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Social Framework for Hydrogen Policies in Latin America: A Case Study of Argentina

Luciana T. Rattaro and Yehia F. Khalil *

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Social Framework for Hydrogen Policies in Latin America: A Case Study of Argentina

Luciana T. Rattaro [1] and Yehia F. Khalil [2,*]

[1] MacMillan Center, Yale University, USA
[2] Chemical and Environmental Engineering Department, Yale University, USA
* Correspondence: yehia.khalil@yale.edu

Abstract

In Latin America, sustainable commitments towards decarbonizing hard-to-abate industrial sectors have identified hydrogen (H2) as a key enabler for the energy transition. This study develops a policy analytical framework to enhance the green H2 economy, using Argentina as the central case study. Key insights from the study include identifying often-overlooked social challenges within the H2 economy and proposing the integration of social indicators into policy design, with a particular focus on the territorial dynamics of Patagonia, labor conditions, indigenous participation, governance, and community impacts. Drawing from Social Life Cycle Assessment (S-LCA) guideline standards and H2 approach, this study highlights key social hotspots that existing S-LCA tools overlook due to their lack of specific focus on regional territories and their communities. The analysis combines six social impact categories, namely, human rights, working conditions, health and safety, cultural heritage, governance, and socio-economic repercussions as recommended by the United Nations Environmental Program (UNEP), analyzed at a three-level dimension, and complemented by the H2 justice approach for Argentina's potential green H2 production sector. These policy recommendations aim to foster a more resilient and sustainable development of the green H2 industry.

Keywords: green hydrogen; decarbonization; social indicators; Latin America; Argentina

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1. Introduction

The transition towards clean energy is essential for mitigating climate change by reducing the carbon footprint of energy production compared to fossil fuel use [1]. Low-carbon hydrogen (viz., Blue and Green H2) has the potential to play a key role in diversifying the global energy matrix, particularly in Latin America. Latin America is the most urbanized developing region (≈ 81%) and relies on fossil fuels for ≈ 75% of its energy needs [2]. In Argentina, the reliance on fossil fuels is evident, with the country's total energy supply comprising 55% natural gas and 33% oil [3]. In 2022, Argentina's CO2 emissions were 29.2% from the transport sector, 25.8% from electricity and heat production, and 12.4% from the industry[4]. In this context, the deployment of hydrogen economies can guide the region towards decarbonization by incorporating H2 usage into their economies. By integrating H2 as both an energy carrier and a source, Argentina can diversify its energy matrix and reduce its dependence on fossil fuels.

Hydrogen is the most abundant chemical element in the universe and can be used both as an energy carrier and an energy source [5]. Unlike other fuels such as oil or gas, H2 cannot be extracted through digging or drilling; it must be extracted from H2-rich materials [6]. Gaseous H2 is classified into different colors based on the primary energy source used for its production. Grey H2 is derived from natural gas (primarily methane gas), brown H2 from coal, blue H2 from natural gas with CO2 capture and storage (CCS), green H2 from water via electrolysis, and purple or pink 2 electrolysis powered by nuclear energy [5].In Argentina, grey and blue H2 have been produced for decades[7]. While these processes have traditionally relied on fossil fuel inputs and industrial use, Argentine

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provinces have recently begun to position green H2 as a strategic pillar for their decarbonization efforts.

With H2 serving as both an energy carrier and an energy source, its applications span various industries such as the steel industry, chemical industry, and refineries [8]. In the transportation sector, H2 can be integrated into the energy matrix for applications in shipping, aviation, and ground transportation. Additionally, H2 can be used for heating and power generation. Given these versatile applications, global interest in hydrogen's role in developing a decarbonized energy system has surged. This increased interest is driven by opportunities to incorporate H2 into various sectors of national economies. Government objectives and pathways toward achieving net-zero energy systems have particularly fueled this renewed interest in H2, often referred to as the "third wave of hydrogen" [9]. This wave emphasizes the strategic incorporation of H2 into economies as a key component in the transition to sustainable energy systems.

Since the first wave of H2-based literature, the focus has predominantly been on a technocratic perspective [9], leaving a significant gap concerning the social impacts and implications of the H2 value chain. This oversight raises the following two central questions:

a) To what extent do Latin American hydrogen policies address the region's social challenges in the energy transition?
b) And further, who bears the cost of these transitions?

The remainder of this study is organized as follows: Subsection 1.1 provides a critical review of the relevant literature. Subsection 1.2 identifies significant gaps in the published literature on the prospective social impacts of hydrogen production and its associated value chain. Section 2 discusses the methodological framework employed in this study, which utilizes various approaches to identify social hotspots in the production of hydrogen within the South American region, with a primary focus on Argentina. Section 3 presents the case study for Argentina. Section 4 features the key policy recommendations (subsection 4.1. and 4.2), followed by the conclusions of this study in Section 5.

1.1. Literature Review

This study identifies two major groups in the literature that analyze green H2 production and address its social dimensions. The first group focuses on the abundant research concerning the technical and environmental feasibility of H production. The second group focuses on the environmental justice. Regarding the first group, multiple studies utilized the Social Life Cycle Assessment (S-LCA) methodology to identify social hotspots in H2 projects [10–16]. However, S-LCA is not yet a settled standard, and there are ongoing debates on how to structure these indicators [17,18]. The UNEP/SETAC framework provides a general structure but leaves substantial discretion in defining categories, indicators, and data requirements. This contributes to the lack of consensus on which social impacts should be included and how they should be assessed [18].

While the Environmental Life Cycle Assessment (E-LCA) assumes a direct causal link between processes and environmental impacts, Social Life Cycle Assessment (S-LCA) has been criticized for lacking a strict causal link between many social impacts and the processes themselves. Instead, the connection is often tied to the conduct of the companies carrying out these processes [17].

Khalil's research [19] makes a significant contribution to this field by proposing the integration of Social Life Cycle Assessment (S-LCA) with Environmental Life Cycle Assessment (E-LCA) to comprehensively evaluate the sustainability of green H2 technologies [19]. Furthermore, Khalil conducted various analyses of different H2 production technologies based on both quantitative and qualitative criteria [12]. For the quantitative criteria, the research considered factors such as cost, energy consumption, global warming potential, and energy efficiency [12]. The qualitative criteria included technology readiness levels and the availability of supply chain materials. Additionally, Khalil explores the current state, technical aspects, and economic considerations for green and sustainable hydrogen production technologies [13,20]. This includes identifying cost drivers and conducting Aspen HYSYS process simulations of Alkaline Water Electrolysis (AWE) and Proton Exchange Membrane Electrolysis (PEME) plants.

