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Hydrogen and the sustainable development goals: Synergies and trade-offs

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ABSTRACT

Sustainable Development Goal 7 highlights the importance of affordable, reliable, and sustainable energy. Transition to clean energy is vital for achieving climate action goals. Hydrogen can serve as a clean energy carrier, with the potential to decarbonize industry, transportation, and other sectors. As of 2021, hydrogen was mainly produced using fossil fuels (grey hydrogen), and only about 1 % of global hydrogen output was produced with renewable energy (green hydrogen). The transition to green hydrogen requires new hydrogen production, storage, and distribution facilities which is challenging to implement due to a lack of associated infrastructure and high upfront costs. This study highlighted barriers and opportunities for hydrogen technologies by reviewing evidence and establishing links with the Sustainable Development Goals (SDGs). The review identified fifty-two opportunities and forty-six challenges linked to SDGs1, 2, 4.6, 7, 9, 11, 12 and 13. Out of all the hydrogen production technologies green hydrogen was the most common choice noted in the. Technical opportunities for green hydrogen production were found to have the potential to positively impact society and environment, but high costs were noted to be a barrier. To reduce economic barriers, recommendations include analysing the impact of subsidies and working further on the development of policies and regulations to support the scaling-up of green hydrogen systems.

1. Introduction

The energy transition involves meeting growing energy demand, reducing the use of fossil fuels and increasing the share of renewable sources in the energy mix. The International Energy Agency, projects that 660–670 million people will still lack access to electricity in 2030 [1,2To meet future energy demand changing the energy mix is crucial to avoid increasing carbon dioxide (CO_2) emissions. For instance, the concentration of CO_2 increased by at least 35 % in the 20th century and is projected to increase by over 100 % this century [1]. Currently, 84.4 % of primary power consumption (electricity and heat generation) is from use of fossil fuels (oil, coal, and gas), followed by 6.4 % of hydropower, 4.3 % of nuclear and other low-carbon sources. Countries such as Paraguay (99 %), Norway (97 %), and Costa Rica (93 %), have already achieved a high percentage of renewable energy in their energy mix. However, to increase the share of low-carbon sources in the global energy matrix from the current 15.6 % urgent decarbonisation of the energy sector is required [2–4].

. This transition to clean fuels has been accelerated in Europe due to factors such as the geopolitical clash in Eastern Europe and its consequences on fuel supply risk. In response, Europe has set an ambitious goal to achieve carbon neutrality by 2050 through initiatives like the European Green Deal, the "Fit for 55″ package, and the "REPowerEU" plan, all of which aim to reduce dependence on fossil fuels [5]. However, the transition faces several challenges, including the more infrastructure and high investment costs associated with renewable energy sources. Another significant hurdle is the intermittent nature of renewable sources, which results in uncertainty about the power capacity to cover the electricity demand. To address this challenge, green hydrogen (H_2) represents a promising alternative to balance electricity generation and consumption by recovering the renewable electricity surplus, thus

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Abbreviations

CO_2	carbon dioxide
H_2	hydrogen
IDB	Inter-American Development Bank
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
NORAD	North American Aerospace Defense Command
PSILCA	Product Social Impact Life Cycle Assessment
RQ	research question
SDG	Sustainable Development Goal

creating greater flexibility in energy systems [6].

Hydrogen can be produced from several sources and is categorised in different colours based on the production method and associated emissions. Grey hydrogen is produced from natural gas via steam methane reforming, while blue hydrogen couples this process with carbon capture and storage to reduce emissions. Green hydrogen is produced through water electrolysis powered by renewable energy sources like solar and wind, resulting in minimal greenhouse gas emissions [6]. Since H_2 is an energy carrier closely related to renewable sources, the most direct link to the Sustainable Development Goals (SDG) is expected to be SDG 7, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all [7]. However, "energy" is part of all planetary and human activities, and any change in the established energy system will impact multiple SDGs. The International Renewable Energy Agency's report tracking progress towards achieving SDG7 concludes that "the COVID-19 pandemic has continued to slow global progress on SDG7, but many governments advanced new policies in support of energy-related SDGs, particularly in advanced economies'' [8].

In the energy sector there has been extensive research on the links between energy systems and SDGs. Fuso Nerini et al. [9] identified links between SDGs and 143 SDG Targets with Bisaga et al. [10] applying this approach to the off-grid energy sector. Beyond energy, systematic studies of SDGs using similar approaches are found within a wide array of topics such as climate action [9], artificial intelligence [11], education [12], COVID-19 [13], neonatal health [14], food security [15], and corporate social responsibility [16]. There is a need for further structured research to better understand the deployment of the hydrogen economy in the energy mix and how that supports the SDGs and Agenda 2030.

. Partnerships across borders are vital to address cross-country energy variability and security of supply issues without jeopardising other SDGs such as poverty, growth, inequality, and peace [17]. The sustainability of hydrogen supply chains has been studied in several works by using multi objective optimisation models where the cost [18], global warming potential [19], risk and social cost-benefit [20–22] have been optimised to design the hydrogen network. When incorporating social cost-benefit analysis, externalities such as air pollution, materials depletion, and noise can be included [23]. With international cooperation, the complexity of hydrogen supply chains increases. However, the emerging hydrogen market has the potential to be both decentralised and inclusive, benefiting both developed and developing countries [1–17,24]. Although these explore the sustainability of hydrogen supply chains, they do not explicitly investigate links of the hydrogen economy with the SDGs.

This study addresses the knowledge gap by identifying opportunities and barriers to scaling up hydrogen technologies through the SDGs. The research question that motivated this study is "What are the links between hydrogen and the Sustainable Development Goals?". The novelty and innovation of this research stems from applying a structured SDG mapping approach to identifying and analysing the linkages, opportunities, and challenges between hydrogen solutions and the SDGs. This study further contributes to the field by examining interactions in the domains of economic, environmental, societal, and technological dimensions, offering a holistic understanding that has not been previously explored.

The structure is as follows: Section 2 provides an overview of hydrogen technologies, focusing on trends concerning its role in a sustainable energy transition. Section 3 describes the description of the methods used, and Section 4 presents the key results (connections, challenges, and opportunities). Section 5 discusses results for the three dimensions of action: economy, biosphere, and society. The conclusions and final remarks are presented in Section 6.

