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Green hydrogen and sustainable development – A social LCA perspective highlighting social hotspots and geopolitical implications of the future hydrogen economy

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ABSTRACT

Developing a global hydrogen economy that contributes to the UN Sustainable Development Goals (SDGs) and achieves net-zero carbon emissions under the Paris Agreement requires evaluating and recognizing the economic, social, and political realities of green hydrogen production. This study performs a cradle-to-gate social life cycle assessment (S-LCA) of green hydrogen production via water electrolysis powered by renewable electricity from solar photovoltaic and wind farms in seven countries (the US, Chile, South Africa, Saudi Arabia, Oman, Australia, and China) to identify the social hotspots in the entire value chain. The results of S-LCA indicate that green hydrogen production in South Africa poses the highest risk to most of the social indicators, especially child labor, fair salary, unemployment, association and bargaining rights, and gender wage gap. However, in the other countries, the risk to most of the social indicators drastically reduces when key equipment is manufactured in the country itself rather than when it is imported from other countries. Due to the increased complexity of the green hydrogen supply chain resulting from components sourced from various parts of the world, the S-LCA results indicate that compared with conventional hydrogen, green hydrogen performed poorly in various social indicators. The S-LCA results revealed that outsourcing key equipment from developing countries with poor working conditions is a major social hotspot in the sustainable development of these countries. In addition, the S-LCA results demonstrate that the hydrogen economy has the potential to be capable of achieving SDGS by developing a domestic green hydrogen supply chain and enhancing working conditions in country-specific sectors. Furthermore, a holistic discussion of socio-geopolitical implications is presented, emphasizing the need to develop standardized international regulations to prevent colonialism in the future hydrogen economy.

1. Introduction

Globally, the present era is confronted by several challenges. Amidst rising global carbon emissions and the looming energy crisis, pandemics, such as COVID-19 and war conflicts, have further complicated the world's efforts to meet climate-action targets. A transformation toward sustainability requires tackling all these crises simultaneously (Soergel et al., 2021; Umenweke et al., 2023). To achieve net-zero carbon emissions by 2050, the energy transition toward renewables, particularly using solar and wind energy to produce hydrogen through water electrolysis is gaining much importance to mitigate major emissions in various sectors worldwide (Salomone et al., 2019). Production and consumption of any goods have both environmental and social impacts, and both need to be considered to steer decision-making (Werker et al., 2019). Sustainable development goals (SDGs) encourage decision-makers to make responsible choices for economic growth, social welfare, and environmental protection (Biggeri et al., 2019; Salvia et al., 2019). Under the current multiple challenges across the globe, it is imperative to evaluate how renewable energy systems can contribute to sustainable development through the production of carbon-free products such as green hydrogen.

Worldwide, hydrogen demand has increased substantially because of the development of national hydrogen strategies, as well as public and private sectors' investment in green hydrogen projects. About 70 million tons of hydrogen are produced globally each year primarily from natural gas and coal, contributing to a significant amount of carbon emissions

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(900 Mt) (International Energy Agency (IEA), 2021). Green hydrogen is considered a game changer and has gained wide acceptance as an energy carrier owing to its decarbonization potential. However, it poses several economic and social challenges because the production pathway must be green, economically viable, and socially acceptable. The economic and environmental indicators of green hydrogen production have been well addressed in numerous recent studies but none of them has evaluated the social impacts of green hydrogen production (Akhtar et al., 2021; Bhandari et al., 2014; Burkhardt et al., 2016; Chisalita et al., 2020; Dincer and Acar, 2014; Guerra et al., 2019; Koj et al., 2017; Lee et al., 2019; Niermann et al., 2019; Palmer et al., 2021; Ren and Toniolo, 2018; Terlouw et al., 2022; Verma and Kumar, 2015; Dickson et al., 2022). However, to facilitate the development of a sustainable green hydrogen economy that not only meets climate targets but also achieves sustainable development, it is imperative that the third pillar of sustainability—social sustainability—be assessed for green hydrogen production worldwide.

There is a paucity of scholarly literature examining the impacts of a green hydrogen economy on society and its sustainable development. To the best of our knowledge, only a few studies have been done to evaluate the social impacts of green hydrogen production and its associated products such as green methanol (Holger et al., 2017; Iribarren et al., 2022; Valente et al., 2021; Werker et al., 2019; You et al., 2020). For instance, Werker et al. (2019) conducted a social life cycle assessment (S-LCA) of green hydrogen production via alkaline water electrolysis (AWE) to evaluate its impact on the working conditions in Germany, Spain, and Austria. They concluded that AWE has the least social impact on working conditions in Germany, followed by Spain and Austria (Werker et al., 2019). The main limitation of this study is that it only considered one category of S-LCA while ignoring other important ones. Similarly, green hydrogen production by AWE in Spain was evaluated from economic, environmental, and social perspectives in a study by Valente et al. (2021). Although the studies conducted comprehensive assessments, their main drawbacks are being regionally specific, not considering other countries that will be major exporters of green hydrogen, failing to link sustainable development to green hydrogen production, and lacking future recommendations for policymakers.

Green hydrogen needs to be assessed from a sustainability perspective to facilitate the adoption of a green hydrogen economy at a global scale. All countries that export green hydrogen or may export it in the future have extensive solar and wind resources. According to a study by KPMG International, regarding the global hydrogen hotspots and distribution corridor, the US, Chile, Africa, and Gulf Cooperation Council (GCC) countries are net exporters; China and Australia are self-sufficient and future exporters due to their excellent solar and wind resources; and Europe and Asia Pacific (Japan and South Korea) are net importers of green hydrogen due to technological development and insufficient renewable sources (KPMG, 2021). Due to their excellent sun-rich regional locations, Saudi Arabia and Oman have the greatest potential for green hydrogen production among the GCC countries (Berger, 2021). Oman and Saudi Arabia have recently published their national frameworks as Saudi Vision 2030 and Oman Vision 2040. They aim to reduce their oil and gas dependency, diversify their economies, and export clean energy to the world to accelerate the sustainable development of their countries (ISFU, 2020; Vision 2030 Kingdom of Saudi Arabia, 2020).