Akhtar identified social hotspots within the green H2 supply chain and evaluated the impact of green H2 on the United Nations Sustainable Development Goals (SDGs) for the large-scale deployment of a green hydrogen economy [14]. Gamboa et al. investigated the use of Product Social Impact Life Cycle Assessment (PSILCA) [11]. In their analysis, they compare two potential hydrogen value chains in the EU: (i) an on-site option, where hydrogen is produced and consumed within the same country, and (ii) an off-site option, where hydrogen production and consumption occur in different countries. The analysis of the social life cycle results indicated that the on-site value chain, producing hydrogen with wind electricity, demonstrates better social performance than the off-site value chain, which produces hydrogen with photovoltaic (PV) electricity, across most of the study's selected indicators. Holger applied 23 social indicators from the Social Hotspots Database (SHDB) to evaluate the social impacts of hydrogen production in Germany, Austria, and Spain across the entire process chain, using Sen's capability approach as a reference [15].

Simultaneously, the literature underscored the importance of social aspects framed within international frameworks such as the Sustainable Development Goals (SDGs) and the Universal Declaration of Human Rights [14,16]. Nonetheless, while regions like the European Union have undertaken more extensive analyses and Africa [11,21–23], the social assessments and impacts associated with hydrogen deployment remain underexplored in Latin America. In this region, there is abundant literature on the technical and environmental feasibility of H2 production in South America [24–26], and on the economic feasibility of H2 production [27]. However, there is a notable gap in the social approach to green H2 production. In the case of Argentina, several studies focused on technical assessments and feasibility prospects for 2pment [7,24,26]. However, the social dimensions of hydrogen production remain insufficiently addressed.

The second group of H2 studies focuses on the environmental justice lens and the broader implications of H2 deployment worldwide. In relation to the environmental justice field, the literature can be summarized as follows:

Sovacool and Dworkin [28] defined energy justice (p. 436) as "a global energy system that fairly disseminates both the benefits and costs of energy services, and one that has representative and impartial energy decision-making". Sovacool and McCauley et al. critically examined low-carbon transitions in the EU using an energy justice framework [21,29]. This framework consists of four dimensions: distributive justice (distribution of costs and benefits), procedural justice (fair and inclusive decision-making processes), cosmopolitan justice (consideration of global externalities), and recognition justice (acknowledgment and protection of vulnerable groups). These dimensions have been widely used in the literature to analyze energy transitions. Expanding on these perspectives, Müller et al. introduces the concept of 'hydrogen justice,' which aims to analyze and address socio-ecological injustices within the hydrogen economy [22]. This expanded concept of H2 justice includes six dimensions: procedural justice (fair decision-making processes), relational justice (fair interactions and relationships), recognition justice (acknowledgment and protection of vulnerable groups), distributive justice (equitable distribution of costs and benefits), restorative justice (correction of past injustices), and epistemic justice (recognition of diverse knowledge systems) [22].

In the context of Argentina, the literature predominantly focuses on the technical and economic dimensions of H2 production [27,30], with less attention given to the socio-ecological impacts, as noted by Tapia Rattaro [31]. Nonetheless, Dorn provided a comprehensive analysis of H2 project development that incorporates social dimensions [7]. Utilizing a global production network approach, Dorn identified three energy imaginaries related to H2 production in Argentina. The first imaginary, green developmentalism, positions green hydrogen as both a solution to the climate crisis and a development opportunity, proposing that Argentina could reposition itself as a clean energy exporter—a perspective strongly supported in the political agenda of Río Negro [7]. The second imaginary, energy autonomy, underscores the tension between promoting green hydrogen and Argentina's current reliance on fossil fuels [7]. This narrative highlights the significance of the Vaca Muerta formation, one of the largest shale reserves in the world, and the role of natural gas in national energy sovereignty. The third imaginary contemplates potential opposition to the hydrogen sector, rooted in environmental protection regulations, legal frameworks, policy demands, and claims for territorial autonomy [7].

1.2. Knowledge Gaps Identified from the Literature and Addressed in This Research

Our study has identified a significant gap in the literature regarding the prospective social impacts of H2 production and its value chain. Since the first wave of H2 literature, social dimensions have been largely overlooked in favor of a technocratic perspective [9]. As Kühnen & Hahn argued, the maturation of S-LCA relies on drawing from accumulated empirical experience in the field [18]. This literature gap is particularly pronounced within the Latin American context. The social assessments and impacts associated with H2 deployment remain underexplored, especially in relation to the development and implementation of public policies in the region. This gap is significant given Latin America's unique socio-economic challenges, which are not adequately captured by existing assessment tools. Persistent challenges in the relationship between green H2 projects and local territories and communities highlight the need to address social acceptance, community participation, and the equitable distribution of benefits within host regions.

2. Methodological Framework

The methodological framework of this study involves employing various methods to identify social hotspots in the production of H2 within the South American region, particularly in Argentina. Our study includes a case study to identify best practices and challenges specific to Latin America, with a focused examination on Argentina. This methodological approach combines the collection of contextual data on political, socio-economic, and environmental aspects in the country, stakeholder mapping, and the analysis of relevant literature and documents proposed by H2 initiatives, as follows:

First, this study considers the S-LCA guidelines, which are not as widely used as E-LCA [32], with a specific focus on raw material extraction, production, and manufacturing processes within the countries under analysis. Due to the absence of an ISO standard for S-LCA, this study utilizes the UNEP/SETAC guidelines for S-LCA. While S-LCA builds on the general logic of LCA, analysis boundary-setting remains one of its least harmonized aspects. S-LCA approaches vary considerably in how they determine which processes, or social impacts should be included in the assessment [17]. Some frameworks rely on expert judgment, while others adapt ISO 14044's criteria by replacing environmental significance with social significance [17].