2. Hydrogen in context

Hydrogen can be obtained from several sources, such as natural gas (called grey H_2) using steam methane reforming technology, coal (brown H_2) through gasification production, nuclear power (pink H_2), biomass, solar, wind, geothermal and hydropower (green H_2) where electricity generated using renewable energy sources is coupled with water electrolysis production. If grey or brown H_2 production is connected to carbon capture and storage, the final product is called blue H_2. Each H_2 colour has a different cost and environmental impact. From the different hydrogen colours, green H_2 represents one of the most promising sustainability options because hydrogen can store intermittent renewable energy sources by utilizing the surplus electricity that cannot be injected into the grid. One of the key advantages of hydrogen as an energy carrier is its ability to store electricity in the form of hydrogen over relatively long periods, compared to electricity in batteries, contributing to greater energy security and flexibility [25–27].Additionally, H_2 can be distributed in liquid or gaseous forms or using metal hydrides.

The hydrogen market consumes grey H_2 in industrial sectors like refineries, ammonia (mainly used in fertilisers), methanol, and other chemical operations. There is a significant potential for hydrogen to be used in energy-intensive industries: iron-steel and cement sectors, partially motivated by more expensive CO_2 allowances [28]. New applications are projected for clean hydrogen in the mobility market. For this purpose, fuel cell private cars and buses are commercially available, and prototypes of heavy duty-trucks, ships, and trains are currently being tested. However, whilst possible, residential applications are limited in use due to costs [29].

In terms of implementation projects, hydrogen valleys are present in several countries in the European Union under the Clean Hydrogen Partnership [30]. These programmes are exploring options for the operation of new hydrogen sites, starting with low-capacity installations from which lessons can be learnt to support scale up. Cooperation and coordination are needed to guarantee a smooth expansion. In the global context of the geopolitics of energy, hydrogen plays an unprecedented role where more focus has been put on policy to enable the hydrogen economy to decarbonize harder-to-abate sectors [29].

Despite the potential of green hydrogen, several barriers have hindered its widespread adoption. Scaling up industrial and commercial deployment of new hydrogen technologies poses risks across multiple fronts. There exists a dilemma between infrastructure development and demand growth, as the absence of one hinders the progress of the other [25]. The infrastructure required for green hydrogen, such as electrolysers and renewable energy systems, is more expensive than traditional hydrogen production facilities [6]. Establishing new hydrogen facilities requires financial investment, access to information, materials, and a skilled workforce. Another challenge is the high cost associated with green hydrogen production compared to conventional fossil fuel-based methods [17]. Moreover, research and development efforts to increase energy efficiency and technology maturity are at early stages. Both centralised and distributed green hydrogen options involve significant sustainability trade-offs in economies of scale, storage and transport [21].

Although some studies explore the sustainability aspects of future hydrogen supply chains using multi objective optimisation [18–22], they need to investigate the impact of and links of the hydrogen economy with the SDGs. In the following sections, such linkages will be investigated.

3. Materials and methodology

Fig. 1 demonstrates the four-step research methodology adapted from the published SDG mapping works [9,31,32] to includeStep 1) literature review, Step 2) SDGs mapping, Step 3) two-round expert validation, and Step 4) framework development. The literature review (Step 1) identifies published evidence linking hydrogen with the SDGs using keyword searches in academic databases. The SDGs mapping (Step 2) categorises the identified evidence based on its relevance to specific SDG targets. In Step 3, a two-round expert validation process is conducted, where co-authors of this work with subject expertise review and validate the SDG linkages found in the literature (Round 1) and expand the evidence base using additional sources such as reports and policy documents (Round 2). Finally, in Step 4, the validated evidence is used to categorise the SDG linkages into three dimensions: economy, society, and biosphere.

In Steps 2 and 4, two research questions (RQ) are applied to the published works selected from the literature review (Step 1) to build the evidence-informed framework.

- RQ1. “Is there published evidence of SDGs linkage with hydrogen?”
- RQ2. “Does the evidence represent an opportunity or a challenge for hydrogen?”

In the first round of Step 3, the co-authors of this work, subject experts, identify relevant publications in the field. Academic databases were used to search the keywords for each SDG target in addition to hydrogen keywords/synonyms. Then, they reviewed the publications to link the studies to the one hundred and sixty-nine SDGs targets. Fig. 2 depicts the PRISMA flowchart applied to narrow down the results according to excluding and including criteria. The next step was applying expert validation to reach consensus on the links between H_2 and SDGs within the three domains of social, economic, and environmental dimensions. In the second round of Step 3, the subject experts supplement academic sources to include external data sources such as reports, policy documents, and communication briefs from international organisations linked to the energy industry. The two-round categorisation merges a structured PRISMA review with an expert’s categorisation method. It can expand the evidence sourcing outside academic work (i.e., grey work and policy documents) and indicate which targets are being addressed without necessarily mentioning SDGs keywords in the studies.

In Step 4, the SDGs framework design reported by Vinuesa et al. [11], comprising three dimensions, i.e., society, biosphere, and economic, is used due to the convenient grid format visualisation around the linkages among hydrogen and the SDGs targets. For this work, the evidence of “opportunity” was defined as a linkage demonstrating a positive connection with the target. It can represent a synergy, an enabler, or a generally positive outcome presented in a case study. “Challenge” is portrayed when the linkage with the target is made through evidence that can inhibit, hinder, or establish a negative relationship with H_2.

Even though the search query did not explicitly include the term "green," the research evaluation recognised green hydrogen as a crucial topic related to the SDGs. By applying the proposed methodology, it was possible to analyse the connections in a deeper manner than the one offered in the Scopus categorisation. Although all the SDGs detected from the Scopus categorisation appeared in the analysis, links with additional SDG targets were identified and reported. The incorporation of the target identification and analysis is one of the main contributions of the methodology used in this study. Some documents refer to more than one target, while others are supported by more than one piece of evidence.

4. Findings and discussion

4.1. Hydrogen and SDGs: a summary of the literature

See Fig. 2 for the categorisation of literature from Scopus (48) and Web of Science (33) databases used for the search conducted in July. After excluding the duplicates and non-adherent works, a total of 29 works were used in the categorisation. After several trials, the most efficient search option to identify applicable works was to use keywords in the title (hydrogen OR H2) AND the abstract (SDG OR Sustainable Development Goal*).

