogen supply chain, except in the case of hydrogen-based renewable microgrids, where the point of hydrogen production and consumption is at the same location [9,107], these two points are generally located at different sites. For this reason, hydrogen (once stored) needs to be transported and distributed. Thus, hydrogen distribution technologies (HDT) can be found to have a TRL of 9 [33], 4–9 [88]. Once hydrogen has been distributed (if necessary), it is time to put it to a final use, which can be achieved by converting the chemical energy of hydrogen into electrical energy via fuel cell or into mechanical energy via internal combustion engine [108], for example. As the different technologies that are used in the final step of the hydrogen supply chain (i.e., hydrogen final use) have a different level of maturity, Table 11 presents an estimation of the TRLs (based on the information provided by the analysed literature for the respective technologies, because few studies analyse explicitly the TRLs of hydrogen final use technologies [37]).

Table 11. TRLs of different hydrogen final use technologies.

Technology		TRL
Fuel cells (FC)	Polymer Exchange Membrane Fuel Cell (PEM-FC)	8 [35,109,110] 8–9 [111–115] 9 [116]
	Anion Exchange Membrane Fuel Cell (AEM-FC)	4 [109,117–119]
	Alkaline Fuel Cell (AFC)	8–9 [109,115,119]
	Direct Methanol Fuel Cell (DMFC *)	5–6 [109,120]
	Phosphoric Acid Fuel Cell (PAFC)	8–9 [109,121]
	Solid Oxide Fuel Cell (SOFC)	8–9 [109,114,122]
	Molten Carbonate Fuel Cell (MCFC)	4–7 [109,123]
Hydrogen Internal Combustion Engines (H_2ICE)		≤7 [124,125] ≤8 [126]
Refineries	Hydrotreating (HT)	7–9 [34]
	Crude oil refining (COR)	9 [34]
Iron and steel	Hydrogen direct reduced ironmaking (H_2DRI)	8 [34]

*: Although DMFC uses methanol as fuel instead of hydrogen, this FC has been included because methanol can be used, in turn, as a method to store hydrogen in the form of an LOHC [127].

Finally, Figure 4 illustrates a graphic comparison of the TRLs of the different stages of the hydrogen supply chain.

