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Analyzing the green hydrogen value chain against the sustainable development goals

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Abstract
The emerging green hydrogen value chain provides an opportunity to develop joint sustainable strategies between different countries and implement measures to mitigate potential adverse effects. We analyze whether the green hydrogen value chain can aid in meeting the objectives outlined in the 2030 Agenda. The Value Chain Assessment methodology that we developed enables the identification of direct and indirect influences, and the categorization of positive and negative effects, of each segment (production, transportation, and end-use) of the green hydrogen value chain on the 17 SDGs and their 169 targets. We also analyze the associated temporal dimensions and reciprocal interdependences, to clarify the dynamics of the value chain over time and across different geographical scales. We present a strategic framework that can help in fostering the green hydrogen value chain for the implementation of sustainable development. We find that the use of green hydrogen can clearly accelerate progress on the SDGs in the short-term, but adverse effects could arise in the medium- to long-term. The realization of the green hydrogen value chain requires synchronized investments and policies across space and time.

1 Introduction

In 2015, the United Nations (UN) adopted the 2030 Agenda, thus providing a global framework for jointly implementing sustainable development. The 2030 Agenda sets forth 17 Sustainable Development Goals (SDGs) and 169 more specific targets to be met by 2030, encompassing economic, environmental, and social dimensions [1]. The implementation of the 2030 Agenda has posed one of the greatest challenges since the creation of the UN for all its member countries. Despite substantial collective efforts over the past years, achieving the 17 SDGs remains uncertain, since none of the goals is presently on track to be globally reached by 2030 [2]. Even as the international community is committed to accelerate attaining progress on all SDGs over the remaining 6 years, a large gap is still to be bridged [2]. We argue that a stepwise approach is needed that steers sustainable development for the short-, medium-, and long-term simultaneously, focusing thus not merely on 2030, but on 2040 and 2050 at the same time.

Acting as a guiding framework, the 2030 Agenda plays a pivotal role as a practical tool that countries can use to plan, develop, and execute strategies and actions for achieving progress on the SDGs. Since its launch, several methodologies for evaluating the advancement of the 17 SDGs and their 169 targets have been developed. Most of these methodologies

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have been applied to broad umbrellas of rather complex subjects, such as energy systems, climate adaptation, and infrastructure in the built environment [3–5]. The large breadth and coverage of the SDGs has necessitated the development of new evaluation methodologies that consider the specificities of different geographical scales (from local to regional, national, and global). Moreover, the interconnectedness of these scales must not be disregarded, and concrete sustainable development actions need to be coordinated and aligned across them. When a new global value chain is created, as is currently the case for green hydrogen, an opportunity presents itself to develop joint short-, medium-, and long-term sustainable development strategies at multiple geographical scales simultaneously.

Green hydrogen is an energy carrier produced through a process called electrolysis [6]. The electricity used for this process is generated from renewable sources, hence the term "green". Green hydrogen may transition from being a niche player today to becoming a widely adopted global energy commodity [7]. Some studies project that by 2050 approximately 12% of global energy demand could be met by hydrogen and its derivatives, with green hydrogen accounting for some two-thirds of the total hydrogen supply [8, 9]. Green hydrogen could thus play an important role in the energy transition, both replacing fossil fuels with a clean alternative and providing a means of energy storage [10]. Green hydrogen may become an essential decarbonization option for the energy system but also an important feedstock for sectors with hard-to-abate emissions, thereby critically contributing to national efforts to reach net-zero greenhouse gas emission targets by 2050 [10]. Despite the benefits that green hydrogen can yield, significant barriers need to be overcome for its widespread adoption, such as high production costs, lack of dedicated infrastructure, inconsistent or insufficient policies and regulations, elevated energy losses, and sometimes even ambiguous sustainability features [7]. Another point of attention is that the three main segments of the green hydrogen value chain (production, transportation, and end-use) are currently unevenly distributed across the globe [11]: countries with great potential for renewable energy generation have, in principle, the capability of producing green hydrogen on a large-scale and exporting it, while today typically quite different countries are developing high demand for green hydrogen [12]. The possible geographical mismatch between sites for green hydrogen production versus demand raises sustainability concerns along the entire value chain [13].

In this work, we analyze whether the green hydrogen value chain can aid in meeting the objectives outlined in the 2030 Agenda. Our Value Chain Assessment (VCA) methodology consists of five steps: (i) literature review; (ii) assessing direct and indirect influences; (iii) identifying positive and negative effects (green and red flags); (iv) analyzing dimensions of temporality; and (v) determining possible reciprocal interdependences. All these steps together enable a better understanding of the complexity of the entire green hydrogen value chain in relation to all sustainable development dimensions and allow for inspecting green hydrogen deployment against all 17 SDGs and their 169 targets. By disaggregating the value chain into three segments (production, transportation, and end-use), we obtain insight into the multiple sustainable development dimensions of adopting green hydrogen as an energy carrier and feedstock. We thus present a strategic framework that can aid in fostering the green hydrogen value chain for sustainable development, addressing the economic, environmental, and social aspects.