Table 1 lists the articles categorised by year, level of analysis, and H_2 colour. Journal articles published before 2015 are out of the scope of this work. Most of the works(79 %) were published from 2020 onwards, with ten papers in 2021 representing the highest count for a single year. In the category “level of analysis”, research differs depending on several

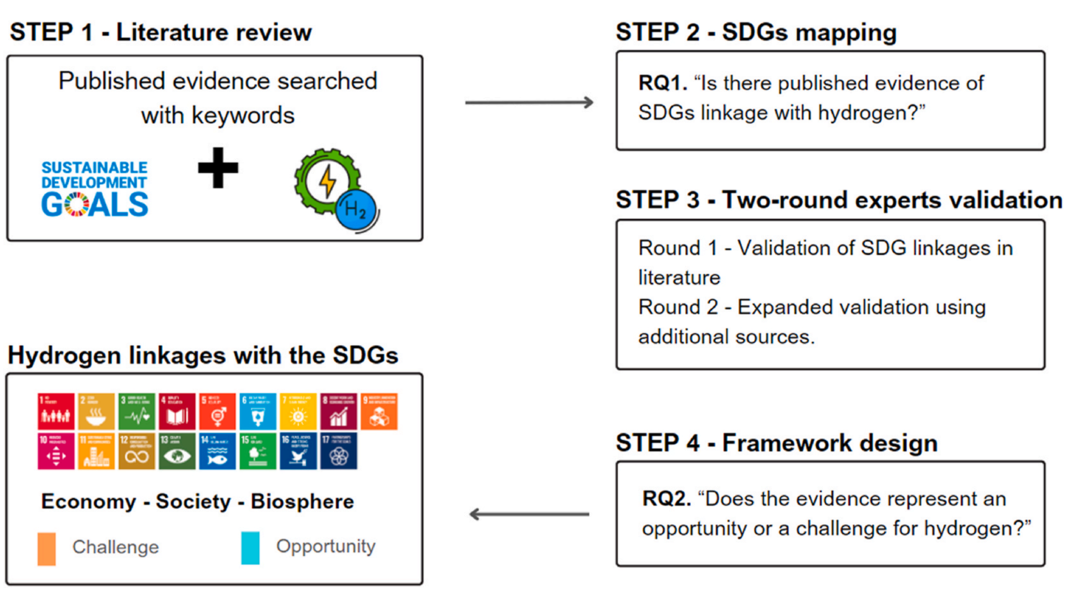

Fig. 1. Research methodology framework.

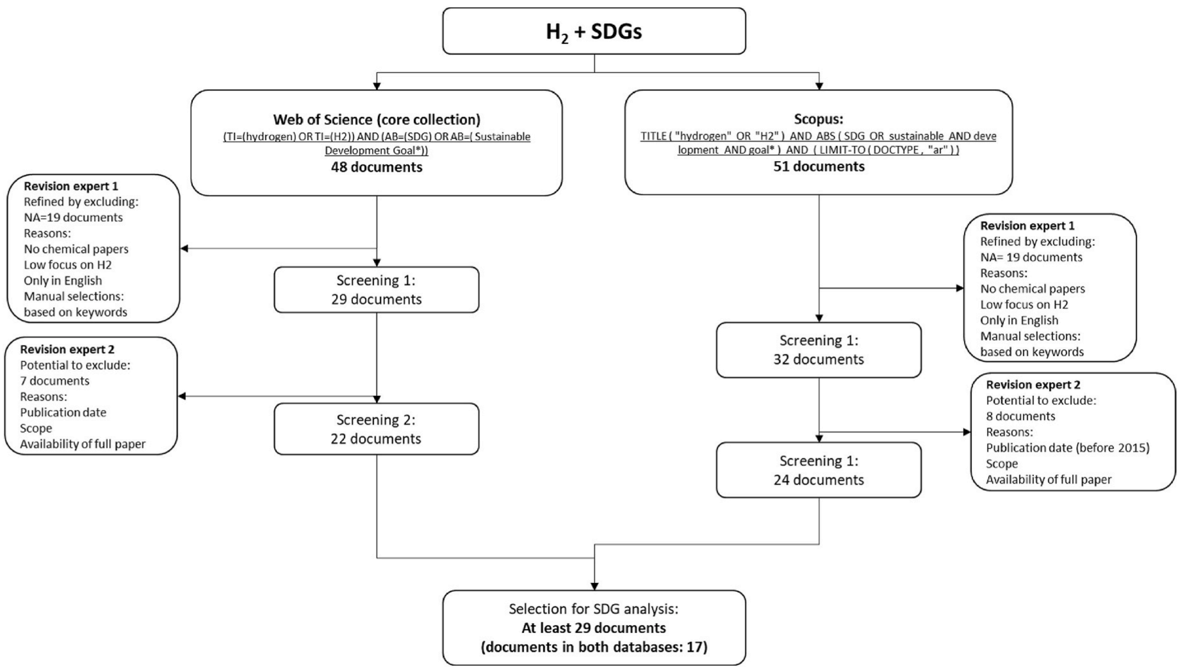

Fig. 2. Literature scoping flow for H_2+SDGs from Web of Science and Scopus databases (NA = number of works excluded).

Table 1
Categorisation of publications according to year, level of analysis, and hydrogen colour.

Year	Count	Level of analysis	Count	Hydrogen colour	Count
2016	1	System	12	Green	21
2017	2	Technology	7	Multiple	6
2018	1	Multi-System	5	Brown	1
2019	2	Market	5	Not defined	1
2020	8				
2021	10				
2022	5				

factors, as shown in Table 1. System level analysis in this instance covers topics such as networks, supply chains, ecosystem design and deployment. This category was the most common, with twelve research articles. Some works link several systems and are labelled “multi-system,” accounting for five papers. Another level of analysis is a “chemical operation” focused on chemical processing to improve efficiencies or new technologies for H_2 generation (these works were excluded from the first revision, as depicted in Fig. 2). Other works focus on a specific technology device, component, or sub-system and are labelled as “technology” (e.g., proton-exchange membrane, and electrolysis efficiency), with seven works n this category. Finally, five cover generic topics such as “market” or “H_2 economy”

Green hydrogen has been identified as a key topic in the literature review. At least 72 % of the twenty-nine scientific works explicitly develop analyses for “green” hydrogen (using renewable energy sources: solar, wind, and biomass). The focus on green H_2 is predominantly noted om 2020–2022 (76 % of related studies), as demonstrated in Fig. 3 where, from twenty-one works, eighteen are related to SDG 7, followed by SDG 9 (ten), SDG 8 (nine SDG 13 (eight DG 12 (five G 11 (two nd SDG 3 and 6 (one paper ach).

