HOW RENEWABLE IS GREEN HYDROGEN? ANALYSIS OF THE EXERGY COST OF ITS PRODUCTION

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ABSTRACT

Green hydrogen is expected to play a pivotal role as an energy carrier in the energy transition. This fuel emerges as the most environmentally sustainable energy vector for non-electric applications, devoid of CO2 emissions. However, the electrolysis of water requires electrolyzers and renewable electricity to produce hydrogen. This infrastructure relies on scarce and energy-intensive metals, such as platinum, palladium, or iridium (PGM), silicon, rare earths elements or silver. Consequently, this paper explores the *non-renewable* exergy cost of the hydrogen infrastructure to assess its *renewability*, considering the technological advances and the increasing mining energy due to ore grade declining, until 2050. Three types of electrolyzers are studied: alkaline electrolysis (AE), proton exchange membrane (PEM), and solid oxide electrolysis cells (SOEC), alongside three renewable energy sources: hydro, wind, and photovoltaic. Renewable energies account for the largest share of the exergy cost. For each MJ of hydrogen, between 0.0062 MJ and 0.0007 MJ are required for electrolyzer infrastructure, while between 2.36 MJ and 0.04 MJ are required for renewable energies infrastructures. The most favorable combination is SOEC with hydro, while the least favorable is PEM with photovoltaic. Regarding metals, steel stands out in AE and SOEC exergy cost, and PGMs in PEM. In renewable energies, steel, concrete, and silicon constitute the main part of the exergy cost. This paper highlights the importance of the *non-renewable* exergy cost of the infrastructure required for green hydrogen and the necessity for cleaner production methods and material recycling to increase the *renewability* of this crucial fuel for the energy transition.

1 INTRODUCTION

Green hydrogen currently represents an essential low-carbon chemical and energy vector essential to the success of the energy transition, especially in challenging-to-electrify applications (Busch et al., 2023; Tabrizi et al., 2023). It is very flexible and possess a very diverse range of applications, involving for example applications in the energy storage sector (Power-to-gas, Power-to-fuel or Power-to-power), as well as a chemical reactant (for the production of ammonia, methanol, and polymers), as a fuel (for industrial high temperature processes and the transport sector), as a reducing agent in the metallurgical industry (iron and steel, copper, aluminum...) (Vidas & Castro, 2021), and other interesting ones.,.

Some regions of the world are already producing green hydrogen from renewable energy sources via the process of water electrolysis (Panchenko et al., 2023). Three electrolyzer technologies, alkaline electrolysis (AE), proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis cells (SOECs), whose degrees of technology readiness level (TRL) significantly differ, are approached in this study. AE is a mature and commercial technology, that has been used since the 1920s, in particular for hydrogen production in the fertilizer and chlorine industries. However, most of these electrolyzers were decommissioned when natural gas and steam methane reforming for hydrogen production took off in the 1970s (International Energy Agency, 2019). This technology uses nickel in the electrodes and zirconium in the separator (Krishnan et al., 2023; Vidas & Castro, 2021), therefore it features a precious materials independence in its construction and operation. On the other hand, its operation is not very flexible and usually produces a low purity hydrogen (Rashid et al., 2015). PEM electrolyzer systems were first introduced in the 1960s by General Electric to overcome some of these operational drawbacks

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of AE systems. They offer a very flexible operation, but they require expensive electrodes made of platinum group metals (PGMs), and their lifespan is currently shorter compared to AE (International Energy Agency, 2019; Jolaoso et al., 2024). SOEC is the most novel electrolysis technology system among these three, and has not yet been commercialized, although individual companies are now aiming to bring them to market. They use ceramics as electrolytes, have low material costs, are capable of operating at high temperatures, and have a high degree of Faradaic/Coulombic efficiency (International Energy Agency, 2019). This technology s zirconium (Zr) in the electrolyte, rare earths elements (REE) (e.g., lanthanum (La)) in the cathode, yttrium (Y) in the interconnections and nickel (Ni) in the anode (Jolaoso et al., 2024). Unfortunately, it also depends on critical metals to operate efficiently. In summary, AE systems yield hydrogen with low purity, and do not depend on rare metals. On the other hand, PEM systems generate high-purity hydrogen with great flexibility, is suitable for integration with renewable sources, but relies on PGMs. And even though SOEC systems avoid the use of some noble metals, they are still in the development phase (Bareiß et al., 2019; Rashid et al., 2015). Thus, the current need for green hydrogen is already triggering the production of more electrolyzers (Figure 1), and consequently increasing the demand for the metals required for their manufacturing. Under this context, Ni and Zr stand out in AE, Pt, Pd and Ir(PGM), in PEMs, and Ni, Zr, La, Y, in SOEC. Complementarily, steel, aluminum or copper are also necessary for the electrolyzer structure and conduction of electricity (International Energy Agency, 2021b). Therefore, based on this uncertain scenario, this investigation focused on the study of the application of these ten metals (Steel, Al, Cu, Ni, Zr, La, Y, Pt, Pd e Ir) and graphite, (utilized on AE systems), on the current and future electrolysis scenarios demand and how they affect the cost of obtaining green hydrogen.

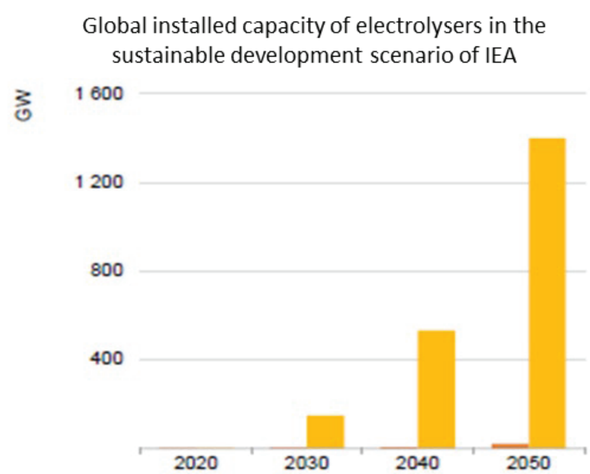

Figure. 1. Evolution of the hydrogen production capacity according to the reference.(International Energy Agency, 2021b).