Green hydrogen is yet to be comprehensively studied for the social impacts of its supply chain because of the relative infancy of the S-LCA methodology, which evaluates the potential positive and negative impacts (UNEP/SETAC, 2020). Although it is in its early stages, S-LCA is widely recognized as an integral part of sustainability sciences, which can be applied by both public and private companies to support policy and decision-making (Ramos Huarachi et al., 2020). Considering the scarcity of literature on the S-LCA of the entire life cycle of the green hydrogen value chain in the existing literature, this study is the first to present the social profile of the entire value chain of the future green hydrogen economy in seven major hydrogen exporting countries (the US, Chile, South Africa, Saudi Arabia, Oman, China, and Australia), with the primary objective of identifying social hotspots throughout the entire life cycle of green hydrogen production using a cradle-to-gate approach. Furthermore, the findings of the S-LCA are discussed holistically to identify key social hotspots and elucidate policy implications required to accelerate the global adoption of a green hydrogen economy. Additionally, recommendations are provided to mitigate the identified social hotspots and maximize the contribution of a future green hydrogen economy to sustainable development.

2. Methodology

The green hydrogen system under study involves two main blocks—the renewable power generation system and the AWE system of 6 MW for hydrogen production (Fig. 1). Each of the seven countries is currently or planning to be a hydrogen energy exporter, so we assume that hydrogen plants are located in each of them. The generation of the required power is achieved through a 3.5 MW of onshore wind turbine and a 3.5 MW solar photovoltaic (PV) farm. Additionally, the renewable power generation blocks include the equipment necessary to manage and distribute the generated power (e.g., transformers and grid connections).

2.1. S-LCA

In 2009, the UN Environment Program (UNEP) working group presented guidelines for S-LCA, which have been used as the principal basis for multiple studies and future development in the S-LCA methodology (UNEP/SETAC, 2020). The S-LCA study was conducted using the Product Social Impact Life Cycle Assessment (PSILCA) database and the social impact weighting method, considering the guidelines provided by UNEP (Maister et al., 2020). SimaPro 9.4.0.2 was used to rigorously evaluate and compare the social impacts of green hydrogen production in all the countries. A key objective of this study is to identify social hotspots within the green hydrogen supply chain, compare them with conventional hydrogen from natural gas, and evaluate the impact of green hydrogen on SDGs to finally present the policy implications and future recommendations for a large-scale deployment of a green hydrogen economy. The methodological framework is presented in Fig. 2. Potential suppliers were identified by building the corresponding supply chain for each hydrogen system. The functional unit was taken as 1 kg of green hydrogen produced. The scope of this S-LCA includes the construction of solar PV, wind farms, and water electrolysis system; generation and transmission of renewable power; and production of hydrogen through AWE.

Following the methodology proposed by Gamboa et al. (2020), a representative country of origin was identified as a potential source of the hydrogen supply chain. This procedure is based on traditional trade and life cycle inventory databases for selecting potential suppliers of components, materials, energy, and services, as well as historical information regarding reliable trade patterns given the common short-term stability of geopolitical relationships (Pucciarelli et al., 2021). In this approach, to identify the potential sources of all the material flow, the production system is divided into two parts—components (infrastructure and equipment) and the primary flows of material and energy (Gamboa et al., 2020). For the components, one country of origin is assumed for one component. Starting from the product manufacturing country, the trade data of respective countries were taken from the UN Comtrade database and Observatory of Economic Complexity (OEC) (OEC, 2021; United Nations, 2021). A country is considered the component country of origin if the total amount of exports to the world (i.e., all countries with which the country trades) is equal to or greater than the total amount of imports from the world (Gamboa et al., 2020). The first importing country of that component was identified, and its imports and exports were compared (Gamboa

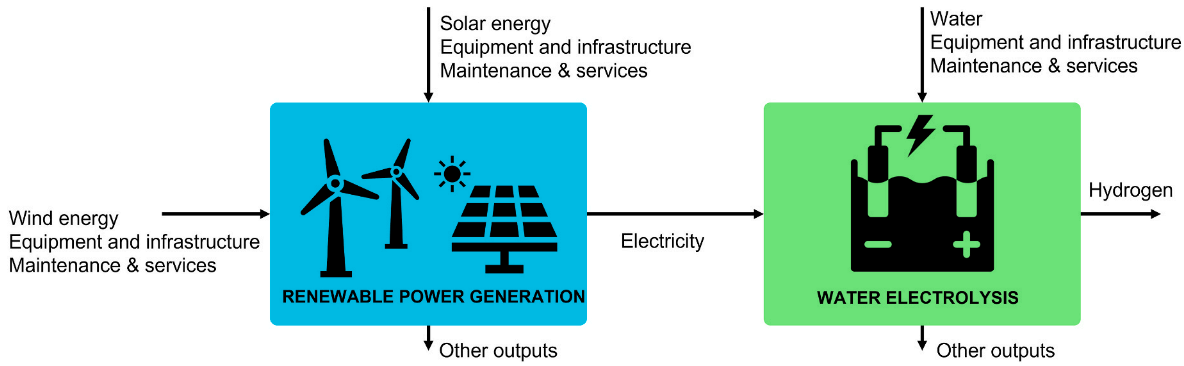

Fig. 1. Green hydrogen production system via water electrolysis powered by renewable electricity from solar and wind farm. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