Fig. 3 presents the Scopus database indices of the works according to the SDGs. From Scopus categorisation, connections with SDG 7 (affordable and clean energy) were the most prominent, followed by SDGs 8 (decent work and economic growth), 9 (industry, innovation, and infrastructure), 12 (responsible consumption, and production) and 13 (Climate action). This indicates a precise alignment with goals related to the economic branch of the 2030 Agenda, in addition to climate action.

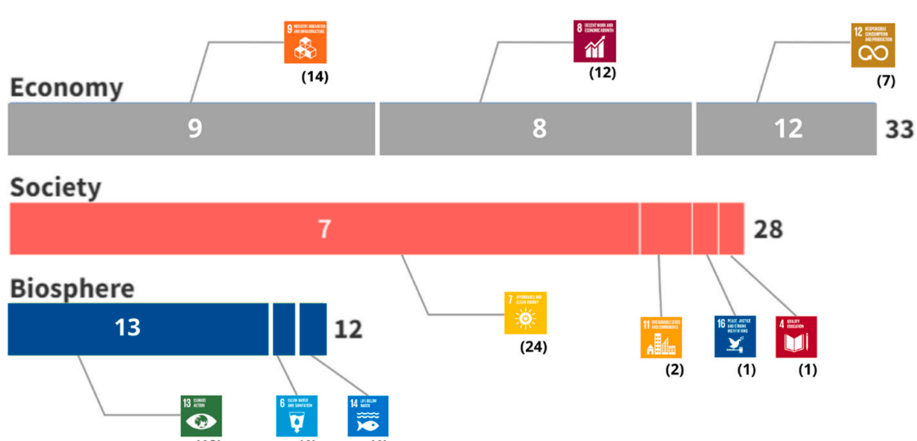

Fig. 3. SDGs indexed in Scopus.

In addition to the twenty-nine works from the literature review, the experts added ninety documents as a basis for the categorisation; these documents were sourced from policy works, reports, grey work and additional academic references not present in the first pool of works. The results of the full analysis are displayed in Section 4.2.

4.2. Connections between hydrogen and SDGs

Although Scopus categorises the SDGs, it does not display the specific targets. In the proposed methodology, the identification of the main targets is considered crucial as it provides a more granular understanding of the hydrogen-SDG nexus, supported by evidence from the literature (see Fig. 4). In addition to links with Targets from SDGs 7 and 13, other works emphasise the importance of infrastructure (target 9.4), education and skills (targets 4.7, 4.4, 4.3), research and development (target 9.5), pollution reduction, and water use efficiency (targets 6.3, 6.4) about green hydrogen development. Fig. 4 shows that target 9.4 (infrastructure and industry retrofit) was the most frequently mentioned, highlighting the need for improved infrastructure to support the transition to a green hydrogen-based energy system and achieve net-zero ambitions. For instance, it is reported that two hundred and twenty-eight green H_2 projects were launched globally, with 55 % located in Europe [34]. Another example is using H_2 instead of carbon in pig iron production. The traditional route for steel production starts with pig iron, which is generally composed of 94.5 % iron, 5 % carbon and 0.5 % impurities, and it is produced after reaction between iron ore concentrated with carbon. The byproduct of this reaction is pig iron and CO_2 emissions. The use of H_2 is beneficial because the reaction generates water rather than CO_2. To achieve this, a significant modification to the entire process is necessary, and several safety developments are crucial to making it possible [35–37]. For this reason, in addition to target 9.4, targets 9.5, 8.4, 7.3, 7.b, 7.2, 12.4, and 12.1 are included to account for the need for economic development, industrial retrofit, and scientific innovations [38].

Hydrogen technologies have the potential to address energy poverty and support sustainable development in rural areas. According to Chen et al. (2019), hybrid energy distribution systems incorporating H2 are crucial for expanding access to renewable energy in rural villages [39]. The combination of ethanol production and H_2 generated by water electrolysis in India is particularly advantageous due to the country's large ethanol production capacity [40]. Improved access to a diverse energy mix that includes hydrogen could help reduce energy poverty [41]. Moreover, H_2 may also play an important role in supplying energy for food production [42,43], further contributing to sustainable development goals. However, there is limited discussion regarding the costs of replacing natural gas with hydrogen for energy generation purposes [44], which is a key consideration in addressing energy poverty.

Despite the term "energy poverty" being mentioned in Ayodele et al.'s works [41], the linkage within the targets of SDG 1 (no poverty) was found to be low, with connections identified only to targets 1.2, 1.3, and 1.4. To fully realise the potential of hydrogen in supporting sustainable development and addressing energy poverty, increased awareness and knowledge sharing are necessary. This relates to Target 4.7, which emphasises education and skills for promoting sustainable development. There is growing interest and discussion surrounding the advantages of H_2 for a net-zero society [45], with the environmental benefits of H_2 production being a key driver for the stronger interest in and acceptance of this technology [45].

4.3. Opportunities and challenges

The work found connections between hydrogen and the SDGs, with 52 (31 %) targets identified as opportunities and 46 (27 %) as challenges. Opportunities (52/169) and challenges (46/169) were categorised into three dimensions according to the framework: Biosphere (5 and 7, respectively), Social (29 and 26), and Economic (18 and 14). Most identified challenges and related opportunities were given similar categorisations (Fig. 5). Key challenges and opportunities are identified in the following areas: industry, innovation, and infrastructure; responsible consumption and production; affordable and clean energy, education; climate action; and clean water. More than half of the analysed challenges and opportunities (societal outcomes) have the potential to have a high impact on society, such as fostering universal healthcare (target 3.8) or supporting rural infrastructure in isolated areas (target 2.a). Therefore, a crucial topic for dealing with understanding, learning, and social utility could be promoting collaborative