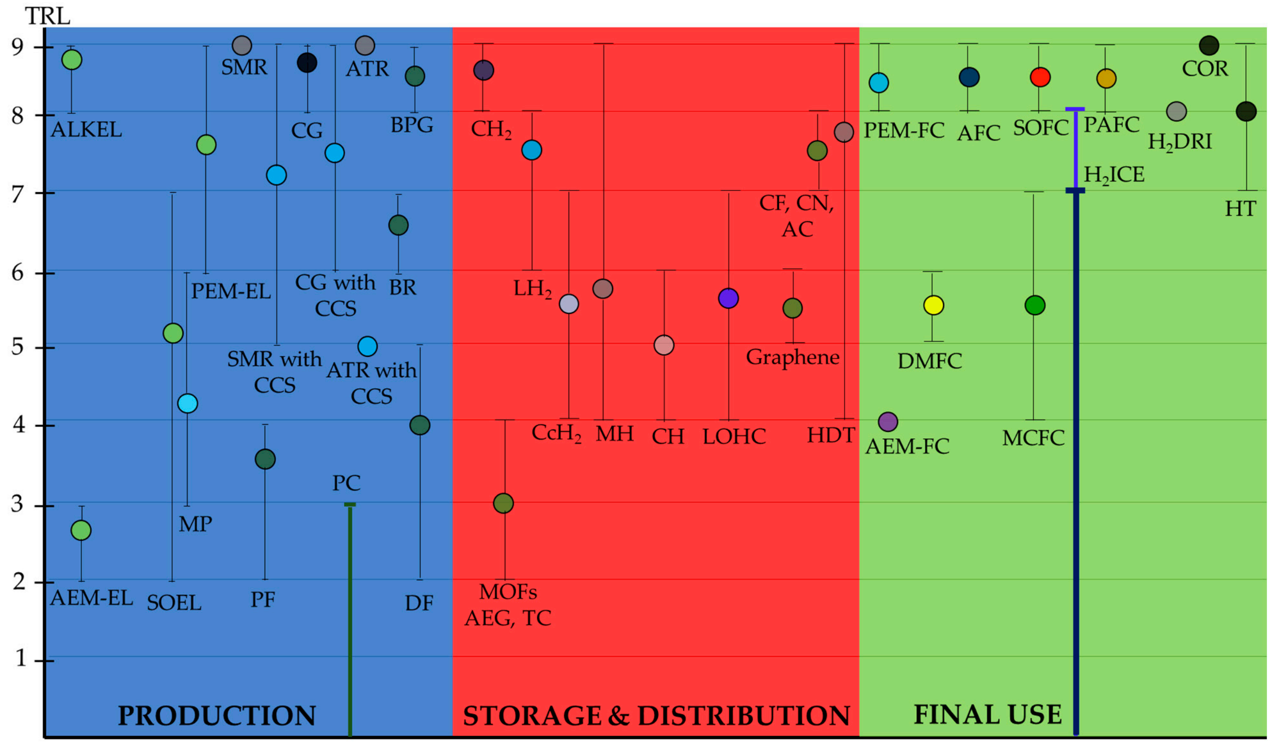


Figure 4. Summary of the different TRLs of the main hydrogen technologies used along the HSC.

5. Green Hydrogen Regulatory Framework: Global Legislation and Guarantees of Origin (GO)

Until now, only technical and technological aspects regarding green hydrogen have been seen. However, how can it be assured that the hydrogen that will be sold in the future is green hydrogen or grey hydrogen "coated in green"? For this purpose, it is necessary to develop a legal framework which involves green hydrogen, so that certifications that guarantee that the sold hydrogen is green hydrogen can be issued. For this reason, although the energy industry is developing standards so that guarantees of origin (GO) certificates can be created, in order to ensure the consumers that the hydrogen they are buying is low-carbon hydrogen or it is obtained thanks to renewable energies [38], it is necessary to implement a sound legislation that defines what is green/clean hydrogen (so GOs certifications can be issued on this basis). Thus, different countries around the world, some of which will be studied next, are developing initiatives to characterise green hydrogen [38,39].

(1) Spain

Regarding the case of Spain, according to article 2.22 of Royal Decree 376/2022, of 17 May 2022, green hydrogen is the one that comes from renewable energies [128]; for the hydrogen to be considered as green hydrogen, its producer needs to be registered in the registry of facilities for the production of gas from renewable energy sources (according to article 19.1 of Royal Decree, RD, 376/2022 [128,129]). This registry will be included in the system of guarantees of origin (GOs) which, in turn, will ensure that the gas is produced from RES [129]. Furthermore, to issue the GOs, according to Order TED/1026/2022, of 28 October 2022 [128,130], the production of renewable gases must derive from a direct production of these gases (i.e., they must come from any source of renewable energy produced on site and not from the consumption of another form of energy, except for auxiliary consumption) or from the conversion of these gases, which is what will take place when they come from any other form of renewable energy (without considering auxiliary consumption) whose renewable character will be accredited by GOs. In the Spanish legislation, RES include [128,131] wind, solar, aerothermal, geothermal, hydrothermal, wave, tidal, hot and dry rock, ocean thermal, ocean current energy, hydroelectric, biomass, biofuel, bioliquid, and biogas in accordance with Section Two b. of Circular 1/2018, of 18 April 2018, of the National Commission of Markets and Competition (CNMV).

(2) European Union (EU)

Regarding the legislation of green hydrogen in the European Union (EU), which prevails over that of each country [132], it establishes in its RE Directive II that electricity used to produce green hydrogen can only be considered renewable if the energy used for the electrolysis process to take place is produced on site, or if the manufacturer can provide enough evidence to demonstrate that the hydrogen has been produced with RES [133], i.e., it establishes standards for certifications of guarantees of origin of hydrogen [134]. This directive is part of the so-called European Green Deal [135,136], presented by the European Commission in December 2019, a European growth strategy that foresees the study, development, and implementation of associated low-carbon technologies. It also envisages the creation of so-called green jobs, as well as achieving climate neutrality by 2050, eliminating pollution and achieving a just and inclusive transition for all citizens. The European Green Deal makes hydrogen one of the main pillars of the economy of the future and key to decarbonisation of industry.

Once the legal framework of green hydrogen has been established, it is possible to issue GOs certifications. Thus, different initiatives aim to create certificates of hydrogen guarantees of origin in different parts of the world; among them, the Certifhy project *"Designing the 1st EU-wide Guarantee of Origin (GO) scheme for Green Hydrogen"* [137] has issued more than 75,000 green hydrogen and low-carbon hydrogen certificates across the EU. Although Certifhy does not define the standards of green hydrogen and, in fact, it also certifies blue hydrogen [138], its objective is to issue certificates for hydrogen beyond Europe in the future [139].