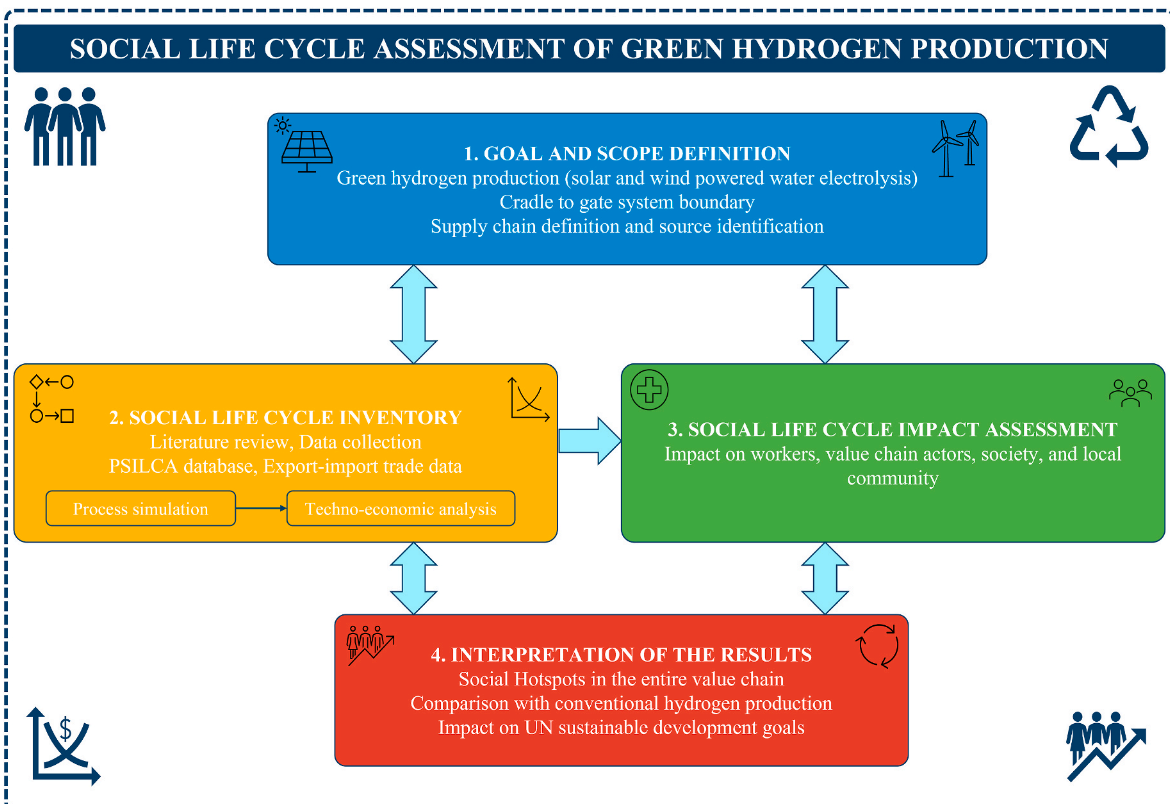

Fig. 2. Methodological framework of the study.

et al., 2020). If its exports were equal to or higher than imports, it was considered a country of manufacturing for that component; otherwise, it was considered an interim country, and its importing countries were identified. This procedure was repeated until a country of origin (primary country) was found for that particular component of the production system (Gamboa et al., 2020). This approach was applied to each block of the green hydrogen system.

Once the possible suppliers of the components involved in the supply chain were identified, the social life cycle inventory (S-LCI) was evaluated using the data obtained from techno-economic analysis (TEA) for each stage. During the life cycle of a product, activity variables are used to describe the impact of the process (Maister et al., 2020). They "reflect the share of a given activity associated with each unit process" (United Nations Environmental Program (UNEP) 2011) and thus quantify the respective social indicators related to the production system. Currently, the most common activity variable is worker hours, i.e., the time workers spend to produce a certain amount of product in a given process or sector. The social impact weighting method by PSILCA was used for the S-LCI analysis (S-LCIA) (Iribarren et al., 2022). A large number of sectors and social indicators are covered by PSILCA, as well as a wide range of social risk indicators. In particular, 19 social indicators addressing 4 stakeholders' categories were evaluated, as presented in Table 1 (Maister et al., 2020). Table 1 also presents the social indicators that contribute to specific SDGs (Our World in Data, 2022).

2.2. Techno-economic analysis

To evaluate the S-LCI required to conduct the S-LCA, a TEA was performed using the data from the process simulation of the water electrolysis block. S-LCA and TEA are interrelated due to the requirement of both direct working hours at a plant and economic flows that are later converted into working hours within a specific country using the

Table 1
Social LCA stakeholder categories and indicators considered in the study (Maister et al., 2020; Our World in Data, 2022).

Stake holder category	Indicator	Abbreviation	Unit[a]	Relevant SDG #
Worker	Child labor	CL	med rh	8 (Decent work and economic growth)
Worker	Frequency of forced labor	FL	med rh	8 (Decent work and economic growth)
Worker	Fair salary	FS	med rh	1 (No poverty)
Worker	Weekly work hours per employee	WH	med rh	8 (Decent work and economic growth)
Worker	Gender wage gap	GW	med rh	5 (Gender equality)
Worker	Women in the sectoral labour force	W	med rh	5 (Gender equality)
Worker	Social security expenditures	SS	med rh	1 (No poverty)
Worker	Workers affected by natural disasters	ND	med rh	1 (No poverty)
Worker	Trade unionism	TU	med rh	16 (Decent work and economic growth)
Worker	Association and bargaining rights	ACB	med rh	16 (Decent work and economic growth)
Value chain actors	Public sector corruption	C	med rh	16 (Decent work and economic growth)
Value chain actors	Promoting social responsibility	PSR	med rh	11 (Sustainable cities and communities)
Value chain actors	Contribution of the sector to economic development	CE	med rh	8 (Decent work and economic growth)
Society	Illiteracy total	I	med rh	4 (Quality education)
Society	Expenditure on education	EE	med rh	4 (Quality education)
Society	Health expenditure	HE	med rh	3 (Good health and well-being)
Local community	Unemployment	U	med rh	8 (Decent work and economic growth)
Local community	Drinking water coverage	DW	med rh	6 (Clean water and sanitation)
Local community	Value added total	VAT	med rh	8 (Decent work and economic growth)

[a] med rh = medium risk hours.

PSILCA database (Maister et al., 2020). The conceptual design of the process includes all operations necessary for the production of pure green hydrogen. The overall process flow diagram (modeled using Aspen Plus V11) of the conceptual design used to produce green hydrogen via AWE is depicted in Fig. 3.

The plant is designed to produce 625,400 tons/y (118 kg/h) of green hydrogen. Pure de-ionized water is the main feedstock of a water desalination plant (excluded from the scope of this study) and is pumped to a working pressure (85 bar) of an electrolyzer. The pressurized water is then heated in a heat exchanger to a temperature of 35 °C. A stoichiometric reactor block was from the Aspen library to model the water electrolyzer. Generally, hydrogen and oxygen are further treated in a series of separation blocks to enhance the purity of the products as both exit the electrolysis stack in a vapor-liquid stream with unconverted water at 30–35 °C, but considering the scope of this study, only hydrogen separation is modeled, while oxygen is considered to be vented into the atmosphere (Akhtar et al., 2022; Brigljević et al., 2022; Sánchez et al., 2020).