Additionally, for analyzing the social implications of green H2 in the region, our study incorporates the dimensions of environmental justice outlined in the literature. These dimensions include distributive justice (allocation of costs and benefits), procedural justice (fair decision-making processes), cosmopolitan justice (consideration of global externalities), and recognition justice (acknowledgment of vulnerable groups) as proposed by McCauley et al. and Sovacool et al. [28,29]. Furthermore, this study integrates these dimensions with the concept of "H2 justice," which addresses socio-ecological injustices, as proposed by Müller et al. [22]. This expanded framework includes six justice dimensions: procedural justice (fair processes), relational justice (human-environment relationships), recognition justice (acknowledgment of vulnerable groups), distributive justice (equitable distribution of costs and benefits), restorative justice (addressing historical injustices), and epistemic justice (recognition of diverse knowledge systems) [22].

Table 1. S-LCA based on the UNEP/SETAC guidelines.

S-LCA Categories and Subcategories	
Category	Subcategories
Worker	Freedom of association and collective bargaining Child labor

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	Fair salary
	Working hours
	Forced labor
	Equal opportunities / discrimination
	Health and safety
	Social benefits / social security
	Employment relationship
	Sexual harassment
	Smallholders including farmers
	Access to material resources
	Access to immaterial resources
	Delocalization and migration
	Cultural heritage
Local community	Safe and healthy living conditions
	Respect for indigenous rights
	Community engagement
	Local employment
	Secure living conditions
	Fair competition
	Promoting social responsibility
Value chain actors	Supplier relationships
	Respect for intellectual property rights
	Wealth distribution
	Health and safety
	Feedback mechanism
Consumer	Consumer privacy
	Transparency
	End-of-life responsibility
	Public commitment to sustainability issues
	Contribution to economic development
	Prevention and mitigation of armed conflicts
Society	Technology development
	Corruption
	Ethical treatment of animals
	Poverty alleviation
	Education provided in the local community
Children	Health issues for children as consumers
	Children's concern regarding marketing practices

Table 2. Hydrogen justice as proposed by Müller et al. [22].

Hydrogen Justice Categories and Subcategories	
Justice Categories	Subcategories
Procedural justice	Due process
Relational justice	Human relationships with environment
Recognitional justice	Vulnerable groups
Distributive justice	Costs and benefits
Restorative justice	Historical injustices
Epistemic justice	Knowledge recognition
Hydrogen justice	Combination of different justice lenses

3. Case Study: Argentina

3.1. Argentina's Hydrogen Policies

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3.1.1. National Hydrogen (H2) Strategy

Since 1998, several efforts have been made to develop a H2 economy in Argentina, beginning with the introduction of bills in the National Congress to regulate the H2 economy [33]. In August 2006, Argentina passed an early law aimed at promoting H2 energy as a matter of national interest. Unfortunately, this law expired on December 31, 2021, as it was never regulated. Concurrently, a pilot project, Hychico, was launched and has been in operation since that year.

In recent years, legislative interest in H2 energy has intensified. Since 2022, multiple initiatives have been introduced and remain under parliamentary consideration. Among them are the Regulatory Framework Bill for the Renewable and Low Emission Hydrogen Industry, presented in September 2024 (Proyecto de Ley de Marco Regulatorio para la Industria del Hidrógeno de Origen Renovable y de Bajas Emisiones), and the Bill on the Regulation and Promotion of Hydrogen, dated March 2024 (Proyecto de Ley sobre Regulación y Fomento del Hidrógeno) [33].

Despite the lack of a specific legal framework for the H2 industry, Argentina introduced its National Hydrogen Strategy (ENH) in 2023. According to the ENH, Argentina aims to produce at least 5 million tons of low-emission H2 annually by 2050 through the combined development of green and blue H2 production. Of the total production, 20% will be allocated to the domestic market, while 80% (approximately 4 million tons annually) will be targeted for export. The ENH identifies Germany and Japan as potential export markets, and current projects also consider Rotterdam and Hamburg as potential destinations for the H2 to be used in key sectors such as the chemical industry, agriculture, transport, and power generation.

Argentina's competitive advantages, such as Patagonia's exceptional wind capacity (60%), availability of biomass in the central region, strong potential for hydropower, and water access near the production clusters, position the country as a competitive exporter of green H2.

Following the ENH, the low-carbon H2 projects involve a complex set of interconnected technological and industrial capabilities along the value chain. These capabilities include the manufacturing of fixed assets, parts, and components, as well as the construction of transport and storage infrastructure. Additionally, the supply of knowledge-intensive services, ranging from engineering to research and development, is crucial. The manufacturing process of industrial goods using low-emission H2 as well as H2 derivatives is also a key component. In this context, Patagonia is a promising region for H2 development due to the availability of land, access to ports, and access to seawater in the region [27].

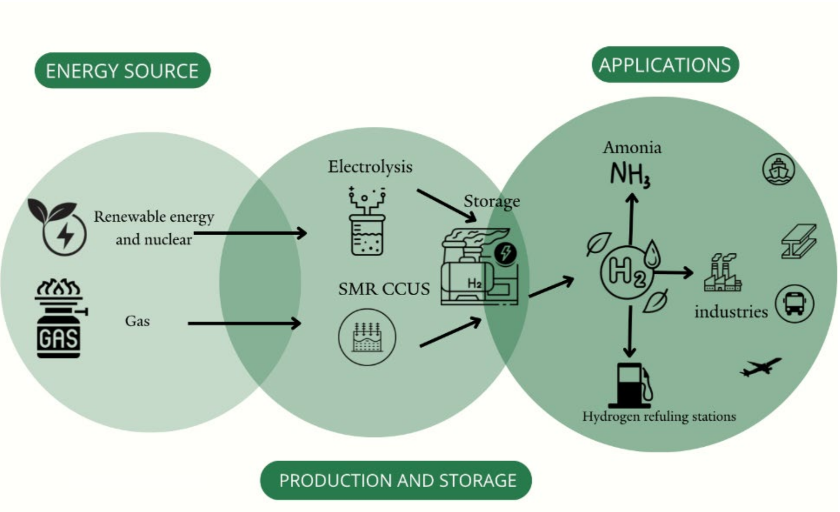

Figure 1. Green electricity production from clean electricity (source: own elaboration based on the National Hydrogen Strategy).

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While the ENH emphasizes Argentina's competitive advantages for the future production of low-carbon H2, less attention has been paid to the social dimension consequently from the production.