(3) United States (US)

Outside the European Union, states like California (in the US) have a certification, Low Carbon Fuel Standard (LCFS), which is included in the California Code of Regulation, Title 17 [140], in which green hydrogen can be included [38,141] (furthermore, the states of Oregon and Washington have recently established the LCFS certification, and the states of Colorado, New York, New Mexico, and Minnesota are considering implementing this certification [142]). In addition, the US has already developed a legal framework for clean hydrogen, in its Public Law 117-58-Nov.15, 2021 [143], in which clean hydrogen is defined as hydrogen produced with a carbon intensity equal to or less than 2 kg of carbon dioxide per kilogram of hydrogen produced.

(4) Australia

In other countries outside the European Union, like Australia, the Australian Energy Council (AEC) is recommending the implementation of a formal GO scheme in the mentioned country (which should focus only on the emissions created in the production of hydrogen) and supports the appointment of the Clean Energy Regulator (CER) as responsible for administering and overseeing the GO scheme [144].

(5) United Kingdom (UK)

In the UK, the Department for Business, Energy, and Industrial Strategy [145] has committed (by December 2022) to setting up a hydrogen certification scheme by 2025 to guarantee the quality and origin of British hydrogen and to guarantee that imported hydrogen meets the British high quality standards.

(6) Japan

In Japan, despite being considered one of the countries with the most ambitious hydrogen strategies, a modernised regulation in relation to hydrogen has not been developed yet [146,147]. However, the Japanese government is aware of the importance of a new regulation concerning hydrogen, in which different aspects such as technical standards or guarantees of origin could be taken into account [146]. In fact, they plan to establish new legislation, in which the exclusion of businesses that handle hydrogen produced through non-environmentally friendly methods will be included [148,149].

(7) Canada

Similarly to Japan, Canada's Ministry of Natural Resources [150] is aware of the need for a regulatory framework including hydrogen and plans to implement consistent policies across the different regions of the country. Currently, the only regulations in which hydrogen could be included are low-carbon fuel regulations, including renewable gas mandates in natural gas networks and carbon pollution pricing.

(8) China

Regarding the case of China, in its Five-Year Plan for National Economic and Social Development of the People's Republic of China and the Long-Range Goals for 2035 [151], hydrogen is recognised as a future industry; while in its 14th Five-Year Plan of Modern Energy System [152], the innovation of hydrogen technologies (mentioning hydrogen can be used as a way to store renewable energy) is encouraged. On the other hand, in its 14th Five-Year Plan of Renewable Energy Development [153], it is mentioned that where the cost of renewable electricity is low, renewable hydrogen production is planned (so it could replace the fossil fuel industry). However, the Chinese government has not implemented a legislation on green hydrogen yet.

(9) Brazil

An other relevant case which can be mentioned is Brazil [154], which has created the Brazilian National Hydrogen Program-PNH2 to encourage the development of the local hydrogen industry and has developed two Bills of Law, which are currently in process, to regulate hydrogen in Brazil: Bill of Law 725/2022, which establishes mechanisms to insert hydrogen into the national energy sector, defines sustainable hydrogen as the one produced from solar, wind, biomass, biogas, or hydraulic resources. It allows the National Agency for Petroleum, Natural Gas and Biofuels (ANP) to regulate the activities in the hydrogen chain and sets a mandatory blending of hydrogen in natural gas transportation pipelines of 5% by 2032 (which, in turn, would contain at least 60% of sustainable hydrogen) and 10% by 2050 (at least 80% of which would be composed of sustainable hydrogen). Additionally, Bill of Law No 1878/2022 establishes that the ANP would be responsible for regulating the activity of green hydrogen chain and for issuing the licenses for green hydrogen production (i.e., called differently, GOs certifications).

(10) India

The government of India is making serious efforts to integrate green hydrogen and to establish a regulatory framework that complies with international standards. Thus, for 2022–2023, [155], regulation and standards will begin to be established in order to let this sector grow (and to allow pilot projects to be approved) and for 2023–2024, relevant international standards (the global green hydrogen standards can be seen in more detail in [156]) will be adopted in order to certify that green hydrogen has been produced through RES.