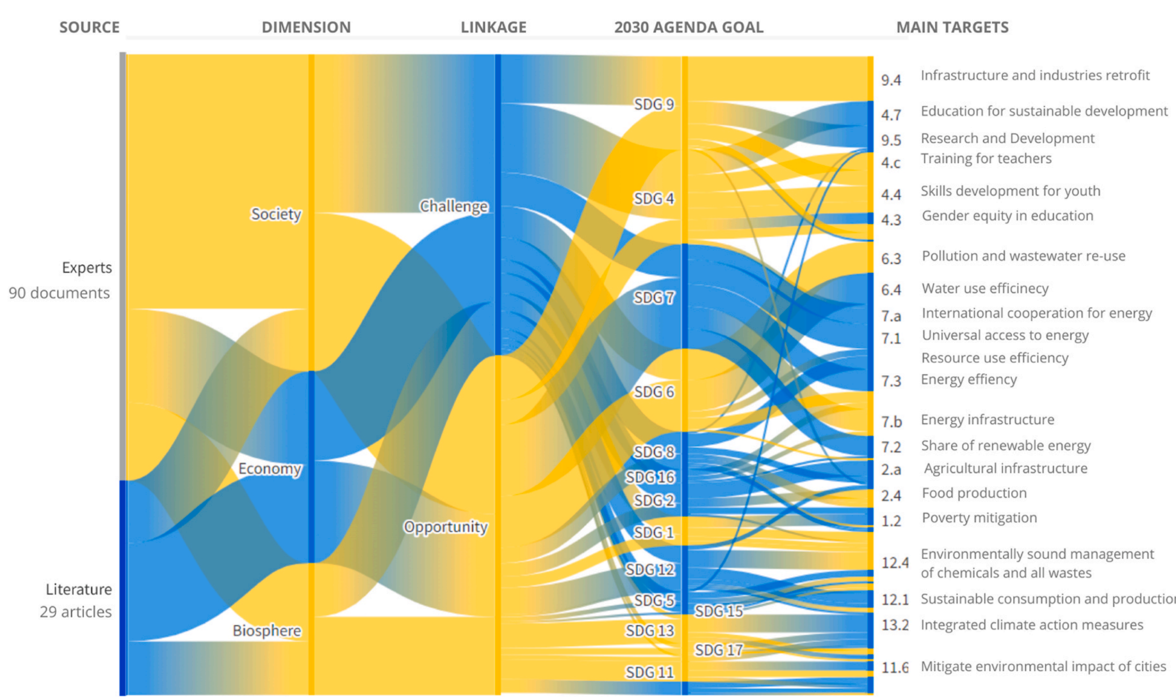

Fig. 4. Evidence linkage flow on research review and experts to SDGs and main targets.

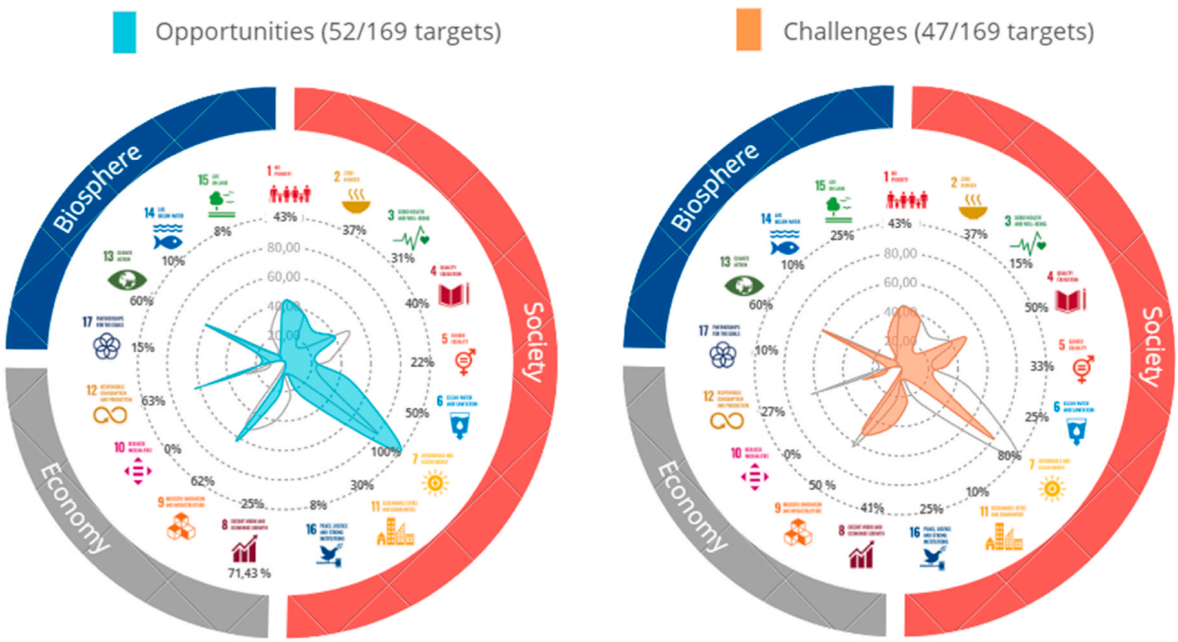

Fig. 5. Summary of opportunities and challenges of green hydrogen.

social networks involving different types of stakeholders. These networks can provide formal support and create a mutual learning ecosystem. This allows for greater benefits and understanding among stakeholders.

Fig. 5 indicates the proportion of all targets potentially affected by green hydrogen production. The outer circles represent the three dimensions - Society, Economy, and Biosphere. The percentages along each SDG in the inner circle represent the percentage of targets from each goal that appeared in the research review (e.g., for opportunities in SDG 7, all five targets (7.1, 7.2, 7.3, 7.a, 7.b) were linked. Hence, the percentage indicated is 100 % - visualisation framework informed by Vinuesa et al. [11].

5. Discussion

In this section the SDG targets are linked as opportunities or challenges to the three dimensions of biosphere, society, and economy. The figures presented in Sections 5.1,8,24 indicate the presence of evidence linking green hydrogen production reviewed in this work with the 2030 Agenda through the SDGs framework, which is important to achieve sustainable development in a diverse and interconnected context through mapping, analysis, and policymaking. Figs. 6–8 provide a comprehensive overview of the interactions between green hydrogen and the SDGs.