3.1.2. Patagonia's Hydrogen (H2) Strategies

A few green H2 projects are underway in the Patagonia region, an area known for its vast lands and abundant natural resources, including oil, gas, and exceptional wind potential. This region is also characterized by its rich biodiversity and the presence of indigenous communities, making the social and environmental aspects of H2 deployment particularly relevant. Patagonian provinces in Argentina are proactively developing green hydrogen strategies, leveraging their extensive renewable resources and infrastructure. These subnational initiatives present an opportunity for provinces to fill the gap if national commitments are lacking. These initial proposals were presented by two provinces within the Patagonian region: Río Negro and Tierra del Fuego, Antártida e Islas del Atlántico Sur.

Río Negro has created various instruments and bodies for comprehensive green H2 development. The province partnered with Germany's Fraunhofer Institute to assess its hydrogen production potential, confirming exceptional wind resources with average speeds between 8 to 12 m/s, among the highest in the world, as well as abundant water availability [34]. Potential development regions identified include El Solito, Pomona, Chocón, and Laguna de la Retención, as recommended by the provincial government. The feasibility study proposed two value chain phases: an initial domestic integration stage to supply hydrogen to regional industrial and mobility sectors, and a long-term export phase, with the San Antonio Oeste Port being key to its integration.

In 2021, Río Negro also created the Rionegrina Green Hydrogen Board (Mesa de Hidrógeno Verde Rionegrina) through Provincial Decree No. 342/21. This board serves as a transversal and interdisciplinary body responsible for defining and maintaining active and sustained public policies in science, innovation, research, and green hydrogen development. Another proposed instrument is the creation of a Participatory Green Hydrogen Council (Consejo Participativo de Hidrógeno Verde), which will include citizen, private, and public representatives to assist the local government on hydrogen projects. The first strategic plan for green hydrogen in Río Negro takes into consideration the natural resources, capacities, and infrastructure within the province. The creation of this plan required an alliance with the Fraunhofer Institute for Energy Economics and Energy System Technology (IEE).

Another provincial H2 strategy from the Patagonian region originates from the province of Tierra del Fuego. The Tierra del Fuego Hydrogen Roadmap aims to produce both green and blue hydrogen in the province and explicitly addresses the socio-environmental dimensions within its value chain. The strategy also envisions a diversified hydrogen economy with applications in green ammonia and methanol production to create synthetic fuels and fertilizers. In developing this strategy, the local government collaborated with the Federal Investment Council (FIC) to evaluate the cumulative impact of H2 projects.

Additionally, other Patagonian provinces such as Neuquén, Chubut, and Santa Cruz have also made advancements in developing hydrogen economies. In 2022, Neuquén joined the Hydrogen Economy Development Consortium. In Chubut, the Hychico projects, which have been operating since 2006, produce green hydrogen through electrolysis powered by wind energy and operate the only hydrogen pipeline in Latin America (2.3 km) [35]. The project is supported by a wind farm with an installed capacity of 6.3 MW. The hydrogen plant has a total production capacity of 120 Nm^3/h of hydrogen and 60 Nm^3/h of oxygen [36]. Additionally, Chubut has signed a Memorandum of Understanding with public and private institutions to establish a hydrogen cluster in the province. This initiative involves the coordination of technological innovation, industrial development, and research to position Chubut as a national leader in H2 production [37].

In 2024, Santa Cruz passed Provincial Law No. 3873, which established the Provincial Hydrogen Board (Mesa de Hidrógeno de Santa Cruz). This interdisciplinary board is responsible for integrating

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hydrogen policies with provincial entities and academic institutions. Additionally, Santa Cruz is home to the most recently announced hydrogen project, Proyecto Gaucho, a public-private partnership with the German development agency Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and the Austrian renewable-energy developer RP Global, now known as New Energy Argentina. In its first phase, the project plans to install 3 GW of electrolysis capacity powered by 4.2 GW of wind energy, capable of generating over 21,000 GWh of electricity and producing 1.7 million tons of green ammonia annually [38]. While the pathway for developing a H2 economy may vary across the region, Patagonia shares socio-economic and territorial conditions that allow for the identification of common social challenges and hotspots within the territory.

3.2. Social Impact Analysis

This section explores these social hotspots at three different levels. To analyze these social challenges, we considered the green H2 value chain as framed by the policy framework in Patagonia, Argentina.

Our analysis combines six key social impact categories: human rights, working conditions, health and safety, cultural heritage, governance, and socio-economic repercussions. These categories are recommended by UNEP and complemented by the H2 justice approach. It is worth noting that certain social hotspots, such as child labor, have not been identified as relevant issues in Argentina.

Table 3. Summary of social challenges for green hydrogen production.

Social indicators according to Argentine context	
Society	Governance: Institutional legitimacy
Society	Governance: Corruption
Society	Human rights: Public commitment to indigenous affairs
Society	Labor rights: employment
Society	Sustainability: Public commitment to sustainability issues
Society	Sustainability: Suppliers
Society	Education
Community	Natural resources
Community	Land use
Community	Indigenous communities
Community	Employment
Community	Public acceptance
Workers	Gender inequality
Workers	Health conditions

3.2.1. Society as Stakeholder

1. Governance: Institutional legitimacy

Argentina's political and institutional stability plays a crucial role in attracting investment and building public trust in large-scale energy projects. However, the current absence of a comprehensive regulatory framework for hydrogen in Argentina could create uncertainty for investors and communities alike. Without clear environmental, social, and technical standards, there is a risk of ad-

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hoc project development that overlooks social impacts. Presently, the General Environmental Law (Ley General de Ambiente No. 25,675) may not fully account for all social dimensions relevant to hydrogen projects, as the environmental and social baseline analysis required under the law is limited to the immediate area of a project's influence.

2. Governance: Corruption

Government corruption remains a significant governance challenge in Argentina, with direct implications for the transparency of large-scale infrastructure projects. The Transparency International Corruption Perception Index (CPI) has ranked Argentina between 94th and 99th out of 180 countries worldwide over the past three years, with specific scored 38/100 in 2022, 37/100 in 2023, and 37/100 in 2024 [39–41].