(11) South Africa

South Africa [157] desires to be a major producer and exporter of green hydrogen, expecting to capture 4% of global market share by 2050. The South African government is collaborating with the German Ministry of Economic Cooperation and Development (BMZ) to promote green hydrogen production in South Africa with the purpose of establishing a regulatory framework.

Once the legislation concerning clean/green hydrogen in the different countries has been studied, in order to synthesise the regulations of the different parts of the world, Table 12 summarises this information and Figure 5 presents, in a world map, the current legal status of hydrogen in the different parts of the world previously analysed.

Table 12. Green hydrogen regulatory framework in the world.

Country	Legislation
Spain	Green hydrogen: The one that comes from renewable energies. Its producer needs to be registered in the registry of facilities for the production of gas from renewable energy sources (article 19.1, RD, 376/2022). To issue the GOs of green hydrogen, it must derive from a direct production from renewable energies produced on site or from the conversion with any other renewable energy (Order TED/1026/1022).
EU	Green hydrogen: Can only be considered renewable if the energy which is used so that the electrolysis process can take place is produced on site or if the manufacturer can provide enough evidence to demonstrate that the hydrogen fuel has been produced with RES (EU RE-Directive II), i.e., it establishes rules for hydrogen GOs certificates.
US	Clean hydrogen: Hydrogen produced with a carbon intensity equal to or less than 2 kg of carbon dioxide per kilogram of hydrogen produced (Public Law 117-58-Nov.15, 2021).
Australia	The AEC is recommending implementing a formal GO scheme (which should focus only on the emissions created in the production of hydrogen) and supports the appointment of CER as responsible for administering and overseeing the GO scheme.
UK	Department for Business, Energy, and Industrial Strategy has committed to setting up a hydrogen certification scheme by 2025.
Japan	The Japanese government is aware of the importance of implementing a new regulation concerning hydrogen to exclude businesses which handle non-environmentally friendly hydrogen.
Canada	Canada's Ministry of Natural Resources is aware of the importance of a regulatory framework including hydrogen consistent with the different regions across the country (currently, there are only low-carbon fuel regulations).
China	No regulation of green hydrogen has been implemented yet (only it is encouraged in its 5-year plans to implement renewable hydrogen production and to use hydrogen as a way to store renewable energy) and no claim of regulating it has been found.
Brazil	Bill of Law 725/2022: Sustainable hydrogen is produced from solar, wind, biomass, biogas, or hydraulic resources; allows the ANP to regulate the activities in the hydrogen chain and sets a hydrogen blending of 5% in natural gas pipelines by 2032 (at least 60% of which is sustainable hydrogen) and of 10% by 2050 (80% of which is sustainable hydrogen). Bill of Law No 1,878/2022: ANP is responsible for regulating green hydrogen chain activity and issuing the licenses for green hydrogen production.
India	2022–2023: Regulation and standards so that pilot projects can be approved. 2023–2024: Relevant international standards adopted for certification of green hydrogen production.
South Africa	Collaboration with BMZ with the purpose of establishing a regulatory framework to promote green hydrogen production in South Africa.