2 Literature review

The world economic landscape is intricately shaped by the integration of global value chains [14]. The complexity of the global value chain includes geopolitical dynamics, trade and investment policies, geographic scope, stakeholder interactions, and, with greater recent emphasis on the sustainability of the value chain [14–16]. The sustainable value chain also needs to be embraced by both the corporate world and public institutions, as it aligns more consistently with sustainability and the creation of shared value [17]. The incorporation of sustainability in the value chain introduces novel market dynamics, managed by sustainable business models, and geopolitical dependencies centered on energy security [18, 19]. However, the cost of supplying green hydrogen still depends on other factors such as renewable electricity prices, resource availability (water and land), and technological options [6]. Even though the best sites with high renewable energy potential do not guarantee the production of green hydrogen [10, 11, 13], many lower-income countries and potential green hydrogen producers will be compelled to export green hydrogen due to their inability to compete in the value-added segments of the value chains [18]. Besides that, recent studies highlight the need to provide stakeholders with insights that can influence investments in the hydrogen sector [20, 21]. Companies also require feasibility studies and cost–benefit analyses to establish and adopt green hydrogen [20, 21]. As the green hydrogen value chain is primarily influenced by cost and technological advancements, analyzing the sustainability of the value chain becomes essential.

More recently, initial approaches to this interlink between hydrogen and SDGs have been investigated. Most articles exploring the relationship between green hydrogen and the SDGs primarily focus on only one specific segment of the value chain or sector, or assess the possible integration of green hydrogen with only one or two dimensions of sustainable development [22–25]. Other articles point to some of the benefits and risk factors of green hydrogen for sustainable development [13, 26]. However, these articles offer limited discussion on how to embed the entire value chain in the broader context of all sustainability dimensions. In relation to government publications, some countries have already released roadmaps outlining future perspectives on deploying the green hydrogen value chain. However, most cases do not mention how the green hydrogen value chain can help achieve the SDGs or clarify how to meet SDG targets according to local needs. In some cases, the SDGs are mentioned, such as in the case of Uruguay [27], or some issues linked to the social dimension, as seen in Australia [28].

3 Methodology and data collection

We develop a novel methodology, the Value Chain Assessment (VCA), aiming to identify sustainable strategies and implement measures to mitigate potential adverse effects in the value chain. In this instance, we apply this methodology to the green hydrogen value chain. Our VCA methodology can be applied to a broad range of other possible value chains, e.g. for different energy carriers or, alternatively, for energy technologies like renewable electricity generation or carbon dioxide capture and storage (CCS). The research is based on a deep investigation using both peer-reviewed articles and available grey literature. After an extensive literature review, we map the influences (direct, indirect or no influence/still unknown; positive or negative) of the deployment of green hydrogen on the three segments of its value chain. Our approach breaks down the green hydrogen value chain into production, transportation, and end-use. By disaggregating the value chain in this way, we obtain insight into the multiple sustainable development dimensions of the adoption of green hydrogen as an energy carrier and feedstock. The next two steps contribute to improving our comprehension of the complexity of the green hydrogen value chain in terms of temporality and across different geographical scales. The conceptualization of our methodology draws from, but substantially adapts and extends, the approach taken in two previous publications that applied similar assessments of infrastructure systems, respectively, ecosystems and socio-economic sectors, both in relation to the SDGs and their targets [4, 5].

3.1 Value chain assessment

Step 1—Review of Literature

We employ five steps in the literature review process: (i) selecting a database capable of systematically mapping the literature available on a given topic; (ii) searching for keywords connected to the topic (in our case, (green) hydrogen and SDGs), (iii) analyzing particular case studies concerning the production, transportation, and utilization of (green) hydrogen; (iv) searching specifically for SDG targets and (green) hydrogen; and (v) reviewing grey literature from international agencies and official government reports. Initially, our broad research resulted in 1522 articles. After applying two exclusion criteria and conducting several analyses, we selected and quoted 94 in the database (See Supplementary Material (T1, T2) for a detailed description of this review process).

Step 2—Classification of influences of segments of the green hydrogen value chain

We classify the influences as direct, indirect, or no influence/still unknown in each segment of the green hydrogen value chain (that is, production, transportation, and end-use) on all 17 SDGs and their 169 SDG targets.

- Assess for each of the 169 SDG targets:
  - Q1: Can one or more green hydrogen value chain segments directly influence the progress of the given target?
    - If 'Yes', classify it as "direct influence" and proceed to the next segment.
    - If 'No', does any publication provide evidence of an indirect influence of the green hydrogen value chain segment on the target?

- If 'Yes', classify it as "indirect influence" and proceed to the next segment.
- If 'No', the green hydrogen value chain segment is considered to have no influence or more knowledge is needed to identify a possible influence, hence classify it as "no influence/still unknown" and proceed to the next target.
- Proceed to Step 3.