In the context of H2 production, these governance risks could lead to irregularities and non-transparent public-private partnerships. As a result, major investments may be perceived negatively by the community, necessitating concerted efforts to ensure transparency. Strengthening transparency mechanisms in the permitting process, such as inclusive consultation processes and the accessibility of Environmental Impact Assessments (EIAs), could potentially ensure better accountability.

3. Human rights: Public commitment to indigenous affairs

Argentina's legal framework formally recognizes Indigenous rights. From the constitutional level in which art. 75 acknowledges the preexisting ethnic and cultural identity of Indigenous People. At international agreement level, Argentina has endorsed the UN Declaration on the Rights of Indigenous People and the American Declaration on the Right of Indigenous People. At national level, Indigenous Policy Law No. 23,302 declares as matter of national interest to provide support to Indigenous people and communities and ensure their protection and participation in socio-economic and cultural processes. Law 24,071 approves Argentina's ratification of ILO Convention 169 which encapsulates the Free, Prior and Informed Consent (FPIC). Several provincial constitutions, such as those of Neuquen (Art. 53) and Río Negro (art. 42)- among others-, have recognized indigenous rights.

According to the National Meeting of Indigenous Pastoral Work (ENDEPA in Spanish), there are 17 different Indigenous Peoples in Argentina [42], whose relationship with energy projects in Argentina is complex. In certain regions or provinces, such as Salar de Olaroz-Cauchari in Jujuy, Indigenous people are involved and accepting of the development of an extractive project while in other cases, the Indigenous people have presented opposition to the development of the same type of projects [43,44].

In terms of H2 projects, there are strong criticism from the Indigenous people of the Mapuche-Tehuelche community based on an export-based model proposed by the ENH [7]. Their concerns are bases on land uses, transparency and institutional legitimacy.

Despite these contrasting approaches towards energy projects, the lack of indigenous involvement in the development of large-scale energy projects can raise environmental justice concerns.

4. Labor rights: Employment

Employment, as an indicator, captures the job creation opportunities and the relationships between workers and employers [45]. In Argentina, it is crucial to apply these indicators at a national scale to further assess the sustainability of such employment.

According to the ENH, Argentina anticipates the creation of 13,000 specialized jobs by 2030 and 82,000 by 2050 in the hydrogen industry. Job creation is expected to occur during the construction, operation, transportation, and refilling phases of each project [27]. However, the sustainability of these employment opportunities largely depends on the country's structural labor conditions.

Argentina's labor market faces significant challenges with high rates of labor informality, where employees carry out activities outside the legal framework of their employment (outside labor legislation, employment guarantees, social protections). By the fourth quarter of 2024, 45.7% of

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Argentina's population was employed. However, labor informality represents 42% of the employment rate, with women being the most affected group, reaching an informality rate of 43.4% [46].

In the wind energy sector specifically, projects have tended to exhibit higher levels of formal employment. This is largely due to the significant investments required for project development [47]. However, the temporary nature of construction work remains a challenge. Addressing this issue requires policy action beyond local hiring. Various approaches can be implemented to ensure a more inclusive hydrogen industry. National and provincial sectors can focus on strengthening efforts to prevent informal employment while also working to mitigate its effects in order to avoid reinforcing existing inequalities.

5. Sustainability: Public commitment to sustainability issues

The Public Commitment to Sustainability assesses how a government or organization aligns with international sustainability objectives and implements them through concrete national frameworks [45]. Argentina has demonstrated its commitment to sustainability through several legal and policy instruments. The country ratified the Paris Agreement with Law No. 27,270 and has adopted Nationally Determined Contributions (NDCs) targeting carbon neutrality by 2050. Argentina has integrated sustainability principles in the National Climate Change Law (Law No. 27,520) and established a robust renewable incentive regime (Law No. 26,190 and Law No. 27,191). At a sectoral level, Argentina's National Hydrogen Strategy (ENH) identifies green hydrogen as a strategic pillar for decarbonization and energy diversification. The ENH explicitly connects hydrogen development to the use of renewable resources (mainly wind in Patagonia) and the creation of high-quality green jobs. However, while these commitments align with Sustainable Development Goals (SDGs) 7, 9, and 13, implementation challenges may persist.

In this context, identifying public commitment to sustainability solely through national frameworks might be limited. From S-LCA perspective, these gaps highlight the limitations in Argentina's institutional coherence across the H2 value chain. Sustainability challenges extend beyond national policies and can also be effectively addressed at the subnational level.

6. Sustainability: Suppliers

The H2 production process relies on inputs and components that are often imported, which can compromise the overall sustainability of Argentina's H2 value chain, particularly in terms of local value creation. According to the Tierra del Fuego Hydrogen Roadmap, it is not feasible in the medium term to exceed 20% local component demand in total plant investment. Foreign supplies are required for equipment segments such as electrolyzers, high pressure vessels, storage, and transport technologies.

The dominance of foreign suppliers means that the relationship between the country and the supplier is not just transactional but also strategic. The development of strong partnerships can contribute to local industrialization, skill transfer, and regional value creation.

7. Education

Social Life Cycle Assessments (S-LCA) do not typically account for education unless it pertains specifically to children's education. However, education emerges as a crucial enabler for the sustainable development of the H2 industry, as it equips the workforce with the specialized knowledge and technical skills necessary to build capacity in the communities where projects are based. Argentina has a robust legal framework for environmental education, but its implementation is marked by discontinuity and heterogeneity. The current framework is established by the General Environmental Law (Ley General de Ambiente) No. 25.675/02, the National Education Law (Ley Nacional de Educación) No. 26.206/06, and the Comprehensive Environmental Education Law (Ley de Educación Ambiental Integral) No. 27.621. The first law introduced environmental education, which was later adopted and integrated at all educational levels [48,49]. The latest law, enacted in 2021, has advanced environmental education as a national state policy, spurring academic discussion around its implementation [50]. At the university level, several initiatives aim to foster coalitions for

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environmental and sustainable practices. The creation of Red UAGAIS, involving more than 50 universities across the country, demonstrates a strong commitment to sustainability. Additionally, over 150 universities offer environmental-related programs, including undergraduate programs, specializations, and master's degrees [51]. These initiatives are pivotal in developing the expertise needed for Argentina's hydrogen industry to thrive sustainably.