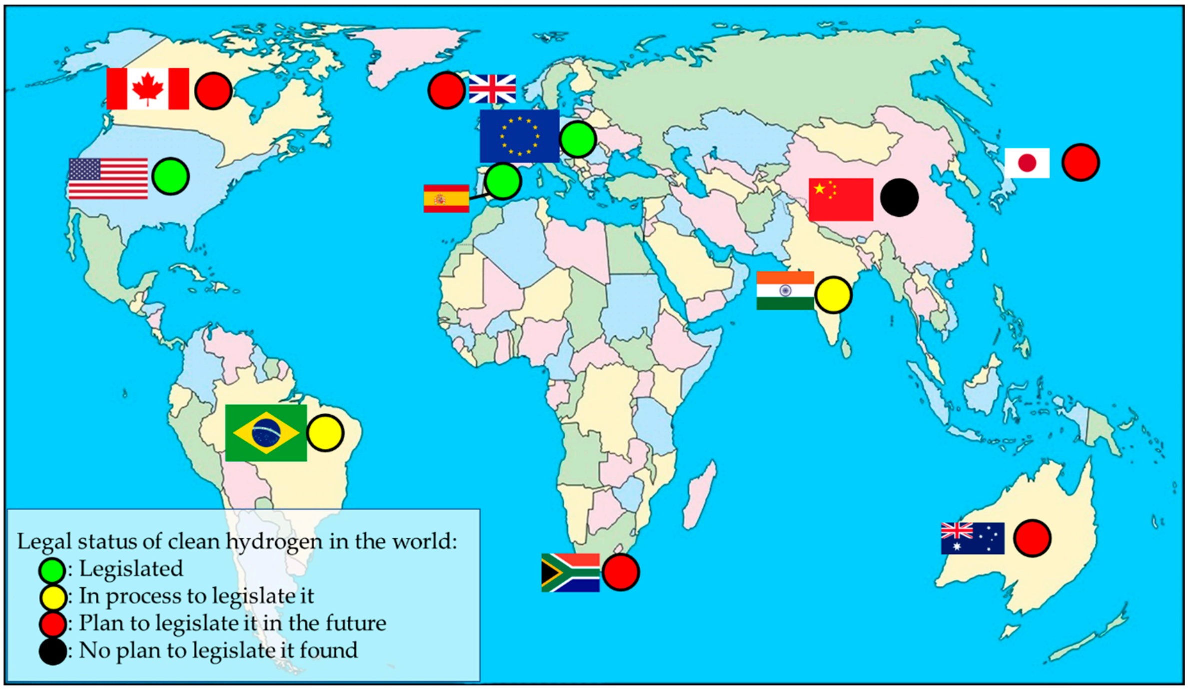


Figure 5. World map with degrees of regulatory framework by countries.

6. Discussion

As a result of the structure of this paper, this section will be divided into the different topics which have been previously analysed through this paper.

(a) Green hydrogen water footprint

Based on the analysed literature, the water footprint of green hydrogen is similar to other types of hydrogen like hydrogen obtained from SMR (the most common method for hydrogen production [158]), and much lower than that of other types of hydrogen (like the hydrogen obtained via BG), but higher than other methods of obtaining hydrogen less sustainable like CG. However, a comparison of the water footprint of green hydrogen and other fuels (both fossil fuels and nuclear energy) shows that green hydrogen, on average, has a significantly lower water footprint than other fuels (both fossil fuels and nuclear energy).

(b) Green hydrogen energy footprint

It can be observed that the energy footprint of green hydrogen is much higher than that of other types of hydrogen (in terms of energy needed to obtain a kilogram of hydrogen) and even much higher than the energy footprint of fossil fuels such as coal or oil (in terms of the energy required to extract a certain amount of energy contained within the respective fuel). However, it must be noticed that hydrogen is an energy vector, i.e., a device which stores energy to be transported and used at a later stage [159]. For this reason, it is more accurate to compare green hydrogen with other energy storage systems. However, for this purpose, it is necessary to consider not only the energy needed to produce green hydrogen per unit of energy contained in the hydrogen fuel produced (1.2–2.5 $kWh_{prod.}/kg\ H_2$), but also the efficiency of the hydrogen final use technology. Thus, considering a PEM fuel cell with an efficiency of 55% [160] (and disregarding losses associated with hydrogen storage and distribution), the energy consumption per unit of final useful energy (i.e., the ratio of the energy entering the ESS to the energy leaving the ESS) of different energy storage systems (ESS) is computed in Table 13.

Table 13. Energy consumption, per final useful energy of different ESS compared to hydrogen systems.

ESS	Pumped Hydro	Compressed Air	Li-ion Battery	Green Hydrogen Systems
Energy consumption ($kWh_{production}/kWh_{useful}$)	1.15–1.54 [161]	1.12–2.5 [161,162]	1.03–1.18 [102]	2.18–4.55

(c) TRL of hydrogen technologies

According to the hydrogen supply chain analysed, it can be observed that the main difference in the TRLs is not between the different stages of the hydrogen supply chain, but within the steps themselves. Very different TRLs are observed, due to the difference in the maturity of the technology. For example, the alkaline electrolysis technology has a TRL much higher than the TRL of an AEM electrolyser. The same goes for storage and distribution options and for final use technologies.