Another essential resource for producing green hydrogen is renewable electricity, since using the electrical grid for hydrogen production could be more polluting than producing it directly from fossil fuels (Busch et al., 2023). Several studies indicate that the supply of renewable electricity is the main environmental concern of green hydrogen production (Bareiß et al., 2019; Bhandari et al., 2014; Busch et al., 2023; Palmer et al., 2021). Thus, this study accounted another dimension on the production of hydrogen by analyzing the production of renewable electricity from three consolidated technologies: hydroelectric, wind and photovoltaic. However, these technologies are also intensive in the use of metals, the most important being steel, Al, Cu, Pb, Zn, Si, REE, Ag and other materials such as concrete (Torrubia et al., 2024b), and those should be included on the cost of green hydrogen production.

Therefore, studying the *renewability* of green hydrogen through its exergy cost involves also understanding the exergy costs associated with all mentioned metals and materials. Thus, this study builds on previous work on the energy footprint of materials (Torrubia et al., 2023) and the exergy cost of the electricity (Torrubia et al., 2024a) by evaluating the exergy costs of pairs of electrolysis technology and renewable energy sources on green hydrogen production. It is of common knowledge

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that the exergy cost of electricity, and consequently, hydrogen, changes over time in a dynamic process for some reasons: (1) technological advancements reduce the amount of materials required for production; (2) shifts in the electricity mix towards renewables decrease the contribution of fossil exergy costs, particularly significant in metal production; (3) the operating hours and conversion efficiency of electrolyzers increase. Thus, this study approaches the problem of exergy cost differentiated between renewable and non-renewable exergy, analyzing the interaction between energy and materials, through exergy.

2 METHODOLOGY AND DATA

Figure 2 shows a diagram of the production phases of green hydrogen using three consolidated renewable energy sources: hydro, wind, and PV. Three cost classifications are taken into consideration: (1) primary renewable energy, (2) energy embedded in the renewable infrastructure, and (3) energy embedded in the hydrogen generation infrastructure, i.e., electrolyzers. In addition, embedded energy (2 and 3) is classified by differentiating its origin, whether fossil, nuclear or renewable.

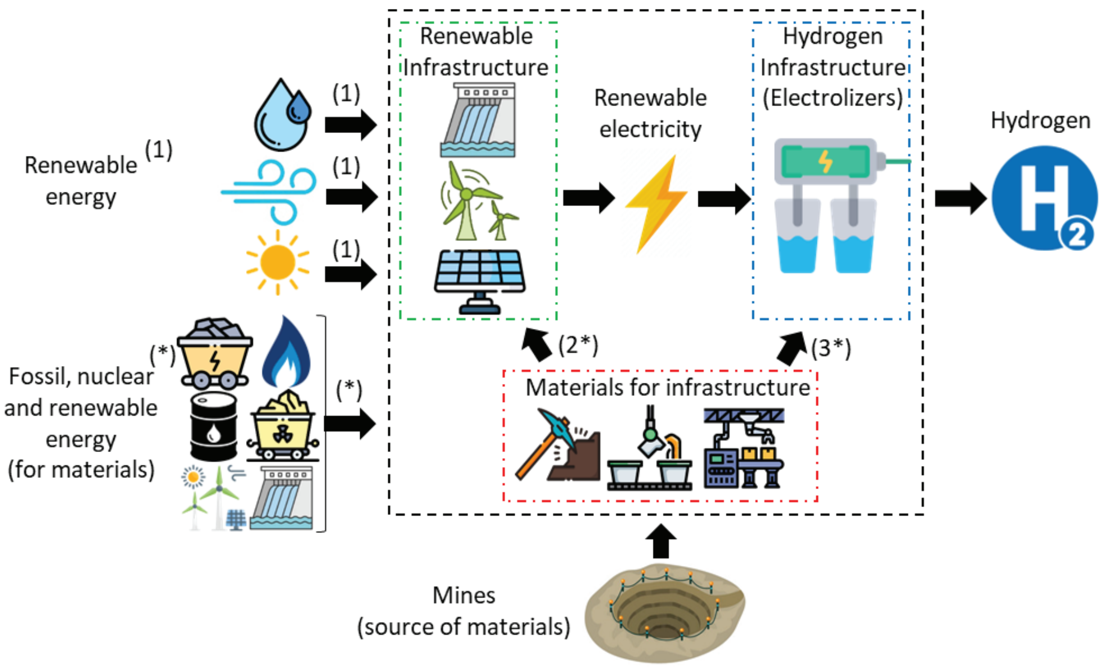

Figure. 2. Results of the exergy cost are divided in (1) renewable energy use, (2) Energy invested in infrastructure for electric production (3) Energy invested in infrastructure for hydrogen production (electrolyzers). (2) and (3) are further divided into fossil, nuclear and renewable* energy.

First, we describe the adopted methodology to obtain the evolution of the exergy cost of electricity (i.e., numbers 1 and 2 of Fig. 2) from the renewable sources and the materials for the infrastructure. Then, we proceed further on elaborating on the exergy costs of producing green hydrogen (number 3 of Fig. 2) from the materials constituting the infrastructure.