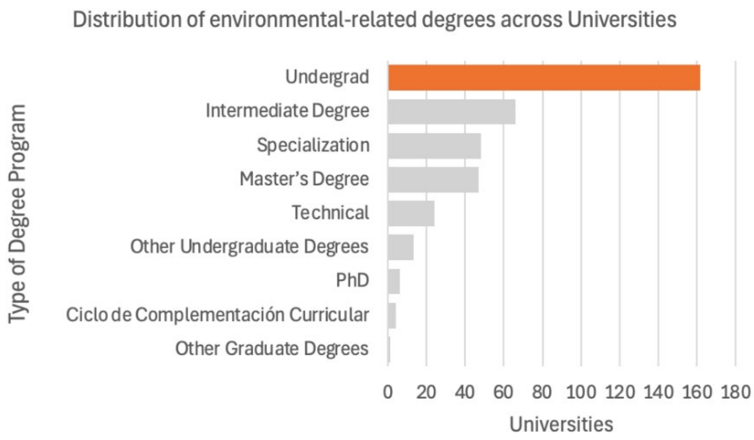

Figure 2. Prepared by the authors based on information from the Ministry of Education of Argentina.

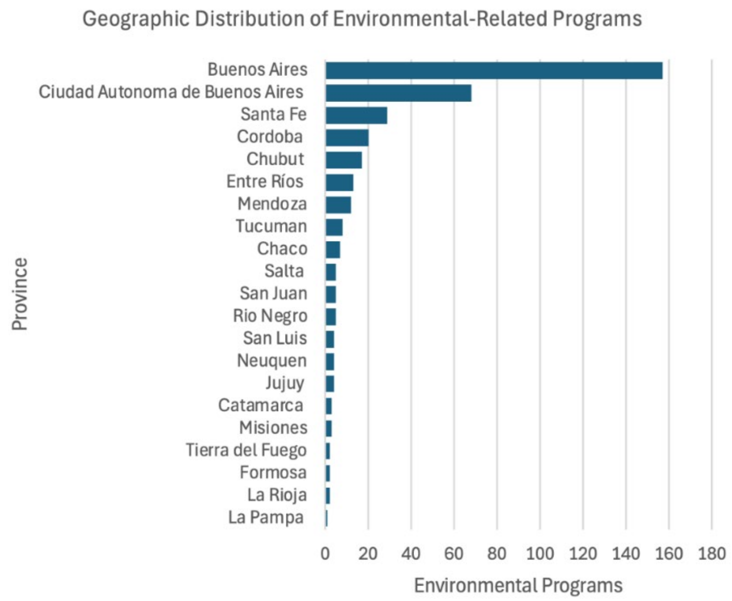

Figure 3. Prepared by the authors based on information from the Ministry of Education of Argentina.

Figures 2 and 3 reveal a strong concentration of environmental-related academic programs in Buenos Aires Province, while most other provinces exhibit a significantly lower presence of such programs. This indicates an uneven distribution of environmental-related academic programs within the country. The southern provinces show a lower concentration of environmental-related programs, which can be problematic given the potential for hydrogen development in the region. Furthermore, there is a strong focus on undergraduate programs, with comparatively fewer opportunities for advanced professional or postgraduate specialization in the field.

Despite these programs, Argentina's environmental education strategy faces contextual challenges. Literature indicates that, despite the existing legal framework, Argentina is not currently providing adequate environmental education [48,49]. Even the Tierra del Fuego Hydrogen Roadmap underscores the need to adapt provincial academic curricula to strengthen capacity-building efforts.

In this context, measuring the availability of environmental-related programs alone may fall short in assessing the capacity-building potential in the sector. Combining academic programs with collaborations between institutions (such as CONICET) and industry can enhance local capacity and employability, contributing to the creation of a skilled talent pool for the hydrogen sector.

3.2.2. Community as Stakeholder

a) Natural resources

Expanding industrial operations might increase the likelihood of conflict over essential resources [45]. Green H2 production demands an interconnected system of infrastructure, including wind or solar farms, electrolysis and desalination plants, storage terminals, transmission lines, and port facilities.

Several subcategories of natural resources are particularly relevant to Argentina's hydrogen development, such as water resources, land use, and biodiversity. From a relational justice perspective, respecting community concerns about water and land are essential to ensure that H2 expansion does not replicate existing inequalities surrounding resource access. The evaluation of these impacts must cover the entire production chain, from energy generation to export logistics, to prevent overlapping pressures on local resources [52]. As provinces will require specific permits for the use of natural resources, including seawater extraction, subnational regulation could help reduce the likelihood of conflicts over natural resources. For example, electrolysis demands large volumes of water. To address this, the Tierra del Fuego Hydrogen Roadmap contemplates the exclusive use of seawater for desalination to avoid pressure on freshwater aquifers. There is also an opportunity to develop a combined assessment and monitoring framework for the impacts on land, water, and biodiversity [53].

b) Land use

Although S-LCA has not yet systematically incorporated land use and its interconnection with indigenous rights as a social subcategory, this aspect is increasingly relevant for evaluating hydrogen production projects in Argentina under an epistemic hydrogen justice perspective. Assessing land use and indigenous rights as a social hotspot remains challenging in Argentina's emerging green H2 sector due to the scarcity of data.

Green H2 production requires extensive infrastructure, including renewable energy fields (such as wind farms in the case of Argentina's current proposal), electrolysis plants, desalination plants, storage terminals, and port infrastructure for transportation. This comprehensive production system may lead to environmental impacts such as land use changes, local pollution if not properly regulated, and biodiversity risks (such as landslides or the spread of communicable diseases) [45]. In Patagonia, the distribution of competitiveness advantages could significantly affect Indigenous territories, where land holds both economic value for their production matrix and spiritual significance. Indigenous communities are often excluded from the development of national strategies for impactful industries. From the perspective of indigenous people, there is a value in maintaining existing productive structures based on agricultural and livestock practices associated with ancestral traditions (Buen Vivir) rather than economic expansion, as expressed by the Vice Lonco of the Mapuche Community.