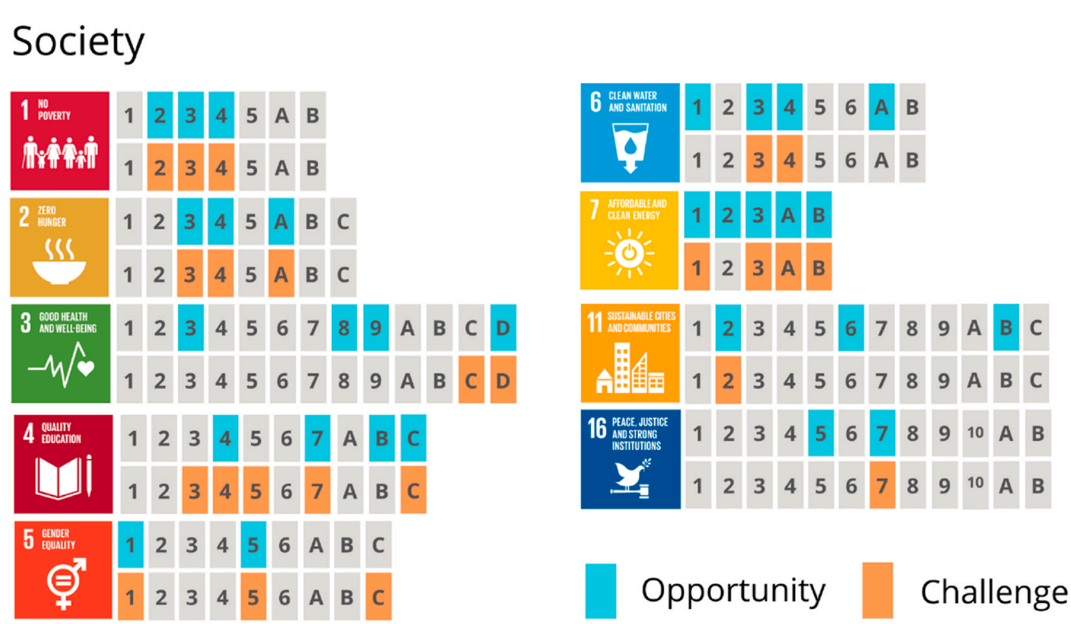

Fig. 6. Green hydrogen social dimension grid. This grid illustrates the connections between the reviewed studies on green hydrogen production and the 169 SDG targets, focusing on the social dimension (SDGs 1–5, 11, and 16). The grid uses a colour-coded system to indicate whether each target represents an opportunity (green) or challenge (orange) based on the evidence found in the research previously published.

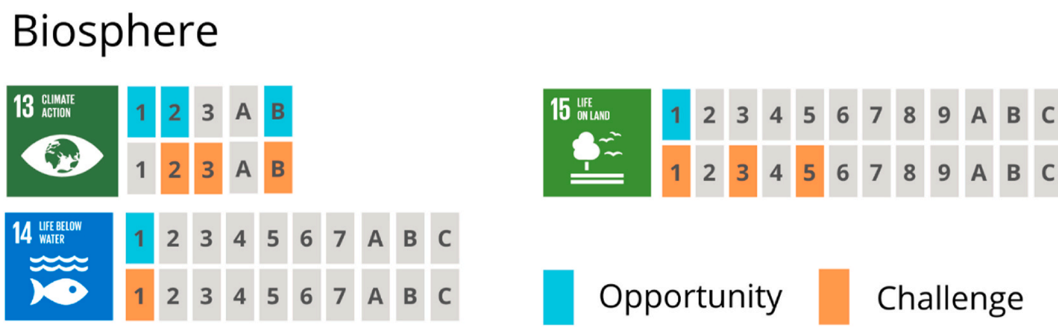

Fig. 7. Green hydrogen biosphere dimension grid. This grid maps the connections between the reviewed studies on green hydrogen production and the 169 SDG targets, concentrating on the biosphere dimension (SDGs 13–15). The grid highlights the opportunities (green) and challenges (orange) identified for each target, providing insights into the potential environmental implications of green hydrogen development.

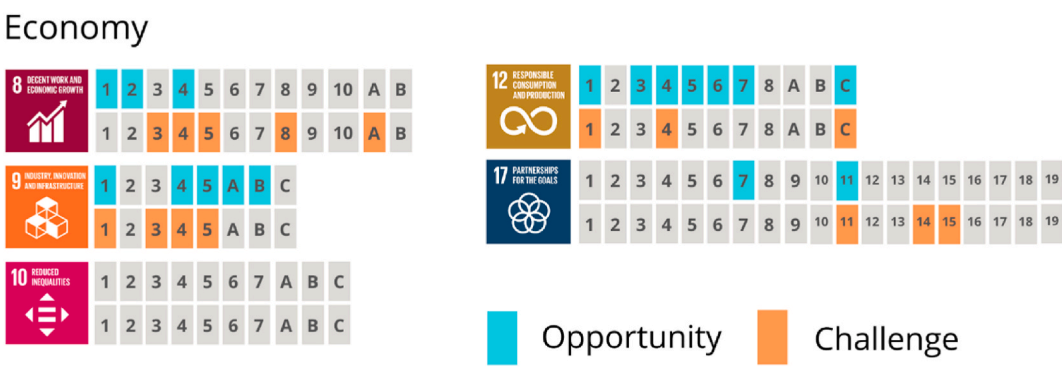

Fig. 8. Green Hydrogen Economic Dimension Grid. This grid visualises the connections between the reviewed studies on green hydrogen production and the 169 SDG targets, focusing on the economic dimension (SDGs 7–12 and 17). The grid employs a colour-coded approach to indicate the opportunities (green) and challenges (orange) associated with each target based on the evidence found, showcasing the potential economic impacts of green hydrogen production.

5.1. Green hydrogen and social dimension

Green hydrogen presents challenges and opportunities regarding its social impact (Fig. 6).On the positive side, green H_2 has the potential to yield social and economic benefits [46]. Renewable energy storage through hydrogen can foster economic growth, health, and life comfort [47]. The flexibility of H_2 production processes increases the likelihood of it being adapted at scale to benefit communities. Moreover, green hydrogen presents opportunities to address systemic inequities, particularly in resource-constrained settings. For instance, a study in rural Africa showed the mutual benefits of using hydrogen storage mini-grids to generate electricity (target 7.2) and desalinate water, improving sanitation conditions (target 6.1) [48]. Similarly, H_2 microgrid storage has been proposed as a viable solution for powering an isolated hospital (target 3.8) in a South African village [49]. Combining desalination with hydrogen-based energy generation in sub-Saharan African rural communities can enhance access to clean water (target 6.1) and electricity (target 7.2) [50]. However, realizing these benefits fully requires overcoming barriers in emerging markets, such as the lack of H_2 integration in primary energy infrastructure (target 9.4) and limited technology and expertise (targets 9.5 and 7.b) [51,52]. Addressing these challenges requires the development of institutional policy frameworks for green energy (targets 7.2, 9.4, and 12.c) [43].