2.1 Electricity Exergy cost

Calculating the exergy cost of electricity from renewable energy is more challenging compared to hydrogen. The reason is that electricity itself is an indispensable resource for the production of the infrastructure that generates electricity. Thus, the study of the cost of electricity is a dynamic process. This process has been studied previously in another work (Torrubia et al., 2024a) considering the exergy embodied in the minerals, the ore grade declining of major metals for producing the electricity

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infrastructure and the decrease in material intensity as a result of technological development. Thus, the electricity produced in a determined year is used to produce the following year's infrastructure. Therefore, the more renewable energy is installed, the more renewable electricity is used in the manufacturing of the new infrastructure, accelerating decarbonization. Table 1 shows the results of this previously described dynamic process by assuming the global electricity system projection according to the IEA NZE scenario (International Energy Agency, 2021a).

The average cost hydro ($AEXC_{HYD}$), wind ($AEXC_{WIND}$) and PV ($AEXC_{PV}$) represent the average exergy cost of electricity produced in a given year by hydro, wind or photovoltaic energy, respectively. The cost of these three technologies is divided into (1) fuel consumption (it is always 1, since these technologies are always renewable), and (2) exergy invested in infrastructure, which is further divided in (i) non-renewable (fossil fuels and nuclear), and (ii) renewable energy. While fossil fuels are used directly in the manufacture of materials, nuclear and renewable energy can only be embedded in the infrastructure through the electricity used in manufacturing.

Table 1 predicted declining exergy cost of electricity, both total and non-renewable (in parentheses), over time. This decline can be attributed primarily to two factors. First, the energy amortization of infrastructure: renewable infrastructure incurs high energy consumption during installation in the initial year but generates electricity over its lifespan. Consequently, the need for investing in new infrastructure decreases in subsequent years, gradually lowering costs. Second, technological advancements play a crucial role on declining the exergy costs of electricity. The PV technology is a particularly noteworthy case that experiences faster cost reductions than any other technology due to its expected rapid improvement, marked by significant decreases in the usage of silicon and silver (Carrara et al., 2020). It's worth mentioning that there's a slight increase in costs for hydro in 2025 compared to 2020. This rise is attributed to the increased extraction energy cost stemming from declining ore grades.

Table 1. Annual average exergy costs of hydro, wind, and PV electricity (number 1 Fig. 2) and their respective annual average exergy cost of electricity (number 2* Fig. 2). (In parentheses non-renewable cost: fossil and nuclear). MJ/MJ.

	Cost (1)			Cost (2)
Year	Average cost Hydro ($AEXC_{HYD}$)	Average cost Wind ($AEXC_{WIND}$)	Average cost PV ($AEXC_{PV}$)	Average cost Electricity (XCE)
2020	1.034 (0.033)	1.164 (0.156)	2.454 (1.369)	2.143 (1.794)
2025	1.035 (0.033)	1.163 (0.151)	1.742 (0.680)	1.811 (1.242)
2030	1.034 (0.032)	1.118 (0.107)	1.418 (0.372)	1.522 (0.791)
2035	1.033 (0.031)	1.094 (0.082)	1.289 (0.248)	1.331 (0.423)
2040	1.032 (0.029)	1.074 (0.063)	1.211 (0.175)	1.188 (0.159)
2045	1.030 (0.027)	1.056 (0.047)	1.159 (0.129)	1.160 (0.129)
2050	1.028 (0.026)	1.049 (0.040)	1.135 (0.107)	1.178 (0.134)

Complementarily, we classify the average cost electricity (XCE) into fossil fuel, nuclear and renewable exergy. This classification includes both direct use (burning coal in a power plant for electricity production) and indirect use (fuel needed to manufacture infrastructure).

2.2 Hydrogen Exergy cost

Based on the exergy costs of renewable and average electricity previously obtained (numbers 1 and 2* from Fig. 2), we estimate on this section the amount of electricity needed for hydrogen production (Sec. 2.2.1) and the cost of this production linked to the infrastructure (Sec. 2.2.2).

2.1.1 Exergy cost of fuel (electricity):

Green hydrogen is produced from renewable electricity. However, part of the electricity is not converted into hydrogen due to the electrolyzer conversion efficiencies. Table 2 shows the electrical efficiency in % of lower heating value of H2" obtained from (International Energy Agency, 2019).

Table 2. Efficiency of the electrolyzers (Eff_{Tec}) (International Energy Agency, 2019).

Year	AE	PEM	SOEC
2020	63.0%	58.0%	77.5%

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2030	68.0%	65.5%	80.5%
2050	75.0%	70.5%	83.5%

The unit exergy cost of hydrogen due to electricity generation (XCF_{Tec-RE}) is calculated dividing the unit exergy cost of electricity for each renewable energy ($AEXC_{RE}$, Table 1) by the efficiencies of each electrolyzers (Eff_{Tec}), as shown by Eq. 1. It is important to remember that $AEXC_{RE}$ already contains all the information regarding the life cycle of each renewable energy source (e.g., the capacity factor, the lifespan, and the cost of the infrastructure). Therefore, $AEXC_{RE}$ has 3 components: fuel (it is always renewable: sun, water or wind, depending on the technology), non-renewable exergy invested in infrastructure, and renewable exergy invested in infrastructure. Therefore, XCF_{Tec-RE} is also disaggregated into these 3 components.

$$XCF_{Tec-RE} = \frac{AEXC_{RE}}{Eff_{Tec}} \quad (1)$$

This equation is repeated for each of the technologies analyzed (Tec): AE, PEM and SOEC; and each of the studied renewable electricity (RE) sources: hydro, wind and photovoltaic. Therefore, a total of 9 scenarios are accounted for here.