Resistance to the development of H2 production by Indigenous People is based on several factors: (i) land purpose, (ii) the use of their land without consultation or approval, and (iii) strong criticism of an export-based model that could potentially perpetuate existing inequalities. To fully understand how an indigenous community might be affected by a hydrogen project and its value chain, site visits and site-specific audits are required, including consultation with the community and different stakeholders such as governmental agencies and the recognition of indigenous land rights. The use of large tracts of land for renewable energy infrastructure and the hydrogen production on-site without a transparent consultation process may perpetuate hidden social costs within Argentina's hydrogen development model.

c) Indigenous communities' participation and consent

Indigenous communities are often disproportionately affected by large-scale energy projects, raising significant environmental justice concerns. Energy policies may continue to reproduce structural inequalities by overlooking indigenous participation in their design. Müller et al. identify that hydrogen policies may lead to epistemic injustices if they fail to acknowledge local knowledge systems and instead reproduce colonial or Eurocentric knowledge orders [22]. Such narratives risk undermining Indigenous People's relationship with their territory. According to the National Institute of Indigenous Affairs, more than 200 recognized indigenous communities are located across the Patagonian provinces [54]. Mamaní highlights that indigenous issues were long excluded from the state agenda and only gradually became institutionalized following the 1994 constitutional reforms [42].

In Argentina, the Mapuche-Tehuelche community has expressed skepticism towards hydrogen projects due to limited participation channels, unclear environmental communication, and weak institutional coordination. As the Vice Lonco explained, Indigenous communities see themselves as the main defenders of the environment but maintain a critical stance because they have been excluded from participating. He further added that distrust would persist as long as their participation is denied. The relationship between indigenous people and energy projects is specific to the territory and the community itself [43]. Recognizing these perspectives is therefore essential in achieving a socially just H2 economy.

d) Employment

The Tierra del Fuego Hydrogen Roadmap identifies the creation of 1,400 temporary jobs per gigawatt for the civil work of wind farms, while the construction and operation of electrolysis plants are expected to create between 60 and 172 jobs per gigawatt. Indigenous communities have expressed concerns about the quality of these jobs, given their temporary nature and limited potential for long-term inclusion. In terms of economic activity, the construction sector shows a high level of informality at 76.6%, compared to 36.1% in manufacturing [46]. To ensure a more inclusive hydrogen industry, several approaches can be taken. National and provincial governments can focus on strengthening efforts to prevent informal employment and mitigate its effects to avoid reinforcing existing inequalities. Hydrogen and wind energy companies can work towards developing local value chains to reduce this issue, while provincial regulatory frameworks promoting local hiring (policy known as compre local in Spanish) could ensure more equitable participation.

Provincial governments can also focus on developing a more skilled labor force. One example is the educational program "Rio Negro Labor Future" proposed by Rio Negro's hydrogen strategy, which aims to strengthen local capabilities through interdisciplinary collaboration between various stakeholders, including universities, labor unions, industrial chambers, and technical education institutions. This initiative can help ensure that the local workforce is better equipped for long-term, skilled employment opportunities in the hydrogen industry.

e) Public acceptance

Public acceptance refers to the degree of social legitimacy and trust that communities attribute to a particular industrial project [45]. Transparency should function as a reciprocal and dialogical process, enabling mutual understanding among stakeholders (states, production companies, local communities, Indigenous People). It requires coordination among affected communities, government institutions, and private and public companies.

In the context of H2 development, public acceptance will depend on the credibility of institutions, the perceived fairness of decision-making processes, and the respect for territorial rights. Education and community participation are interdependent pillars of public trust. As Palanca et al. highlights, community participation through trusted local leaders and tailored educational initiatives is crucial to clarifying the complexities of the technology and fostering confidence in green hydrogen production [55].

For Argentina, this approach is particularly relevant in indigenous territories, where acceptance depends on designing participatory mechanisms that align with local values. The different instruments available for indigenous consultation and participation should be accountable, ensuring that transparency is understood as a foundation for sustainable production. This transparency should be based on open communication, institutional accountability, and the co-production of shared knowledge, rather than functioning merely as an administrative requirement.

3.2.3. Workers as Stakeholders

1. Gender inequality

The complexities of gender inequalities in the labor market extend far beyond access to employment. Women face both horizontal and vertical segregation in the workforce [56]. Horizontal segregation refers to gender disparities in sectors where women are often concentrated in informal employment and lower-wage jobs. Vertical segregation, on the other hand, pertains to women's limited representation in leadership and decision-making positions [56]. These disparities are particularly pronounced in the energy sector. According to the World Economic Forum's Gender Gap Report, only 20% of leadership positions in the energy sector are held by women [57]. In Argentina, the labor force participation rate among women is 52% for 2024 [58]. However, there is still limited data available to assess women's current employability within the national energy sector or the emerging H2 sector specifically.

Partnerships between production companies, local universities, NGOs, and gender institutions (such as gender observatories) offer the potential to incorporate gender-sensitive monitoring tools into hydrogen workforce policies. An example of such coordination is seen in New Energy Argentina's capacity-building series, conducted in collaboration with stakeholders like GIZ. The purpose of these activities is to integrate an inclusive approach into technical and professional training within the sector.

2. Health conditions

Health and safety conditions are a critical social hotspot within the green H2 value chain, particularly in regions such as Patagonia. This area poses distinctive challenges due to extreme climatic conditions that intersect with complex industrial processes. Green H2 production involves occupational hazards associated with renewable electricity generation, including large-scale wind farms, electrolysis systems, hydrogen compression and storage, high-voltage electrical equipment, chemical handling, and, where applicable, the synthesis and transport of hydrogen derivatives such as green ammonia.

To address specific health issues, Social Life Cycle Assessment (S-LCA) guidelines contemplate quantitative measures to help assess and manage overall health risks within H2 production facilities. This includes the frequency of workplace accidents, availability of protective equipment, and access to health services as quantifiable indicators of health risk. These quantitative indicators are widely recognized tools for assessing workplace safety in the hydrogen production value chain. However, these measurements can fall short without specific regulatory frameworks designed to address the unique health and safety challenges of the hydrogen production sector.

In Argentina, due to the lack of specific national regulations, green hydrogen production follows international standards as a reference framework, such as ISO/TC 197 and the ASME B31.12 code [52]. Additional standards include NFPA 2 Hydrogen Technologies Code of 2020 (later reviewed and updated by the Hydrogen Technologies Code of 2026) [59], IEC 62282-3-100:2019, ISO/TS 20100, ISO 14687-2, EN 17127, ISO 19880-1, and EN 17124. Hydrogen and ammonia present significant risks due to their physicochemical properties, making general industrial safety or hazardous substances regulations insufficient. Instead, H2-specific safety frameworks are required to address prevention, detection, emergency response, and worker protection throughout the entire project lifecycle.