The evaluated data obtained from the process simulation were then used to perform the TEA to calculate the economic contribution of the

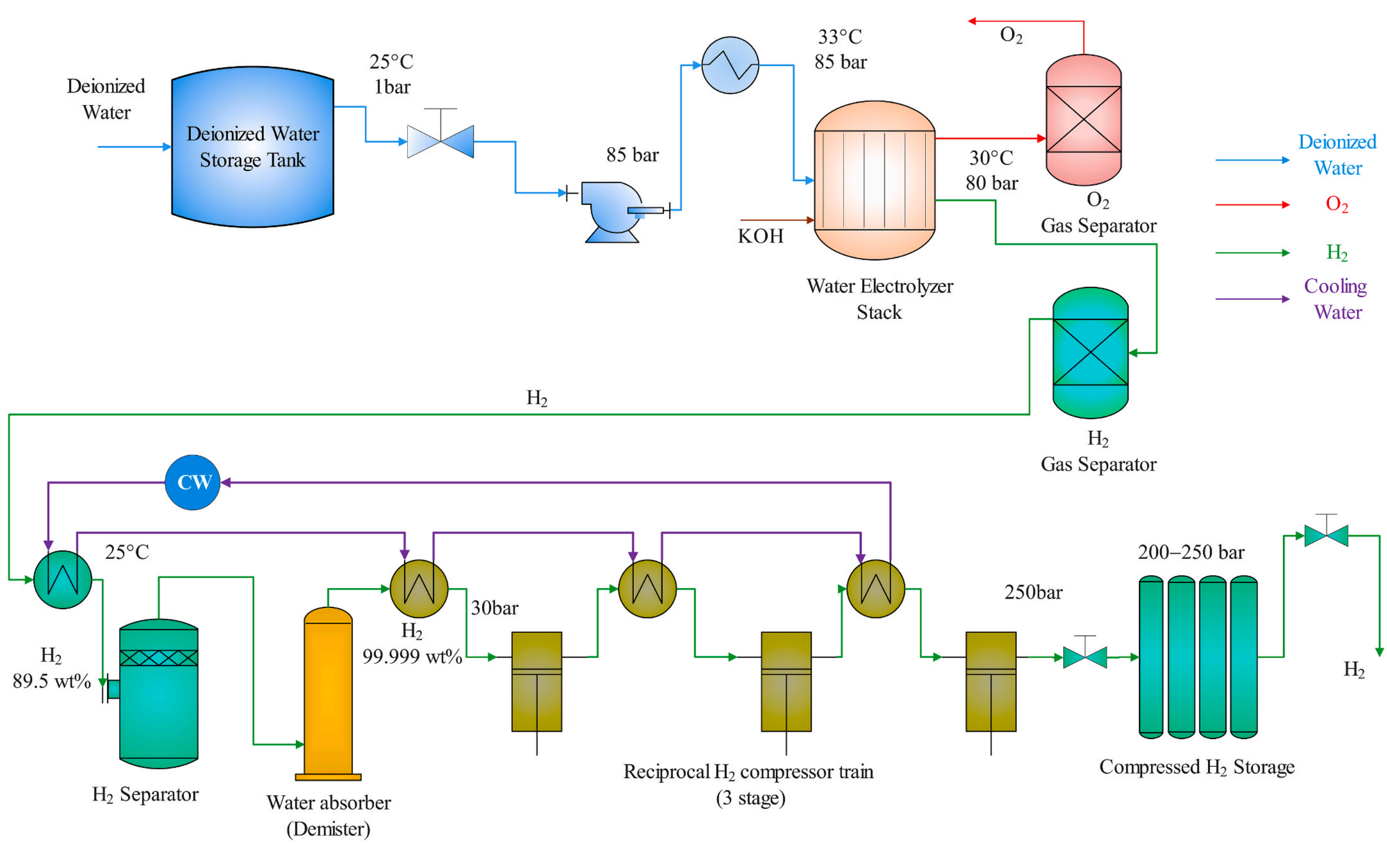

Fig. 3. Process flow diagram of green hydrogen production via alkaline water electrolysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

blocks considered in the green hydrogen production system. First, the mass and energy balance from the process simulation was used to estimate their purchase costs. Based on the purchase costs, the other costs inside the battery limits, including piping, instrumentation, electrical and construction infrastructure, civil engineering, coatings, and building on-site, were estimated (Iribarren et al., 2022). The total capital costs also include the other costs outside the battery limits, such as site preparation, home office, portable expenses, and contingency costs, which were estimated using the approach presented by Turton (2013). Capital costs were then used to evaluate the total capital investment and annual manufacturing cost (Akhtar et al., 2022; Turton, 2013). The contribution of all the equipment, raw materials, and maintenance and operation to the total annualized capital investment was then evaluated based on the functional unit of 1 kg hydrogen. For renewable power generation systems, the contribution of labor working hours required for maintenance and operation was quantified on a monetary basis using the national labor wage data of a country. However, the economic characterization of water electrolysis was directly taken from the studies by Akhtar et al. (2021, 2022) and Valente et al. (2021). The economic assumption and other parameters are presented in Table 2.

3. Results and discussion

The mass and energy balance and the costing data calculated from the process simulation were used to perform the TEA. The levelized cost of hydrogen (LCOH) was evaluated as \$4.80/kg, and the main contributors to LCOH were the capital cost associated with the key equipment required for green hydrogen production. Considering the price of \$4.80/kg, green hydrogen is currently not competitive compared with conventional hydrogen (grey hydrogen) produced via steam methane reforming (SMR), which is priced within a range of \$0.70–2.20/kg (International Energy Agency, 2019; IRENA, 2021). According to BloombergNEF (2020), the price of green hydrogen will fall to \$1/kg by 2030 and can compete with grey hydrogen in some countries because of the rapid decline in the capital costs of equipment due to technological development and the large-scale deployment of green hydrogen worldwide. As mentioned earlier, all the countries are assumed to have renewable power plants and a water electrolysis unit. As the primary goal of the study was to analyze the social impacts of green hydrogen production, TEA was conducted regardless of location-specific parameters. Environmentally, green hydrogen is more beneficial than conventional hydrogen owing to its lowest global warming potential, which ranges from 0.66 to 2.4 $kgCO_2$. eq/kgH_2 (Cetinkaya et al., 2012).

Fig. 4 depicts the S-LCI of the green hydrogen production system

Table 2
Economic parameters and values used in the techno-economic analysis.