2.1.1 Exergy cost of infrastructure (electrolyzers):
First step is calculating the exergy needed for manufacturing 1 MW of each technology of electrolyzer ($XCI(MW)_{Tec}$). Then, it is necessary to know the material intensity of each technology ($MI_{TEC-MAT}$ measured in kg/MW), obtained from the references (International Energy Agency, 2021b, 2023) and the exergy intensity of the materials ($XC_{MAT(FF)} + XC_{MAT(E)} \cdot XCE$, measured in MJ/kg), as shown by Eq. 2. In total, 11 different materials have been considered: aluminum, copper, iridium, lanthanum, nickel, palladium, platinum, yttrium, zirconium, steel and graphite. The calculation of the exergy intensity of materials has two parts, one due to fossil fuels ($XC_{MAT(FF)}$) and one due to electricity ($XC_{MAT(E)} \cdot XCE$). The latter part is calculated multiplying the electrical energy required to produce a material ($XC_{MAT(E)}$) by the cost of electricity (XCE, Table 1). Thus, we classify the cost due to electricity into non-renewable and renewable, as we did with XCE. Finally, $XC_{MAT(FF)}$ and $XC_{MAT(E)}$ were obtained from (Torrubia et al., 2023).

$$XCI(MW)_{Tec} = \sum_{MAT=1}^{n} MI_{TEC-MAT} \cdot (XC_{MAT(FF)} + XC_{MAT(E)} \cdot XCE) \quad (2)$$

Once $XCI(MW)_{Tec}$ (measured in MJ/MW) is obtained, it is possible to calculate the exergy cost due to infrastructure for each technology and renewable energy (XCI_{Tec-RE}), measured in (MJ/MJ). This calculation is developed by Eq. 3, where $XCI(MW)_{Tec}$ is divided by top_{Tec} (measured in hours), which represents the operating time of each technology. For transforming the units to (MJ/MJ) it is necessary to multiply the hours by 3600.

Table 3. Operating time of electrolyzers, in hours (top_{Tec}) (International Energy Agency, 2019).

Year	AE	PEM	SOEC
2020	75,000	60,000	20,000
2030	95,000	75,000	50,000
2050	125,000	125,000	87,500

Thus, XCI_{Tec} represents the exergy invested for producing H2 along its lifetime.

$$XCI_{Tec} = \frac{XCI(MW)_{Tec}}{top_{Tec} \cdot 3600} \quad (3)$$

Although XCF_{Tec-RE} is calculated for 3 technologies and 3 renewable sources, XCI_{Tec} is only calculated for each technology since renewable energy sources only affect to the production of hydrogen, but not the production of the electrolyzer.
Thus, the main results of this work are the XCF_{Tec-RE} and XCI_{Tec}, matrices, nine in total: one for each technology and renewable energy source pair.

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3 RESULTS AND DISCUSSION

First, we present an analysis of the evolution of the exergy costs under the different projected scenarios. Then, we follow with an analysis of the exergy costs of the materials constituting the infrastructure.

3.1 Evolution of renewable and non-renewable exergy costs

Figure 3 shows the main results of this study, depicting the unit exergy costs of hydrogen production for the three electrolysis technologies (AE, PEM, and SOEC) and the three renewable energy sources (hydro, wind, and photovoltaic) examined. These unit costs are categorized into two groups (1) Fuel, which solely denotes the direct exergy cost of renewable electricity required for hydrogen production, and (2) infrastructure, by encompassing the exergy cost associated with infrastructure production. The second group was further divided into four components: (i) the renewable portion derived from the electric infrastructure (REN Infras. (EL)); (ii) the exergy sourced from fossil fuels within the electric infrastructure (FF Infras. (EL)); (iii) the renewable exergy utilized for constructing the hydrogen infrastructure, i.e., the electrolyzers (REN Infras. (H2)); and (iv) the fossil fuel-derived exergy for the hydrogen infrastructure (FF Infras. (H2)).

Figure 3 shows that the exergy cost will likely decrease over time for all nine cases, despite the rise in mineral exergy cost resulting from declining ore grades. This decline might be attributed to four combined factors: (i) the reduction in exergy cost of renewable electricity production (see Table 1), (ii) the decrease in material requirement of the electrolyzers, (iii) the improvement in electrolyzer efficiency (see Table 2), and (iv) the extension of electrolyzer operation time. The first factor is the most influential due to the significant role of electricity production in hydrogen generation. Thus, the declining exergy cost over time can be attributed to the decrease in material intensity of renewable technologies and energy amortization, wherein the energy invested in renewable infrastructure during installation yields energy throughout its lifespan (Torrubia et al., 2024a).

In 2020, PV incurred the highest costs (4.2-3.2 MJ/MJ), followed by wind (1.5-2 MJ/MJ) and hydro (1.3-1.8 MJ/MJ). However, by 2050, PV costs dropped 57-62% (1.4-1.6 MJ/MJ), whereas wind costs 17-26% (1.3-1.5 MJ/MJ), and hydro by 8-18% (1.2-1.5 MJ/MJ). Consequently, the highest costs in 2020, which were attributed to PV, experienced the most rapid decline. Thus, even though the cost disparity between technologies was significant in 2020 (hydro costs were half those of PV), by 2050, this difference reduced considerably to just 10%. Consequently, speaking in a general perspective, the results suggest that the most favorable renewable sources are likely hydro, wind, and photovoltaic, in this order. Other studies (Bhandari et al., 2014; Palmer et al., 2021) reached the same conclusions.

Regarding electrolyzer technologies, SOECs exhibit lower costs (1.2-3.1 MJ/MJ) and are followed by AE (1.4-3.9 MJ/MJ) and PEMs (1.5-4.2 MJ/MJ). This disparity is attributed to the efficiency of the electrolyzers (refer to Table 2), with PEMs displaying the lowest conversion efficiency (58-70.5%) compared to AE (63-75%) and SOECs (77.5-83.5%). Thus, electrolyzer efficiency emerges as the most important factor influencing costs, given that the cost of electrical infrastructure overcomes that of hydrogen infrastructure. Consequently, a lower conversion efficiency leads to a greater electricity consumption and, a higher infrastructure demand. Krishnan et al., 2023 also stated that there is no clear winner between AE and PEMs in terms of environmental impact.