(d) Green hydrogen current global legislation and GOs certificates

Based on the current legislation of green hydrogen that has been studied, as well as the certification of GOs, a huge legal inequality in different countries or regions can be found. Thus, in the case of Europe, there is a robust and well-defined legislation and a legal framework on which to establish requirements for issuing GOs. On the other hand, although other countries such as the US have legislation for clean hydrogen and a standard for low-carbon fuels in some of their states, the degree of development and implementation is lower than in Europe. In fact, the carbon footprint per unit of energy (taking into account the LHV of hydrogen) up to which hydrogen can be considered clean in the US is 0.06 kg CO_2/kWh. This figure is lower than the carbon footprint of coal (0.31–0.35 kg CO_2/kWh [163]), carbon footprint of natural gas (0.18 kg CO_2/kWh [163]), carbon footprint of petroleum (0.21–0.27 kg CO_2/kWh [163]), or hydrogen obtained via steam and methane reforming and via coal gasification, which are 0.27 and 0.6 kg CO_2/kWh [164], respectively. But it is higher than the carbon footprint of nuclear energy (on average, 0.012 kg CO_2/kWh [164]) and that expected for electricity production in 2050 (0.01–0.02 kg CO_2/kWh [164]). Other countries such as Brazil and India, although they do not have legislation in place, are in the process of implementing it. Finally, the rest of the countries analysed are either planning to implement a regulation allowing them to establish certificates of origin for green hydrogen or, in the case of China, no action in this sense is even contemplated. This difference in regulations concerning green hydrogen in different countries has prompted attempts to establish international standards, such as CEN-CENELEC (a set of hydrogen standards that facilitate the issuance of GO certificates) and ISO-IEC (a set of international standards on hydrogen standardisation) [165].

7. Conclusions

This paper has presented a detailed study of the three key pillars underpinning green hydrogen: resource consumption (i.e., water and energy footprint), technology development, and regulatory framework.

The study of the water and energy footprint is essential to perform an analysis of the viability and sustainability of green hydrogen (which is not limited to a simple carbon footprint analysis). The water footprint analysis shows that green hydrogen is more sustainable than nuclear power or fossil fuels and is also competitive with the most common method of hydrogen production (SMR). But from the point of view of energy consumption, the energy footprint analysis shows that green hydrogen consumes a higher amount of energy to be obtained (per unit of energy contained in the fuel) than other fossil fuels or other types of hydrogen, as well as requiring more energy to obtain the same amount of useful energy than other ESSs.

On the other hand, regarding the analysis of the TRLs of the different technologies that can be found in the hydrogen supply chain, these show a great disparity, with, for example, very different TRLs for electrolysis technologies.

Regarding the regulatory framework for green hydrogen, the main challenge is to standardise the definition of green hydrogen at the international level, so that GO certifications can be common (or at least accepted) among different countries. In this respect, the European Union is far ahead of its main competitor, the United States, whose definition of clean hydrogen has a higher maximum carbon footprint than that of nuclear energy, and even that expected for electricity production in 2050, but lower than that of other types of hydrogen, such as that obtained from SMRs or GC.

The research conducted in this paper reinforces the thesis that green hydrogen technologies have not yet reached their full potential in terms of water and energy footprint, technology development, and regulatory framework. Based on this, the authors strongly recommend that the governments of the different countries invest heavily in research and development as a way to achieve the reduction in the water and energy footprint and, on the other hand, to favour the implementation of hydrogen technologies that for the moment are far from being commercialised, although they have a promising potential (such as AEM electrolysers, for example). In addition, within the legislative and standardisation framework, it is essential to reach international agreements that allow the production, export/import, and uses of green hydrogen through clear and fair rules, thus favouring the generation of a true global hydrogen economy. If this is carried out, green hydrogen can contribute to a more sustainable and also a more egalitarian world, as it can be produced almost anywhere in the world.

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Abbreviations

AAEM	Acid-Assisted Extraction Method.
AC	Activated Carbon.
AEC	Australian Energy Council.
AEG	Aerogel.
AEM	Anion Exchange Membrane.
AEM-FC	Anion Exchange Membrane Fuel Cell.
AEM-WE	Anion Exchange Membrane Water Electrolysis.
AFC	Alkaline Fuel Cell.
ANP	National Agency for Petroleum, Natural Gas and Biofuels.
ATR	Autothermal Reforming.
AWE	Alkaline Water Electrolysis.
BG	Biogas Gasification.
BMZ	Ministry of Economic Cooperation and Development.
BPG	Biowaste Pyrogasification.
BR	Biogas Reforming.
CcH_2	Cryocompressed Hydrogen.
CER	Clean Energy Regulator.