Parameter	Value	Reference
Analysis year	2022	Own
Operating hours	5300	Akhtar et al. (2021)
Discount rate	4.5%	Akhtar et al. (2022)
<u>CAPEX</u>		
Wind-Turbine (\$/kW)	1000	IRENA (2019a)
Solar -PV (\$/kW)	700	IRENA (2019b)
AWE (\$/kW)	750	International Energy Agency (2019)
<u>Labor wage (\$/hr)</u>		
Australia	16	ILO (2021)
Saudi Arabia	7	ILO (2021)
Oman	25	ILO (2021)
China	4	ILO (2021)
United states of America	7.25	ILO (2021)
South Africa	1.43	ILO (2021)
Chile	6.44	ILO (2021)
Process water (\$/t)	0.07	Turton (2013)
High-pressure steam (\$/GJ)	17.89	Turton (2013)
Low-pressure steam (\$/GJ)	13.42	Turton (2013)
Solar electricity (\$/kW)	0.055	Agency (2020)
Wind electricity (\$/kW)-average	0.065	Agency (2020)

considered in the study based on the contribution of each step involved in the construction and operation of a green hydrogen production system. The detailed S-LCI, with the contribution of the countries in the supply of key equipment, is included in the supplementary file. Table 3 presents the results of all the 19 social impact categories reported in medium-risk hours (med rh) or medium-opportunity hours (med oh) per functional unit, i.e., per kg of green hydrogen. The med rh represent the number of worker hours in the supply chain that is characterized by a specific or aggregate level of social risk. PSILCA characterizations of potential social risks use these units to evaluate medium-risk/opportunity. Taking this into consideration, the results of the social characterization provide an estimate of the corresponding number of working hours within the supply chain associated with a medium social risk or opportunity relevant to a specific social aspect. In total, 19 social impact categories were evaluated for 7 different countries, making the number of the results above 100. Therefore, five impact categories were chosen based on the following four stakeholder categories: workers, value chain actors, society, and local community (Maister et al., 2020). Here the results for the social life cycle profile are presented only for five selected impact categories—child labor (CL), gender wage gap (GW), the contribution of the sector to economic development (CE), health expenditure (HE), and value-added total (VAT). A comparison of green hydrogen produced via water electrolysis powered by renewable energy and conventional hydrogen production via SMR revealed that green hydrogen has underperformed in terms of sustainability on both economic and social fronts (Valente et al., 2021). For instance, in the US the risk to CL and HE is very low for conventional hydrogen production (CL = 0.040 med rh, HE = 0.44 med rh) and medium-to-high (CL = 0.88 med rh, HE = 2.30 med rh) for green hydrogen production via water electrolysis, respectively (Valente et al., 2021).

Fig. 5 depicts the overall social life cycle profile of the green hydrogen production system. In PISLCA, characterization factors are reported for each social risk level within each impact category. For instance, the impact category CE presents high, low, and medium opportunities for a value of 10, 0.1, and 1 med rh, respectively. Thus, a product or aspect with a high CE value will have a greater chance of being able to contribute to the economic development of a country. In comparison with other countries, in China, the green hydrogen production system is found to have the highest potential to contribute to its economic development with a value of 2.57 med rh, which is the highest as compared with that of other countries. This validates China's leadership in exporting the key components (e.g., generators, inverters, converters, rotor blades, PV array, PV modules, electrolyzer components, and gas conditioning units) of the complex supply chain of a green hydrogen system to the rest of the world. Conversely, the social risk for CL was found to be the second highest in China with a value of 4.14 med rh, followed by 9.13 for South Africa. The US was found to be comparatively a medium-risk country in terms of CL, having a value of 0.87 med rh.

The results of the green hydrogen production system were compared with the one reported in the study by Valente et al. (2021) for conventional hydrogen produced from fossil fuels. Socially, green hydrogen has a much poorer performance than conventional hydrogen produced by steam-methane reforming. Despite this, it has been demonstrated that the new and complex supply chain of renewable energy systems contributes more significantly to economic development (CE) than conventional technologies because it provides greater opportunities for employment creation and adds value to a country's multiple sectors. PSILCA and other S-LCA tools demonstrate that most plants are based on industry sectors that are subject to non-null levels of social risk. This is a consequence of both resource availability and the effectiveness of S-LCA tools (Maister et al., 2020). Green hydrogen has a greater value in all social indicators when considering both factors—a high working hour rate and a non-null level of risk. Therefore, it is anticipated that additional positive indicators other than "CE" will be implemented in S-LCA soon. Green hydrogen can partially alleviate the relatively poor social

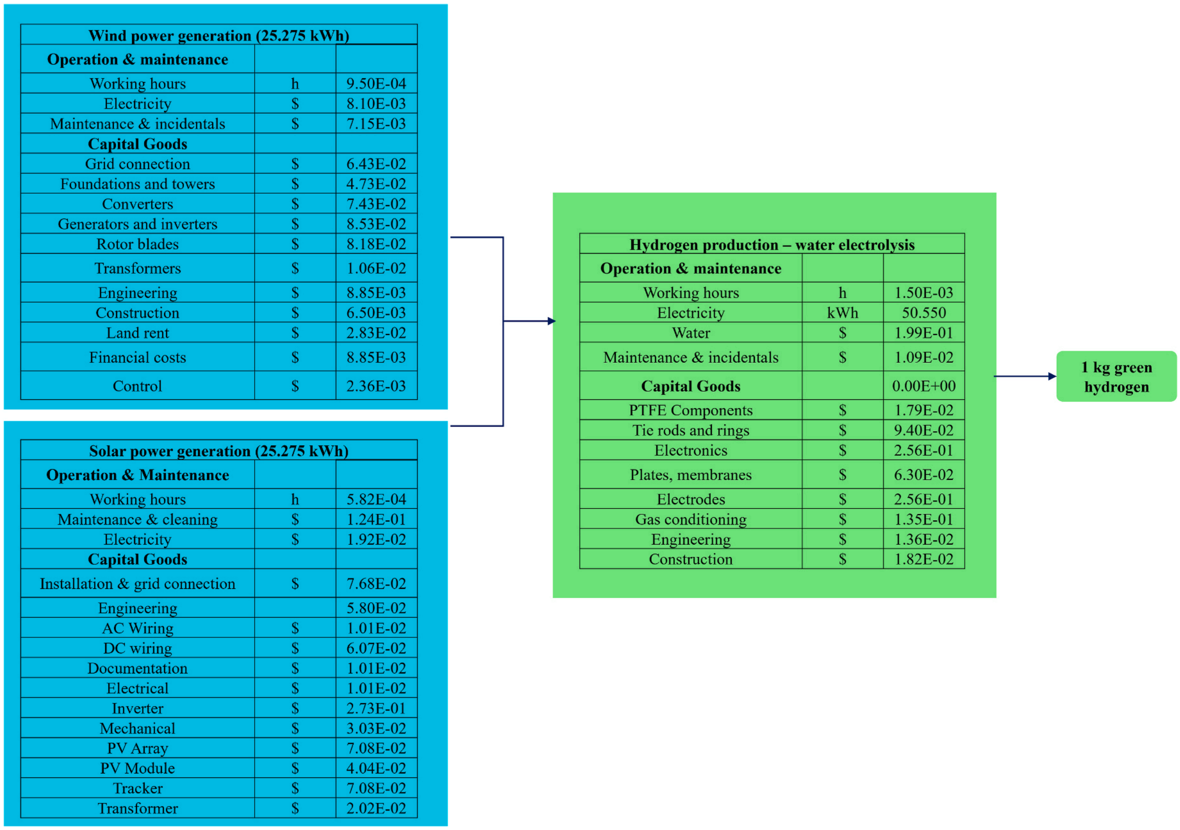

Fig. 4. Social life cycle inventory of green hydrogen production system. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Results of the social life cycle assessment of green hydrogen production. Country codes: CHL (Chile), CHN (China), SAU (Saudi Arabia), OMN (Oman), ZAF (South Africa), USA (United States of America).