Tables 4 and 5 present the non-renewable exergy cost associated with electrolyzers (Table 4) and electric technologies (Table 5). The non-renewable exergy cost reflects the *non-renewablility* of hydrogen production, encompassing all exergy sources not derived from water (hydro), wind, or sun (photovoltaic). In essence, Tables 4 and 5 indicate the non-renewable MJ required for each MJ of hydrogen produced, solely attributable to infrastructure production. To determine the total non-renewable cost of one technology is necessary to sum the electrolyzer cost (Table 4) with electricity production cost (Table 5).

Tables 4 and 5 indicate that the infrastructure exergy cost of hydrogen is considerably lower than the infrastructure cost of renewable energies. For instance, for hydro, the hydrogen infrastructure cost ranges from 12.3% to 2.1%, whereas for wind ranges from 4.3% to 1.4%, and for solar ranges from 1.6% to 0.3%. This discrepancy arises due to the significantly higher energy intensities of renewable energies infrastructure compared to those of electrolyzers. The energy intensity of photovoltaics ranges from 143 to 8.1 TJ/MW, while wind is around 6.9 TJ/MW, and hydro is 10.5 TJ/MW (Torrubia et al., 2024a). In contrast, the energy intensity of electrolyzers is 1.4 TJ/MW for AE, 1.2 TJ/MW for PEM,

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and 0.3 TJ/MW for SOEC. Hence, the environmental footprint of hydrogen production is directly influenced by the electricity source utilized. Other studies have similarly highlighted this point (Bareiß et al., 2019; Bhandari et al., 2014). For instance, Bhandari et al., 2014 pointed out that only 4% of the carbon footprint (which shows similar trends with exergy cost) corresponds to electrolyzers.

Table 4. Non-renewable exergy cost of the electrolyzer infrastructure.

	Electrolyzers		
	AE	PEM	SOEC
2020	0.0062	0.0080	0.0053
2025	0.0048	0.0056	0.0025
2030	0.0038	0.0040	0.0014
2035	0.0032	0.0028	0.0011
2040	0.0027	0.0020	0.0009
2045	0.0025	0.0017	0.0007
2050	0.0024	0.0015	0.0007

Table 5. Non-renewable exergy cost of the renewable energies infrastructure.

	Hydro			Wind			Photovoltaic		
	AE	PEM	SOEC	AE	PEM	SOEC	AE	PEM	SOEC
2020	0.05	0.06	0.04	0.25	0.27	0.20	2.17	2.36	1.77
2025	0.05	0.05	0.04	0.23	0.24	0.19	1.04	1.10	0.86
2030	0.05	0.05	0.04	0.16	0.16	0.13	0.55	0.57	0.46
2035	0.04	0.05	0.04	0.12	0.12	0.10	0.36	0.37	0.31
2040	0.04	0.04	0.04	0.09	0.09	0.08	0.25	0.26	0.21
2045	0.04	0.04	0.03	0.06	0.07	0.06	0.18	0.19	0.16
2050	0.03	0.04	0.03	0.05	0.06	0.05	0.14	0.15	0.13

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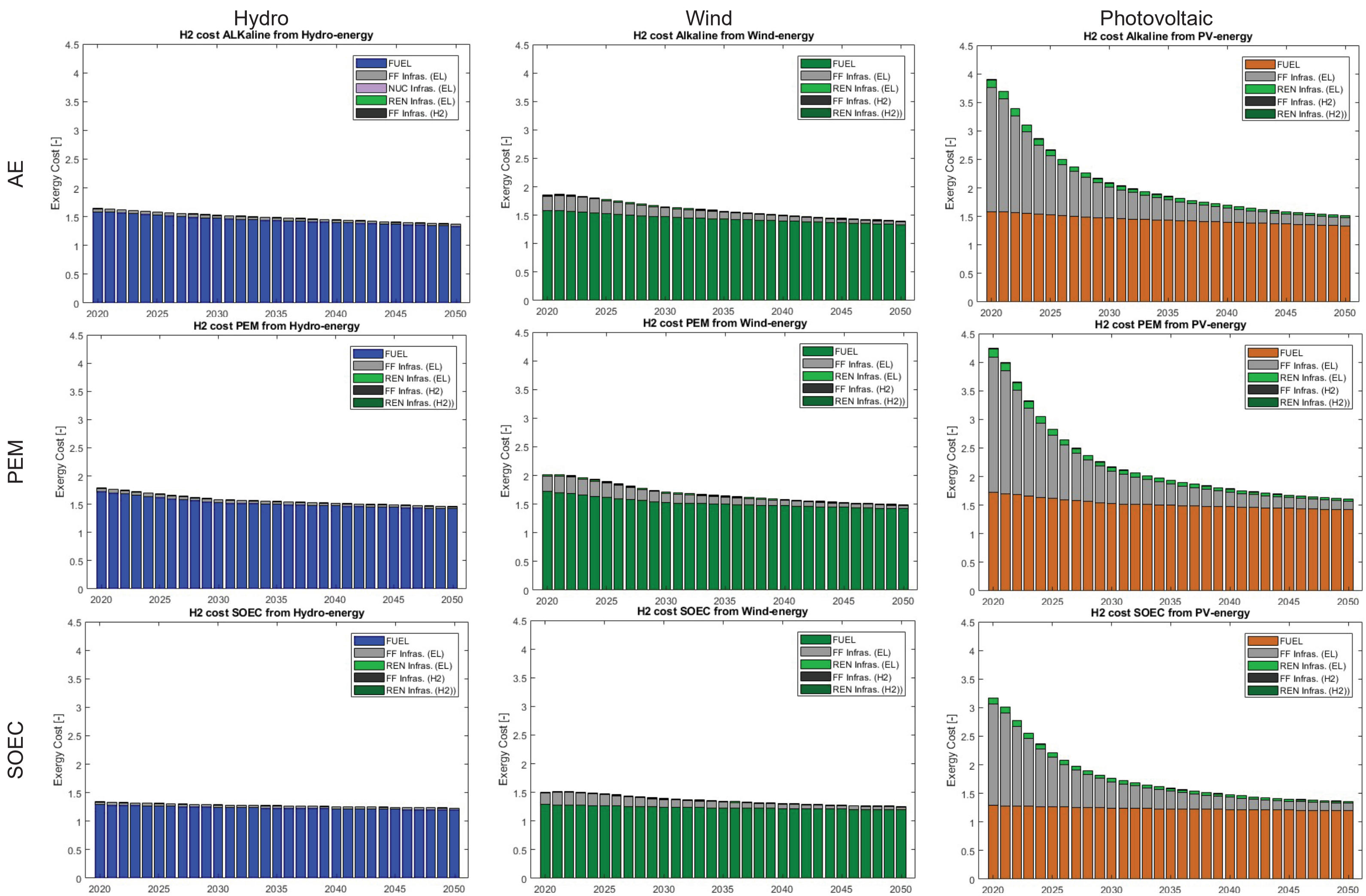