Despite the potential advantages, green hydrogen also presents challenges regarding social equity and workforce development. In the work context, the safety risks associated with hydrogen production pose a challenge in ensuring decent work conditions (targets 8.8 and 7.1) [53,54]. Gender inequalities persist in the hydrogen technology sector, even in high-income countries (targets 5.1 and 5.5) [55]. A study conducted in Germany, Spain, and Austria using the Product Social Impact Life Cycle Assessment (PSILCA) highlighted concerns in hydrogen production in European countries, such as the gender wage gap (targets 5.1 and 8.5), insufficient salaries (target 8.5), and inadequate working rights (target 8.8) [55].

Furthermore, inequalities in education and awareness hinder equitable participation in the hydrogen economy. There is a need for interdisciplinary training and literacy programs on hydrogen and climate action (targets 4.7 and 13.3) [56]. Public awareness of hydrogen (target 4.7) remains low [45], and gender disparities in engineering education are more pronounced in emerging economies [57,58]. Several social aspects of the hydrogen economy require further research [59]. In summary, while green hydrogen presents challenges regarding social equity, workforce development, and education, it also offers significant opportunities to address systemic inequities and promote sustainable development.

5.2. Green hydrogen and biosphere dimension

The primary connection between green H2 and the SDGs was identified in relation to climate action and the GHG mitigation potential of green H2. Evidence indicated the vital role that green hydrogen plays at the policy level in fulfilling net-zero emission agreements, such as the European Green Deal (target 13.2) [60]. Most of the benefits are linked to retrofitting and decarbonising sectors, such as the chemical industry [61]. These connections are illustrated in the green hydrogen biosphere dimension grid for SDGs 13, 14, and 15 (Fig. 7).

Biosphere dimensions are intertwined with clean energy production, with multiple connections between SDGs and H_2. For instance, Nasr et al. (2021) highlight a nexus connecting bio-energy generation (target 7.1) and soil recovery through the use of biochar (target 2.4) [62]. Their study demonstrates that hydrogen production from black liquor yields clean energy and produces biochar, enhancing soil fertility and supporting sustainable agriculture. Despite the upfront label of clean energy, the production chain contains non-sustainable aspects, with trade-offs involving land and water. This can lead to undesirable outcomes; such as soil degradation, erosion, deforestation (targets 2.4, 15.1, and 15.3), biodiversity loss (target 15.5), and pesticides' pollution (target 2.4) [63]. One example is the use of thermal plants in the H_2 supply chain [64] or the emission of pollutants such as nitrogen [53], creating a trade-off between mitigation of CO_2 emissions (target 13.1) and reduction of pollutants released (target 12.4).

Concerning water resources and marine ecosystems, the debate is fuelled by disputes over using water and land for H_2 and the pollution caused by the production process. Thermal or chemical production of hydrogen can be a source of contamination [65], liberating pollutants (target 12.4) such as nitrogen oxide gases, carbon monoxide, and volatile organic compounds. In addition to contamination issues, H_2 production has a water footprint that can generate trade-offs on water availability and ecosystem health, implying some impacts on human health (target 3.9). For example, in the case of steel production, about 9 kg of water per kg of hydrogen is needed during water electrolysis [8,66]. Water is a scarce resource and water intensive energy processes makes the hydrogen-energy-water nexus a critical issue for marine ecosystems. Coastal areas, where energy infrastructure is often located, are particularly vulnerable to these impacts. Kim & Kim [67] address the viability of offshore infrastructure for wind-powered hydrogen supply in South Korea, highlighting the potential trade-offs between energy production, water and land use, and marine ecosystem health, connecting water and land-use trade-offs with environmental regulation (target 14.5) [67,68]. The H_2 production aims for carbon-free outcomes, and the adoption of clean energy may potentially impact water availability or marine biodiversity (target 14.1), necessitating a thorough evaluation of its effects on aquatic ecosystems [69].

Positive impacts on marine ecosystems can foster broader climate goals by using hydrogen as a cleaner shipping fuel and promoting green port operations. As for shipping fuels, H_2 faces efficiency challenges related to low temperature and high-pressure storage needs, which opens a pathway for solutions to reduce emissions and protect marine environments [70,71]. Furthermore, the practical implications of making ports greener can mitigate aerial and noise pollution (target 12.4), as well as linking with targets related to innovation, climate action, and sustainable supply chains. Positive impacts were observed in the study conducted on the Greek port of Adamas: where energy efficiency improved by 51.8 % (target 7.3). At the same time, net-zero emissions were reached by hydrogen production using cold-ironing technology (target 9.5) [72]. Decarbonising shipping transportation (target 12.1) holds significant potential for climate action agreements (target 13.2) such as the European Green Deal [73], thus driving calls for the development of this emerging technology and integrating its benefits into broader climate policies to safeguard marine ecosystems.

5.3. Green hydrogen and economic dimension

Fig. 8 displays the green hydrogen economic dimension grid for SDGs 9–10, 12 and 17. Trade-offs between socioeconomic dimension and environmental protection put the SDGs attainment at risk [74], especially with the high costs associated with H_2. For instance, it is estimated that the cost of transporting blended H_2 is 32 % higher than natural gas [60]. A study conducted by Litvinenko et al. [53] ran simulations on a hundred different technical combinations and still found barriers linked to the cost of energy generation (target 7.3 and 7.1), and lack of infrastructure (target 9.4 and 7.b), which can hinder the adoption of green hydrogen and its potential benefits for marine ecosystems. In addition, international energy trade comprises a set of complex barriers that involve immature transportation technologies (target 9.1), and lack of demand since green hydrogen fuel is still a "buyers' market" (targets, 7.a, 8.4 and 12.1) [54]. To counterbalance the barriers to green hydrogen economics, there is a call for incentives related to administrative, price, and capacity. On the policy level, green hydrogen connects with climate action (target 13.2), budget support, relief of tax burden, the introduction of quotas for green energy (target 7.2), sanctions, certificates, cap-and-trade alternatives, and awareness propaganda (target 13.3) [75], all of which can contribute to the protection of marine environments through the promotion of cleaner energy sources.