Social indicator	CHL	CHN	SAU	OMN	ZAF	AUS	USA
Child labor (CL)	1.00	4.14	1.30	1.80	9.13	1.19	0.88
Frequency of forced labor (FL)	0.01	0.01	0.01	0.01	0.01	0.00	0.01
Fair salary (FS)	20.72	41.44	23.55	23.30	42.92	21.56	25.87
Weekly work hours per employee (WH)	0.38	0.44	1.08	1.65	0.41	0.33	0.39
Gender wage gap (GW)	0.49	0.28	0.31	0.29	7.24	0.35	0.32
Women in the sectoral labour force (W)	0.38	0.14	5.18	0.78	0.51	0.22	0.31
Social security expenditures (SS)	3.64	4.94	15.73	16.80	3.79	2.75	3.67
Workers affected by natural disasters (ND)	1.44	3.99	1.16	1.19	1.48	1.12	0.82
Trade unionism (TU)	12.11	2.03	11.97	12.72	10.53	5.39	9.36
Association and bargaining rights (ACB)	8.49	42.68	11.76	12.17	12.31	11.27	8.09
Public sector corruption (C)	14.43	41.02	26.44	27.45	22.79	12.50	11.54
Promoting social responsibility (PSR)	7.68	12.54	7.03	7.31	8.01	5.55	4.51
Contribution of the sector to economic dev. (CE)	1.02	2.57	1.21	1.22	1.33	0.95	0.88
Illiteracy total (I)	2.11	1.22	9.07	10.02	1.36	1.48	2.76
Expenditure on education (EE)	0.05	0.06	0.12	0.13	0.05	0.04	0.05
Health expenditure (HE)	2.34	5.55	5.28	6.65	3.44	2.09	2.30
Unemployment (U)	0.12	0.10	0.09	0.08	7.80	0.08	0.07
Drinking water coverage (DW)	2.50	1.09	9.24	10.30	1.92	1.48	3.21
Value added total (VAT)	6.08	2.62	5.77	6.20	6.04	2.78	4.05

performance of the industry by increasing the number of working hours in new renewable systems, thereby benefiting from an increase in economic development, career development, and social satisfaction (Di Cesare et al., 2018).

As part of the process of evaluating social hotspots, the green hydrogen production system is divided into two stages—capital and operation. Capital refers to the necessary equipment to produce hydrogen, while operation refers to the raw materials, electricity, and labor required to operate a plant. Fig. 6 presents the stage-wise breakdown of green hydrogen production in the seven countries. The figure depicts that the operation stage has the lowest social risk in all countries, except South Africa, where the sectors involved in water electrolysis and solar power generation have a relatively high degree of social risk, especially when compared with the other countries in terms of GW and CL. Fig. 6 further demonstrates that in all the presented social impact categories, the capital stage contributes more than the operation stage. This is because the supply chain of green systems is complex, requiring the procurement of key parts and equipment from different countries. Consequently, the risks associated with the country that exports the key equipment can be seen in the results of the country that produces green

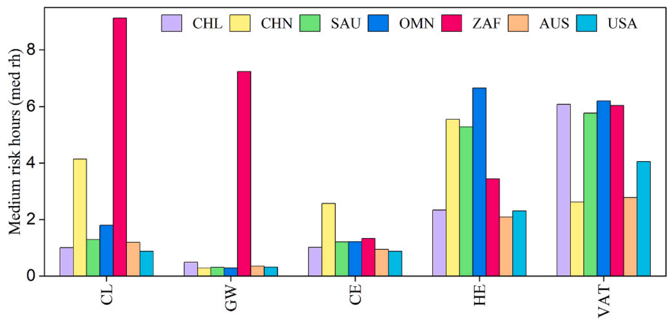

Fig. 5. Overall social life-cycle profile of green hydrogen production system. CL = Child labor, GW = Gender wage gap, CE = Contribution of the sector to economic development, HE = Health expenditure, VAT = Value added total. Country codes: CHL(Chile), CHN(China), SAU(Saudi Arabia), OMN(Oman), ZAF(South Africa), USA(United States of America). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

hydrogen. Ideally, the risk associated with the country in which a product is manufactured must be accounted for heavily by the country itself.

4. Green hydrogen economy and sustainable development—social and geopolitical implications

To complement the findings of previous studies and gain a more comprehensive understanding of sustainability performance, this study provides an insight into the social implication of producing green hydrogen for current and future major energy exporters. A greater focus on social indicators is necessary for green systems because of their complexity, such as positive impacts and/or suppliers with low social risks. The results in Fig. 6 demonstrate that major social hotspots are in the supply chain of key equipment that is imported to produce hydrogen. To further evaluate this, the authors have redefined the entire supply chain of key equipment by assuming that all the equipment is manufactured and sourced within the country. Fig. 7 compares the results of the international and domestic sources of the key equipment in all the selected countries. Fig. 7 clearly illustrates the considerable decrease in most of the social indicators when the key equipment is manufactured domestically rather than importing it from other countries. For instance, the social risk to CL reduced by more than 50% in Chile, Saudi Arabia, Australia, and the US. However, in South Africa, the social risk to CL and GW increased by more than 51% because of multiple national issues, such as poor economic conditions, limited access to quality and free education, and a high unemployment rate.

According to the analysis, China is the largest exporter of key equipment to each country considered. Thus, it is expected to produce green hydrogen independently in the future as it has announced a long-term hydrogen plan that contributes to achieving net-zero carbon emissions in the country by 2060 (KPMG, 2021; Shell, 2019). In the entire supply chain, China imports 13% of tie rods and rings, electronics, and electrodes from Norway. It is also visible in Fig. 7 that there was an increase in the social risks to CL (9%), GW (4%), and HE (12%) when 13% of key equipment was assumed to be sourced within China rather than imported from Norway. Approximately 7.74% of Chinese children from the ages of 10–15 are employed as child workers because poverty and development have discouraged many rural children from pursuing secular education and have pushed them into CL (Tang et al., 2018). International politics have become increasingly concerned with climate change, which poses the possibility of developed countries externalizing their carbon-intensive activities to developing countries while decarbonizing their domestic economies and simultaneously exploiting the resources and labor of developing nations (Clairmont, 2019; International Energy Agency, 2022; Rossana et al., 2020).