Figure 3. Projections on the evolution of the exergy cost of green hydrogen production (2020-2050).

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3.2 Exergy cost of infrastructure by materials

The previous section highlights that the only non-renewable costs stem from infrastructure. Therefore, this section delves into the materials required for constructing the infrastructure. The infrastructure is categorized into two components: electrolyzers and renewable energies. Table 6 displays the proportion of infrastructure attributed to electrolyzers; consequently, the remainder corresponds to the renewable exergy infrastructure utilized in each scenario. The least significant contribution from electrolyzers occurs when photovoltaic energy is employed to power them, with PV panels accounting for 98.2% to 99.7% of the cost. For wind, this percentage decreases to between 95.2% and 98.8%, and for hydro, it ranges from 88.5% to 97.3%. This suggests that PV energy consumes the most exergy resources, followed by wind and hydro, given that the production cost of electrolyzers exhibits minimal variation compared to electric technologies (refer to Tables 4 and 5). Section 3.2.1 analyzes the materials comprising electrolyzers in terms of exergy cost, while Section 3.2.2 focuses on the materials of renewable energies.

Table 6. Percentage of the exergy cost of the infrastructure from electrolyzers (the rest of the contribution is due to renewable energies infrastructure).

	Hydro			Wind			Photovoltaic		
	AE	PEM	SOEC	AE	PEM	SOEC	AE	PEM	SOEC
Min	7.67%	6.07%	2.67%	2.09%	2.48%	1.18%	0.29%	0.35%	0.28%
Max	10.92%	13.05%	11.47%	4.76%	3.62%	2.63%	1.78%	1.33%	0.57%

3.2.1 Exergy cost of infrastructure (electrolyzers):

Figure 4 graphically illustrates the contribution of each metal to the exergy cost of electrolyzer infrastructure. Given that a significant portion of this exergy cost originates from fossil sources, it becomes crucial to identify the metals that show the greatest influence on the exergy cost. Focusing future research efforts on the decarbonization of these metals will consequently lead to the increase the decarbonization and *renewability* of green hydrogen.

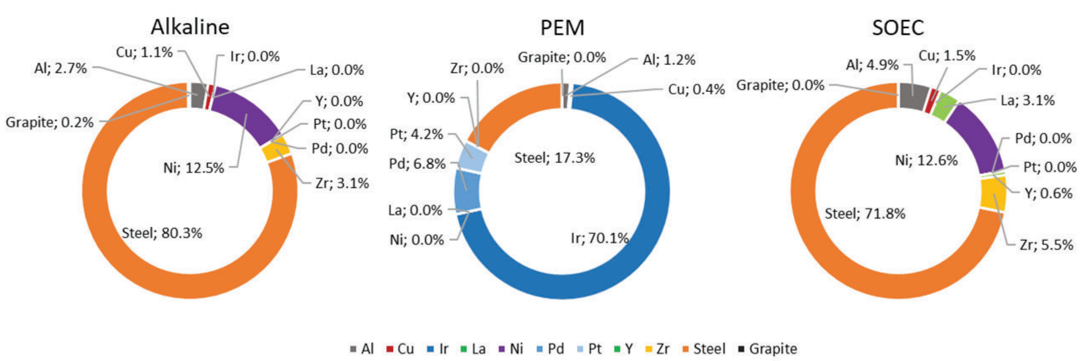

Figure 4. Metal and material contribution to exergy cost for the electrolyzers infrastructure.

AE and SOECs share a similar composition, with steel being the primary contributor (71.8-80.3%), followed by nickel (12.5-12.6%), zirconium (3.1-5.5%), aluminum (2.7-4.9%), and copper (1.1-1.5%). However, SOECs incorporate a certain amount of rare earths (3.1% lanthanum and 0.6% yttrium). The major discrepancy between the two lies in their total energy intensity, ranging from 1.4 TJ/MW for AE to 0.3 TJ/MW for SOECs. Thus, despite their similar composition, AE systems require 4.5 times more energy for manufacturing compared to SOECs. Conversely, PEMs exhibit an energy intensity of 1.3 TJ/MW, slightly lower than AE, but with a distinct composition. In this case, steel constitutes only 17.3% of the exergy cost, while 81.2% is attributed to PGM (iridium 70.1%, palladium 6.8%, platinum 4.2%). Aluminum (1.2%) and copper (0.4%) make up for the remaining. Consequently, steel and PGMs emerge as the primary contributors to the exergy cost of electrolyzers. Krishnan et al., 2023 also identify steel and PGMs as the most environmentally impactful metals. Hence, to mitigate the environmental footprint of electrolyzers, adopting low-carbon intensity steel and minimizing the use of PGMs or

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enhancing their recycling are essential steps, especially considering their limited availability due to rarity in the Earth's crust (Krishnan et al., 2023).