Comparative experiences from other jurisdictions illustrate different regulatory schemes. In the United States, for example, the National Fire Protection Association has developed the NFPA 2 Hydrogen Technologies Code, which regulates hydrogen safety [59]. The latest version of 2026 provides safeguards for the generation, storage, compression, piping, transfer, and use of hydrogen in gaseous and liquid forms (art. 1.2). This code serves as an example of regulatory safeguards for the

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hydrogen lifecycle and applications, conforming to art. 1.3, which could be considered when designing regulations in other jurisdictions for health and safety.

The development of a H2 economy will require new regulatory mandates from national or provincial authorities designated to oversee the sector. Without hydrogen-specific safety requirements embedded in permitting processes, Environmental Impact Assessments (EIAs) may underestimate cumulative occupational risks, which combine wind generation, desalination, chemical processing, and export infrastructure. Adopting a specific regulatory framework can secure the safety requirements that hydrogen facilities must meet throughout all stages of their lifecycle. This also presents an opportunity for further provincial regulation and protection of worker health. For example, Chubut explicitly requires through Provincial Decree No. 192/2009 that hydrogen and oxygen production plants present an environmental impact assessment prior to their operation.

4. Policy Recommendation

The policy recommendations outlined in this study stress the need for a comprehensive regulatory framework that includes health and safety standards, transparent decision-making processes, and effective engagement with indigenous and local communities. These measures aim to foster public acceptance and trust, ensure gender inclusivity, and create sustainable economic opportunities.

Since injustices in H2 production are closely linked with pre-existing structural injustices [22], well-rounded policies are necessary to address these inequalities. Although low-carbon hydrogen is still an emerging sector in Latin America, this presents an opportunity to develop sustainable policies that can effectively tackle these inequalities. In this context, the following policy recommendations are proposed to strengthen Patagonia's emerging H2 sector:

4.1. Policy Design at National Level

- Integrate the social dimension into national H2 frameworks, strategies, roadmaps, regulations, and permits.
- Promote a specific regulatory framework that ensures health and safety standards for hydrogen production facilities throughout all stages of their lifecycle, including design, construction, operation, maintenance, inspection, and decommissioning.
- Adopt combined Environmental Life Cycle Assessment (E-LCA) and Social Life Cycle Assessment (S-LCA) standards for hydrogen projects to identify social hotspots across production, transport, and export stages.
- Implement policies and recognize the rights of Indigenous Peoples to ensure their territorial and participation rights in areas where projects will be based.
- Strengthen national transparency and accountability mechanisms. The national government should institutionalize transparency mechanisms for access to EIAs, H2 project data, contracts, and monitoring results.
- Incorporate renewable energy and hydrogen-related content into undergraduate and graduate programs, with a specific focus on education programs available in the provinces where projects will take place.
- Promote domestic industrial capabilities linked to H2 by incentivizing local manufacturing and technical services for renewable industry components and encouraging technology transfer partnerships.

4.2. Policy Design at Provincial Level

- Foster coordination between provincial governments and local municipalities to pursue integrated and value-driven H2 projects.

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- Create green H2 councils to advise on policy formulation and project evaluation, facilitating coordination among provincial ministries, academic institutions, industrial chambers, and indigenous communities.
- Promote integrated Environmental Impact Assessments (EIAs) and monitoring systems to identify transversal environmental and social challenges across the H2 production scheme.
- Implement affirmative actions to promote gender inclusion in interdisciplinary decision-making spaces, such as local provincial hydrogen councils.
- Enforce Free, Prior, and Informed Consent (FPIC) processes for green H2 projects, incorporating transparency mechanisms within companies for consultation processes at the provincial level.
- Ensure compliance with provincial regulations on local hiring laws throughout all phases of H2-related infrastructure development (pre-investment, construction, operation, and maintenance).
- Promote the sharing of infrastructure (such as ports, transmission lines, and pipelines) to minimize cumulative environmental impacts.
- Ensure health and safety requirement compliance in accordance with federal law.

In sum, public commitment to sustainability should encompass not only the existence of environmental policies but also the coherence and effectiveness of actions across the entire H2 value chain, from sourcing and production to end-of-life (EoL) management.

5. Conclusions

The development of green H2 policies in Latin America, particularly in Argentina, faces both significant opportunities and substantial challenges. The transition to green H2 can not only contribute to the decarbonization of energy systems but also promote socio-economic development. However, it is imperative to address the social dimensions associated with this transition to ensure that the benefits are equitably distributed.

Our study highlights the critical importance of integrating social Life Cycle Assessment (S-LCA) methodologies and hydrogen justice frameworks into policy design. This approach enables the identification of social hotspots within the hydrogen value chain, emphasizing the need for fair and inclusive processes that recognize and protect vulnerable groups, distribute costs and benefits equitably, address historical injustices, and acknowledge diverse knowledge systems.

Moving forward, the development of educational and capacity-building programs will be pivotal in enhancing local capabilities and fostering a skilled labor force that can thrive in a green H2 economy. Additionally, fostering collaboration between government entities, academic institutions, industrial stakeholders, and indigenous groups will be essential for the coherent and effective implementation of hydrogen policies.

Ultimately, the successful integration of social indicators into green H2 policies will not only contribute to the sustainable advancement of the hydrogen sector in Latin America but also ensure that the transition to cleaner energy is just and equitable for all stakeholders involved.

Limitations of this study. Supplementary: The policy recommendations provided in this study are focused exclusively on the social framework for integrated green H2 development. Accordingly, this proposal will consider social dimensions and indicators but will not address tax incentives, additional regulatory proposals, or economic incentives with or without specific targets. Furthermore, the scope of this proposal is limited to green hydrogen production within the analyzed country and does not extend to other types of hydrogen production pathways.

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Acronyms

E-LCA	Environmental life cycle assessment
EoL	End of life
H2	Hydrogen
SDGs	Sustainable development goals
S-LCA	Social life cycle assessment
UNEP	United Nations Environmental Program

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