The promotion of sustainable development should not be limited to environmental concerns. Instead, it should encourage sustainable development for all humans. The concept of sustainable development goes beyond economic and environmental concerns to also consider social concerns, which are of even greater importance for sustainable development. Fig. 8 categorizes the three pillars of sustainability and their respective SDGs (Vinuesa et al., 2020). Fig. 7 and Table 3 reveal that although green hydrogen production has a negative impact (with a risk level of medium to high) on certain social indicators, it also has a positive impact on various indicators such as CE and VAT, thus helping to achieve SDG 8: “Decent Work and Economic Growth.”

Moreover, Fig. 7 and Table 3 demonstrate the negative impacts of green hydrogen production on other social indicators related to SDG 8 such as CL, frequency of forced labor, trade unionism, association and bargaining rights, and public sector corruption (C). Previous works have already demonstrated the environmental benefit (SDG 13 and 15) of green hydrogen production over the conventional hydrogen produced from fossil fuels (Acar and Dincer, 2014; Akhtar et al., 2022; Koj et al., 2017; Lee et al., 2019). There are significant interactions between SDGs despite their formulation as individual goals, which leads to synergies and trade-offs (Pradhan et al., 2017; Nilsson et al., 2018; Xue et al., 2018). Achieving one SDG may have a positive or negative effect on another SDG (Wang et al., 2022). Moreover, the simultaneous achievement of SGDs entails several challenges and complications. Bringing together an appropriate group of stakeholders at the right time and place, developing a methodology for determining trade-offs, and ensuring accountability for action measures are the major challenges (James et al., 2015). Managing conflicting interests among multiple stakeholders can cause governments, businesses, non-profit organizations, and communities to make tough decisions. Strengthening governance in the various sectors of a country and among countries is the most effective way to overcome these challenges. Therefore, it is difficult to predict the future of a green hydrogen economy that not only contributes to climate change but also contributes to the achievement of SDGs.

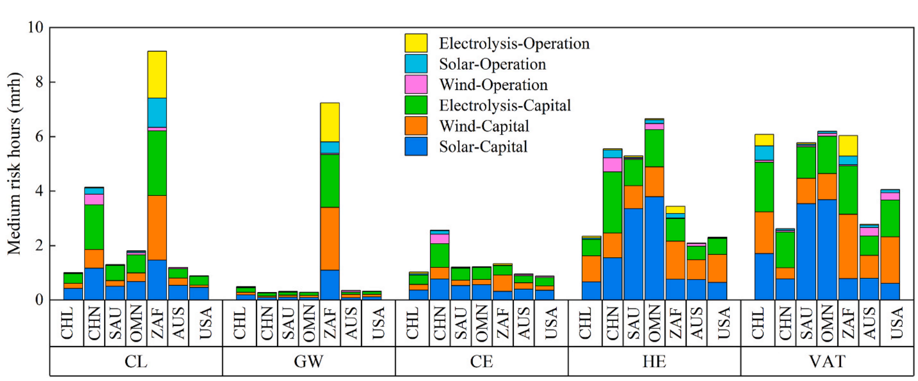

Fig. 6. Contribution of each system block to the social life-cycle profile of green hydrogen production. CL = Child labor, GW = Gender wage gap, CE = Contribution of the sector to economic development, HE = Health expenditure, VAT = Value added total. Country codes: CHL(Chile), CHN(China), SAU(Saudi Arabia), OMN(Oman), ZAF(South Africa), USA (United States of America). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