3.2.2 Exergy cost of infrastructure (renewable energies):
Table 6 shows that between 86.9% and 99.7% of the infrastructure cost is attributed to renewable electricity generation. Figure 5 depicts the contribution of the primary materials to the energy cost of (a) hydro, (b) wind, and (c) photovoltaic sources.

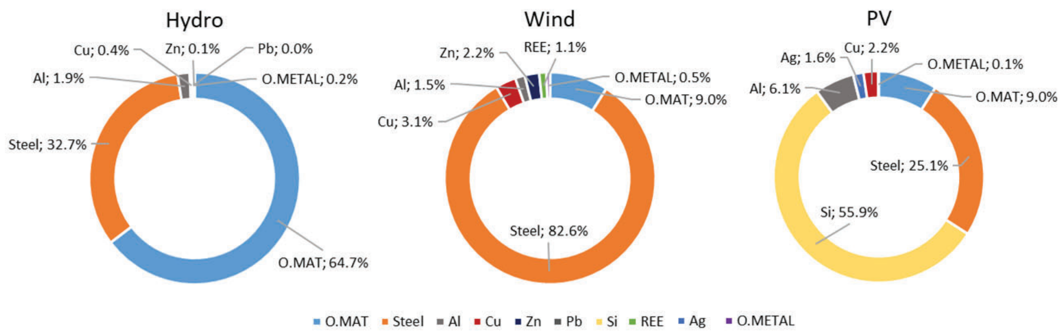

Figure 5. Metal and material contribution to exergy cost for the renewable energy infrastructure.

Figure 5 highlights a significant contrast in the composition of the technologies. Moreover, there is a substantial disparity in their total exergy cost, ranging from 1,034-1,028 MJ/MJ for hydro to 1,135-2,454 MJ/MJ for PV (Tab. 1). Despite exhibiting similar energy intensity, with PV ranging between 143 and 8.1 TJ/MW, wind 6.9 TJ/MW, and hydro 10.5 TJ/MW, the discrepancies in electricity cost primarily stem from the lifespan of each technology. Therefore, the cost of hydroelectricity is lower due to its longer lifespan (between 75-100 years), followed by wind (between 25-30 years), and finally, photovoltaic (20-30 years) (Torrubia et al., 2024a).
Regarding materials, the exergy cost of steel and other materials (concrete being the most significant) plays a crucial role in all three technologies. These materials represent 97.4% of hydro, 91.5% of wind, and 34.1% of photovoltaic of the exergy costs, owing to their substantial presence in infrastructure construction. For hydro, concrete impacts more (64.7%) than steel (32.7%) due to the extensive material usage in dam construction. Conversely, in wind power, steel (82.6%) affects more than concrete (9%), owing to its utilization in the tower and nacelle. In photovoltaics, steel utilized in the structure constitutes a larger portion of the cost (25.1%) than other materials (9%), which include concrete for the foundation, as well as plastics and solar glass. Following these metals, silicon for photovoltaics emerges as the most significant contributor (55.9%), attributed to the substantial energy required for its refinement (approximately 1400 MJ/kg) (Torrubia et al., 2023). Other metals utilized in both the structure and electrical circuits, with significant importance, include aluminum (contributing 1.9% in hydro, 1.5% in wind, and 6.1% in photovoltaic) and copper (0.4% in hydro, 3.1% in wind, and 2.2% in photovoltaic). Additionally, the utilization of zinc as a protective coating against corrosion in wind turbines (2.2%), REE (1.1%), in the permanent magnets of wind turbines and silver (1.6%) used in the electrical connections of photovoltaic panels, are also noteworthy (Carrara et al., 2020).

4 CONCLUSIONS

Ensuring the production of cleaner green hydrogen is crucial to address the challenges of the energy transition. This study examines the *renewability* of green hydrogen production through analyzing the exergy cost of hydrogen infrastructure, encompassing electrolyzers and renewable energies, with a particular focus on their metallic composition. Three types of electrolyzers are studied: AE, PEM, and SOEC, alongside three renewable energy sources: hydro, wind, and photovoltaic. Despite the rise in the exergy cost of metal extraction due to declining ore grades, the exergy cost diminishes over time for all cases, thanks to technological advancements such as lower material intensity in both renewables and electrolyzers, enhanced efficiency, and prolonged electrolyzer operation time. SOEC exhibit the lowest non-renewable cost (ranging from 0.0053 to 0.0007 MJ/MJ), followed by PEM (0.0080 to 0.0015) and

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AE (0.0062 to 0.0024 MJ/MJ). However, renewable energies infrastructure incurs significantly higher costs: 0.06 to 0.04 MJ/MJ for hydro, 0.27 to 0.05 MJ/MJ for wind, and 2.36 to 0.13 MJ/MJ for PV. Thus, the most favorable scenario is SOEC with hydro, while the least favorable is PEM with photovoltaic. The considerable disparities between electrolyzer and renewable costs stem from the significantly higher material (and therefore energy) intensity of renewables (ranging from 143-6.9 TJ/MW) compared to electrolyzers (1.4-0.3 TJ/MW). Regarding metals, steel predominantly contributes to the cost in AE (80%) and SOECs (71%), whereas PGMs (81%) contributes in PEM. In renewable energies, steel and concrete constitute a substantial portion of the exergy cost across all technologies (97.4% in hydro, 91.5% in wind, and 34.1% in PV), followed by silicon, primarily in PV (55.9%). In conclusion, while green hydrogen production is predominantly renewable, the materials required for its production entail a non-renewable cost. Although this cost is expected to decrease over time due to technological advancements, it will persist mainly for steel, concrete, silicon, and PGMs. Therefore, reducing the reliance on non-renewable energies in their manufacturing processes and promoting recycling will be pivotal in achieving *truly renewable* green hydrogen production. In addition, there are other challenges related to the hydrogen economy. These issues concern the economic costs of production, transportation, storage and safety, which will also have to be overcome to be successfully implemented as an energy carrier in the energy transition context. Finally, this study provides a basis for assessing the exergy costs, of any industry using green hydrogen to reduce its environmental impact, such as the fertilizer or metallurgical industries.