CF Carbon Fibres.
CG Coal Gasification.
CH Complex Hydrides.
CH_2 Compressed Hydrogen.
CN Carbon Nanotubes.
CNMV National Commission of Markets and Competition.
COR Crude Oil Refining.
DEM Dry Extraction Method.
DF Dark-Fermentation.
DMFC Direct Methanol Fuel Cell.
EROI Energy Return On Investment.
ESS Energy Storage Systems.
EU European Union.
GH Green Hydrogen.
GO Guarantee of Origin.
H_2ICE Hydrogen Internal Combustion Engine.
H_2DRI Hydrogen Direct Reduced Ironmaking.
HCI Hydrogen Cleanness Index.
HDT Hydrogen Distribution Technologies.
HT Hydrotreating.
LCFS Low Carbon Fuel Standard.
LHV Lower Heating Value.
LOHC Liquid Organic Hydrogen Carrier.
MCFC Molten Carbonate Fuel Cell.
MH Metal Hydrides.
MOF Metal Organic Framework.
MP Methane Pyrolisis.
PAFC Phosphoric Acid Fuel Cell.
PC Photocatalysis.
PEM Polymer Exchange Membrane.
PEM-FC Polymer Exchange Membrane Fuel Cell.
PEM-WE Polymer Exchange Membrane Water Electrolysis.
PF Photo-Fermentation.
PG Plasma Gasification.
PH Physisorption.
PV PhotoVoltaic.
RD Royal Decree.
RES Renewable Energy Sources.
SMR Steam and Methane Reforming.
SOFC Solid Oxide Fuel Cell.
SO-WE Solid Oxide Water Electrolysis.
TC Templated Carbon.
TRL Technology Readiness Level.
UHU University of Huelva.
UK United Kingdom.
US United States.

Notation and Symbols

ΔG Gibbs free energy (kJ/mol).
ΔH enthalpy of formation (kJ/mol).
ΔS entropy (kJ/(mol·K)).
$E_{a.\ PV\ microgrid}$ PV energy generated annually in the studied microgrid (22,590 kWh).
$E_{a.\ PV\ world}$ PV energy generated annually worldwide (830,741·10^6 kWh/year).
$E_{a.\ wind\ China}$ wind energy generated annually in China (800·10^9 kWh/year).
$E_{a.\ wind\ microgrid}$ wind energy generated annually in the studied microgrid (1087 kWh).
$E_{electrolysis}$ energy required in the electrolyser so that the electrolysis takes place (36.14–54.6 kWh/kg H_2).

F	Faraday constant (96485 C/mol).
P_{PV}	PV power installed in the considered location (15 kW).
$P_{PV\ world}$	total PV power installed worldwide ($710 \cdot 10^6$ kW).
P_{wind}	wind power in the considered location (3.4 kW).
$P_{wind\ China}$	total wind power installed in China ($278.353 \cdot 10^6$ kW).
T	temperature (K).
$T_{PV\ panel}$	average lifetime of a PV panel (25–30 years/panel).
T_{WT}	average lifetime of a wind turbine (20 years/wind turbine).
U_0	standard equilibrium voltage of the water electrolysis cell ($U_0 = 1.229V$).
$WF_{electrolyser}$	electrolyser water footprint (9.1–18 L H_2O/kg H_2).
$WF_{Huelva\ gr.\ H_2}$	water footprint of green hydrogen produced in Huelva (L H_2O/kg H_2).
$WF_{Huelva\ H_2 solar}$	water footprint of green hydrogen produced via solar energy in Huelva (L H_2O/kg H_2).
$WF_{Huelva\ H_2\ wind}$	water footprint of green hydrogen produced via wind energy in Huelva (L H_2O/kg H_2).
$WF_{PV}\left(\frac{L\ H_2O}{kW}\right)$	water footprint of PV power.
$WF_{PV-Huelva}\left(\frac{L\ H_2O}{kWh}\right)$	water footprint of PV energy at "La Rábida Campus" (University of Huelva).
$WF_{PV\ world}\left(\frac{L\ H_2O}{kWh}\right)$	water footprint of PV energy worldwide (0–0.11 L H_2O/kWh).
$WF_{wind}\left(\frac{L\ H_2O}{kW}\right)$	water footprint of wind power.
$WF_{wind\ China}\left(\frac{L\ H_2O}{kWh}\right)$	water footprint of wind energy in China (0–0.64 L H_2O/kWh).
$WF_{wind-Huelva}\left(\frac{L\ H_2O}{kWh}\right)$	water footprint of wind energy at "La Rábida Campus" (University of Huelva).
z	number of electrons converted per H_2 molecule (z = 2).

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