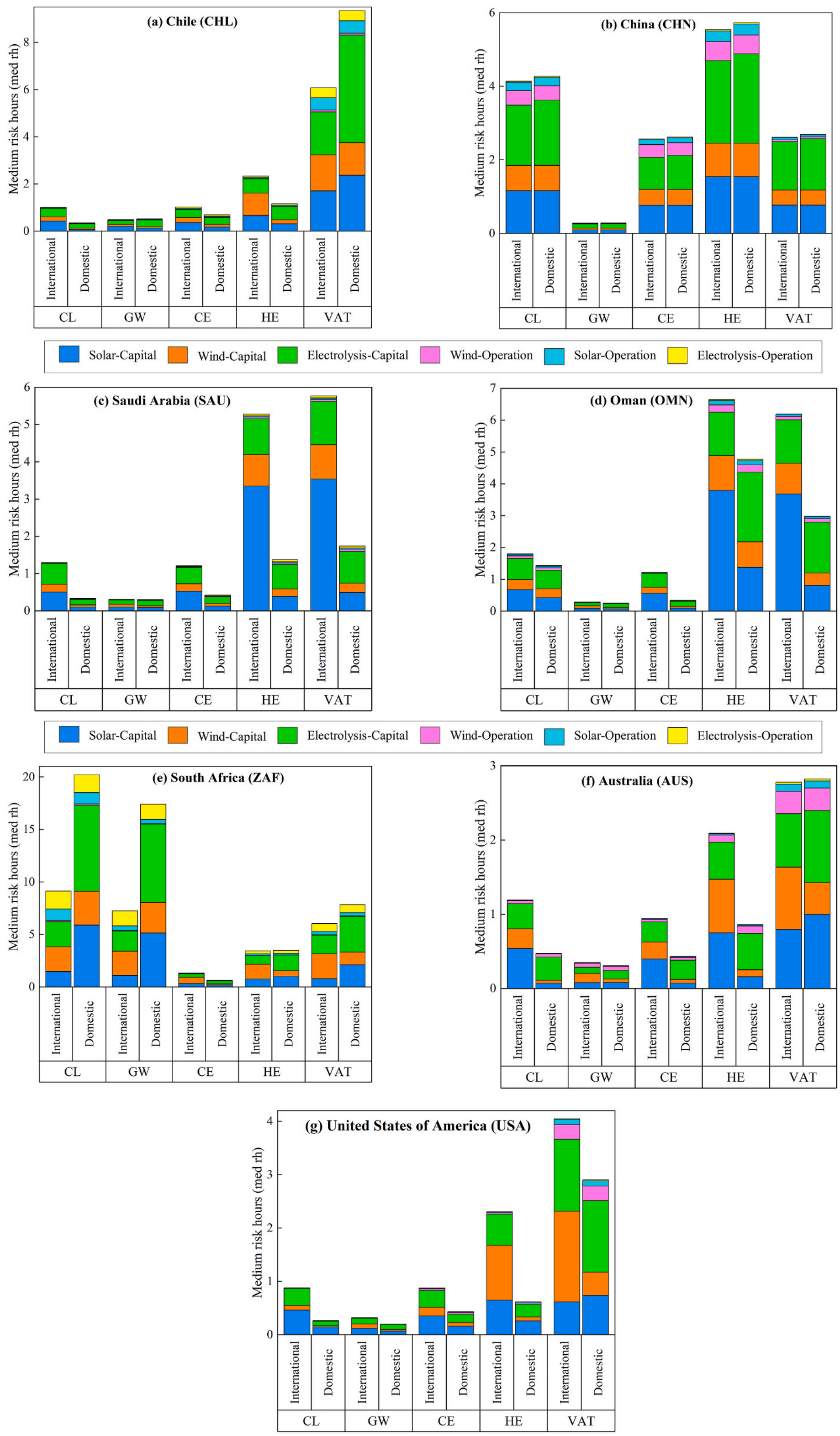

Fig. 7. Comparison of social life-cycle profile of green hydrogen with international and domestic supply of key equipment. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Globally, countries that are heavily reliant on fossil fuel trade, such as GCC countries, should diversify their economies by adapting to the energy transition to address climate change concerns and achieve the SDGs of the UN (Rossana et al., 2020). With ample land and excellent solar and wind resources, Saudi Arabia and Oman have the biggest potential for producing and exporting green hydrogen among the GCC countries (Heinemann et al., 2022). However, in both countries, the scarcity of freshwater and the ease of access to seawater necessitate heavy investment in water desalination. To achieve international climate targets, such as SDGs and net-zero carbon emission, Saudi Arabia and Oman have recently announced their national strategic visions for energy transition as Vision 2030 Kingdom of Saudi Arabia,

Fig. 8. Pillars of sustainability and categorization of the sustainable development goals (https://www.un.org/sustainabledevelopment/news/communications-material/). (The content of this figure has not been reviewed by the United Nations and does not reflect its views).

2020 and Vison 2040, respectively (ISFU, 2020; Vision 2030 Kingdom of Saudi Arabia, 2020 Kingdom of Saudi Arabia, 2020). In Vision (2030), the Saudi Arabia seeks to diversify its economy by building a huge green hydrogen plant in NEOM. Air Products, a US chemical and industrial gas company, and Acwa Power, a Saudi Arabian power and desalination utility, will cooperate on the plant located in NEOM—a megacity for sustainable living (John, 2020; Shearman & Sterling, 2020). This green hydrogen project, which would be the world's largest green hydrogen project, will produce 650 tons of hydrogen every day, which is enough to fuel 20,000 hydrogen buses (John, 2020; Vision 2030 Kingdom of Saudi Arabia, 2020 Kingdom of Saudi Arabia, 2020). As part of Vision 2040), the Oman Ministry of Energy and Minerals launched a national hydrogen alliance named Hy-Fly that seeks to invest 34 billion dollars in green hydrogen over the next decade to enable Oman to become a leading green hydrogen hub (ISFU, 2020; Zones, 2021).

Currently, the concept of a decarbonized economy is extremely difficult to envision in the long-term. The future energy mix will eventually lead to a transformation in energy, trade, and geopolitical relationships due to the transition to renewable energy sources. Moreover, the International Renewable Energy Agency stated that "just as fossil fuels have shaped the geopolitical map over the last two centuries, the energy transformation will alter the global distribution of power, relations between states, the risk of conflict, and the social, economic and, environmental drivers of geopolitical instability" (Clairmont, 2019). A strong and comprehensive hydrogen policy would enable hydrogen to meet nearly 25% of global energy demand by 2050, thereby strongly influencing geopolitical dynamics (BloombergNEF, 2020). A green hydrogen economy is expected to be deployed at a larger scale in the foreseeable future because of the various national hydrogen strategies defined by various countries, necessitating new international agreements between different countries to establish an import–export value chain for hydrogen trade based on comparative advantages, which will create a global hydrogen diplomacy (International Energy Agency, 2022; Rossana et al., 2020). This global hydrogen trade may affect relations between developed countries and the Global South (International Energy Agency, 2022; Rossana et al., 2020). Therefore, developed countries should support countries in the Global South in decarbonizing their energy networks by developing a domestic green hydrogen market to ensure global equity, stability, and sustainability (International Energy Agency, 2022).

5. Conclusion

Green hydrogen has gained substantial momentum over the last decade because of its immense potential in decarbonizing the global energy, transportation, and industrial sectors. To fully realize the potential of both the Paris Agreement and SDGs worldwide, it is imperative to ensure that sustainable development and climate action go hand in hand, and a green hydrogen economy is not developed at the expense of indigenous communities. This is a novel study to present the social profile of the entire value chain of a future green hydrogen economy in seven major hydrogen exporting countries, with a primary objective of identifying social hotspots throughout the entire life cycle of green hydrogen production using a cradle-to-gate approach.

The results of S-LCA reveal that green hydrogen production in South Africa poses the highest risk to most of the social indicators, especially CL, fair salary, unemployment (U), association and bargaining rights (ACE), and GW, because of the poor working conditions and the lower gross domestic product/purchasing power parity per capita compared with those of other countries. On the contrary, in all other countries, the risk to most of the social indicators drastically reduces when key equipment was assumed to be manufactured within the country itself rather than imported from other countries. Based on the findings of the study, improvement actions should consider lowering energy and equipment requirements in a representative supply chain of green hydrogen, improving working conditions in the energy sector to minimize the risk level to social indicators, and developing international regulations for green hydrogen to ensure that carbon-intensive activities are not out-sourced from third world countries to address the identified social hotspots. As long as there is no common regulatory framework and good working conditions in the energy sectors of the countries, hydrogen economies with zero carbon emissions are considered to be a long-term solution to sustainable development that contributes positively to most of the SDGs. In the future, researchers may investigate potential methods of manufacturing the key equipment required for green hydrogen production within the countries to assess the sustainability of the process.

CRediT authorship contribution statement

Malik Sajawal Akhtar: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Software, Visualization, Writing – original draft, Writing – review & editing. **Hafsa Khan:** Data curation, Writing – original draft. **J. Jay Liu:** Writing – review & editing, Project administration, Supervision, Funding acquisition. **Jonggeol Na:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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