NOMENCLATURE

AE	Alkaline electrolyzer	Pt	Platinum
AEXC	Average electricity exergy cost	PV	Photovoltaic
Ag	number (–)	RE	Renewable energies (Hydro, wind or PV)
Al	Aluminum	REE	Rare Earth Elements
Cu	Copper	Si	Silicon
H2	Hydrogen	SOEC	Solid Oxid Electrolysis cells
IEA	International Energy Agency	TEC	Electrolyser technology (AE, PEM or
Ir	Iridium	SOEC)	
La	Lanthanum	XC	Exergy cost of materials
Ni	Nickel	XCE	Exergy cost of electricity
NZE	Net-Zero Scenario of IEA	XCF	Exergy cost of fuel
Pb	Lead	XCI	Exergy cost of Infrastructure
Pd	Palladium	Y	Yttrium
PEM	Proton Exchange Membrane	Zn	Zinc
PGM	Platinum group metals	Zr	Zirconium

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REFERENCES

Bareiß, K., de la Rua, C., Möckl, M., & Hamacher, T. (2019). Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems. *Applied Energy*, *237*, 862–872. https://doi.org/10.1016/j.apenergy.2019.01.001

Bhandari, R., Trudewind, C. A., & Zapp, P. (2014). Life cycle assessment of hydrogen production via electrolysis - A review. In *Journal of Cleaner Production* (Vol. 85, pp. 151–163). Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2013.07.048

Busch, P., Kendall, A., & Lipman, T. (2023). A systematic review of life cycle greenhouse gas intensity values for hydrogen production pathways. In *Renewable and Sustainable Energy Reviews* (Vol. 184). Elsevier Ltd. https://doi.org/10.1016/j.rser.2023.113588

 https://doi.org/10.52202/077185-0110

Carrara, S., Alves Dias, P., Plazzotta, B., & Pavel, C. (2020). *Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system.*

International Energy Agency. (2019). *The Future of Hydrogen*. https://www.iea.org/reports/the-future-of-hydrogen

International Energy Agency. (2021a). *Net Zero by 2050 - A Roadmap for the Global Energy Sector*. www.iea.org/t&c/

International Energy Agency. (2021b). *The Role of Critical World Energy Outlook Special Report Minerals in Clean Energy Transitions*. www.iea.org/t&c/

International Energy Agency. (2023). *Energy Technology Perspectives 2023*. www.iea.org

Jolaoso, L. A., Duan, C., & Kazempoor, P. (2024). Life cycle analysis of a hydrogen production system based on solid oxide electrolysis cells integrated with different energy and wastewater sources. *International Journal of Hydrogen Energy*, *52*, 485–501. https://doi.org/10.1016/j.ijhydene.2023.07.129

Krishnan, S., Corona, B., Kramer, G. J., Junginger, M., & Koning, V. (2023). Prospective LCA of alkaline and PEM electrolyser systems. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2023.10.192

Palmer, G., Roberts, A., Hoadley, A., Dargaville, R., & Honnery, D. (2021). Life-cycle greenhouse gas emissions and net energy assessment of large-scale hydrogen production via electrolysis and solar PV. *Energy and Environmental Science*, *14*(10), 5113–5131. https://doi.org/10.1039/d1ee01288f

Panchenko, V. A., Daus, Y. V., Kovalev, A. A., Yudaev, I. V., & Litti, Y. V. (2023). Prospects for the production of green hydrogen: Review of countries with high potential. *International Journal of Hydrogen Energy*, *48*(12), 4551–4571. https://doi.org/10.1016/j.ijhydene.2022.10.084

Rashid, M., Al Mesfer, M. K., Naseem, H., & Danish, M. (2015). Hydrogen Production by Water Electrolysis: A Review of Alkaline Water Electrolysis, PEM Water Electrolysis and High Temperature Water Electrolysis. In *International Journal of Engineering and Advanced Technology (IJEAT)* (Issue 3).

Tabrizi, M. K., Famiglietti, J., Bonalumi, D., & Campanari, S. (2023). The Carbon Footprint of Hydrogen Produced with State-of-the-Art Photovoltaic Electricity Using Life-Cycle Assessment Methodology. In *Energies* (Vol. 16, Issue 13). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/en16135190

Torrubia, J., Valero, A., & Valero, A. (2023). Energy and carbon footprint of metals through physical allocation. Implications for energy transition. *Resources, Conservation and Recycling*, *199*, 107281. https://doi.org/10.1016/j.resconrec.2023.107281

Torrubia, J., Valero, A., & Valero, A. (2024a). Fossil and renewable exergy cost of electrity production: 1900-2050. *Manuscript Submitted for Publication*.

Torrubia, J., Valero, A., & Valero, A. (2024b). From mines to electricity. The exergy cost and carbon footprint of photovoltaic panels. *Manuscript Submitted for Publication*.

Vidas, L., & Castro, R. (2021). Recent developments on hydrogen production technologies: State-of-the-art review with a focus on green-electrolysis. In *Applied Sciences (Switzerland)* (Vol. 11, Issue 23). MDPI. https://doi.org/10.3390/app112311363

https://doi.org/10.52202/077185-0110