The sustainability potential of H_2 on a supply chain level is grounded in exploring the synergic potential of dual green solutions, such as in the nexuses of waste-to-hydrogen and waste-to-energy [75]. Evidence from a study conducted in China indicated that hydrogen electricity generation from food waste-derived biogas (target 12.3) reduces municipal waste generation (target 12.5) [76]. A case study on hydrogen production from biogas using food waste in Nigeria portrayed 94 % of ecological efficiency [41]. Other sources of waste, such as industrial water, sludge or farming (target 12.4), can act as raw materials and are technically feasible to integrate the waste-to-energy; nevertheless, the production is comparatively higher; when it comes to food waste, for instance, the production cost can surpass the selling price [77]. Challenges related to this dimension of green H_2 rest on the lack of infrastructure (target 9.4) and primarily hydrogen production-oriented policies (target 12.1) [76]. The waste-to-energy nexus is a perfect example of how technological advances can unlock hydrogen potential to convert trade-offs into synergies, closing the loop within different supply chains into a circular economy approach.

Global South countries see hydrogen as an opportunity to foster local investment, attract external funding, or facilitate North-South co-operations. Funds have been directed to hydrogen research and development in North-South cooperations: Germany is providing 12.5 million euros for hydrogen projects in the south of Africa [78]. Regional cooperation agencies are also a big part of it: the Inter-American Development Bank (IDB) and the United Nations' Green Climate Fund (GCF) are fostering hydrogen-powered public transportation in Latin America and Caribe with $ 450 in loans and grants [79]; the North American Aerospace Defence Command (NORAD) is also supporting the development of projects in Egypt, Tunisia, Morocco, and South Africa [80]. In Latin America, Chile plans to close or retrofit twenty-eight of its coal plants (targets 7.2 and 9.4) and estimates that external investment from green hydrogen projects will overcompensate for the loss of jobs (target 8.3) [81]. Countries from the southern cone, such as Argentina, Paraguay, Uruguay, and Brazil, are covered by an extensive network of rivers; in these countries, studies have been conducted on how to move one more step in the direction of the sustainable energy mix by using surplus energy from hydroelectric and wind farms to generate hydrogen [82,83]. Raízen Company (a joint venture between Shell and Cosan) is investing in H_2 production and use in buses of the University of Sao Paulo, in Brazil, as a laboratory to expand to the cities [84]. The company is also investing 3.3 billion euros until 2027 to build five factories in Brazil to supply 2.2 million m^3 of ethanol, which is crucial to producing green hydrogen [85].

6. Conclusion

The United Nations 2030 Agenda for Sustainable Development can be an important sustainability roadmap for using green H_2 in the future energy mix. This study identified wide-ranging links between SDG targets and hydrogen. The evidence from the literature review identified fifty-two opportunities and forty-seven challenges linked to the SDGs with hydrogen, especially green hydrogen. Synergies and trade-offs related to green hydrogen must support the low-carbon transition using collaborative scientific development and innovation as foundations. Most barriers were found in the economic and social dimensions, especially around upfront costs and a lack of supply chains. These findings have implications for energy systems, as green hydrogen has some potential to address global energy access gaps while contributing to net zero ambitions. However, green hydrogen systems are highly interconnected and depend on the availability of renewable energy sources. There needs to be more studies covering other low-carbon hydrogen options. This constitutes a research opportunity due to geographical, infrastructural, and socio-political constraints that might affect implementing green hydrogen projects to achieve the connected SDGs. Another point that requires additional analysis is the impact of the production and installation of new hydrogen technologies (e.g., fuel cells, electrolysers, pipelines, and hydrogen vehicles) in terms of using critical or scarce materials and circularity.

The study identified links between green hydrogen infrastructure, education and skills, research and development, pollution, and water usage. The nexus approach allows for introducing hydrogen as part of the energy mix whilst yielding benefits in sectors such as water. While specific challenges and opportunities may vary across regions, the framework and methodology presented in this study can be adapted to local contexts. Lessons learned from successful initiatives in one region can inform strategies elsewhere. Subsidies, policies, and incentives to scale up H_2 technologies may also address societal concerns over a lack of skills and knowledge, touching on the social aspect of the environmental, social, and governance-based investing framework (ESG). By fostering international collaboration and knowledge sharing, the global community can accelerate the scale-up of green hydrogen and maximise its contributions to achieving the SDGs worldwide. Although there is a long way to go in mainstreaming green H_2, this study provides a tool for policymakers to identify and address barriers, develop incentives, and promote substantial environmental benefits, particularly for addressing emissions and the climate crisis, a key focus of ESG.

The contribution of this study is relevant compared to other studies in the same domain in two ways: (i) the SDGs can be interrelated and operationalised from the hydrogen perspective, and (ii) the proposed framework establishes clear connections between the processes needed not only at a goal level but also at a target level to manage sustainability systematically. One of the strengths of the proposed framework is its multidimensional focus, which allows for the management of economic, environmental, and social challenges and opportunities through its expanded application. Operational advantages of the framework include broad stakeholder involvement, including greater transparency, a high level of adaptability, and organised development and ongoing evaluation of the system. Future research should focus on the most critical dimensions, such as the economic one, to promote a constructive and collaborative debate around the possible futures and paths of green or low-carbon hydrogen globally. As with all types of research reviews, this study has some limitations. To create clear boundaries and transparency for the review, predominantly peer-reviewed scientific works in English from internationally recognised databases were included. The validation bias from the researchers is also acknowledged, and efforts to mitigate it were made by involving five specialists who worked on revisions to reduce bias, improving and balancing the review approach adopted for analysing the findings. However, as a research based on a literature review, the analysis represents a perspective at a given time, and future research could benefit from involving new sources and a more diverse group of experts to further reduce potential biases.

Regarding hydrogen, policymakers may assess which hydrogen type or colour (i.e., a used based on the energy source and production type used for its production) provides the best synergies or trade-offs for scale up. To make informed policy and practice decisions, a clear assessment of hydrogen impacts, both positive and negative, on the environment would be required. The cost differences of hydrogen compared to fossil fuels, which vary depending on the country and the resources used for its production, serve as one example. Collaboration and partnerships across borders are crucial to address cross-country energy variability and supply security issues without jeopardising other SDGs such as poverty eradication, decent work and economic growth, reduced inequalities, and peace and justice.

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

No data was used for the research described in the article.

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