Step 3—Classification of the positive or negative influence of the green hydrogen value chain segments

We classify whether the influences of the value chain segments on all SDG targets selected under Step 2 are possibly positive or negative. The outcome of this classification can act as either a green or a red flag.

- Assess for each selected green hydrogen value chain segment and SDG target classified under Step 2:
  - Q2: Is there published evidence that the selected segment of the green hydrogen value chain can have a positive or negative influence on the progress of the given target?
    - Select one of the options based on the literature review findings.
      - Proceed to Step 4.

Step 4—Classification of the dimensions of temporality of the green hydrogen value chain

Dimensions of temporality refer to the timing of when the green hydrogen value chain may have a possible influence on the progress of a given target. We analyze the impact of the green hydrogen value chain on the selected SDG target from Step 2, considering whether these effects will occur in the short-term (≤ 2030) or the medium- to long-term (> 2030).

- Assess for each selected SDG target from Step 2:
- Q3: Can the green hydrogen value chain influence the progress of the given target in the short-, or medium- to long-term?
  - Select one of the two options based on the literature review findings.
    - Short-term (≤ 2030); or
    - Medium- to long-term (> 2030);
    - Proceed to Step 5.

Step 5—Classification of the reciprocal interdependence among the segments of the green hydrogen value chain.

Reciprocal interdependence refers to the mutual and interconnected relationship between different segments of the value chain in their joint influence on individual SDG targets.

- Assess for each of the 169 SDG targets:
- Q4: Does reciprocal interdependence exist between each possible pair of segments of the green hydrogen value chain in meeting the SDG target?
  - A value of '0' is assigned, if there is no reciprocal interdependence between a pair of segments of the green hydrogen value chain in meeting the target.
  - A value of '1' is assigned, if there is reciprocal interdependence between a pair of segments in the green hydrogen value chain in meeting the target.
- End of the classification process.

3.2 Conceptual definition

We here describe the concepts used in our VCA methodology to clarify the rigor of our approach.

Direct influence: Direct influence occurs through a clear relationship between the green hydrogen value chain segments and the SDG target in terms of what the chain provides. Direct influence happens when there is an immediate connection between a segment of the green hydrogen value chain and the SDG target under consideration. For example, target 7.2 (increase the share of renewable energy substantially in the global energy mix) can be directly influenced by all the segments of the green hydrogen value chain, promoting the use of renewable energy. In terms of production, green hydrogen can offer scalability and flexibility in energy systems. In the case of transportation, green hydrogen can enable the storage of surplus renewable energy. In terms of end-use, adopting green hydrogen in industrial applications or as fuel for transportation can contribute to the increased use of renewable energy.

Indirect influence: Indirect influence occurs if one or more segments of the green hydrogen value chain can serve as a development vector for other fields or sectors, occurring through intermediate or secondary processes, effects, or interactions. For example, target 8.1 (sustain per capita economic growth in accordance with national circumstances) can be indirectly influenced by the production, transportation, and end-use of the green hydrogen value chain. The green hydrogen value chain has the potential to boost per capita economic growth by considering unique national circumstances.

No influence/still unknown: No influence/still unknown indicates that no direct or indirect influences on the SDG target were identified. For example, target 16.9 (provide legal identity for all, including birth registration) can neither be directly nor indirectly influenced by any of the green hydrogen value chain segments.

Different types of influences can affect a single SDG target. For example, while one segment can directly influence a given target, the other two segments may have an indirect influence or possess no influence at all on that target.

Positive influence (green flag): A green flag refers to the possible positive influence that the development, implementation, or advancement of the green hydrogen value chain can have on the progress of a given SDG target. For example, target 7.1 (ensure universal access to affordable, reliable, and modern energy services) can be positively influenced by the green hydrogen value chain by deploying renewable energy, producing green hydrogen for seasonal storage purposes, and replacing fossil fuels in cooking and heating applications.

Negative influence (red flag): A red flag applies when segments of the green hydrogen value chain still require improvement or demand careful attention in order for them to contribute to sustainable development. For example, target 7.3 (double the global rate of improvement in energy efficiency) may involve a negative influence from the green hydrogen value chain. The green hydrogen value chain still requires technological advancements to improve the efficiency of electrolysis, storage, and fuel cells so as to contribute effectively to progress for this target.

Dimensions of temporality: With short-term (≤ 2030), we refer to those influences of the green hydrogen value chain on the SDGs that are currently ongoing or set to commence until 2030 (with the possibility for these influences to persist in the medium- to long-term). With medium- to long-term (> 2030), we refer to influences of the green hydrogen value chain that undergo growing significance over time, encompassing activities such as strategic policy planning and gradual technological progress. In our case, part of the collected evidence is based on green hydrogen roadmaps of some countries and individual case studies. While each country may have its particularities, these analyses provide a general overview of temporality.

Value chain reciprocal interdependence: Reciprocal interdependence in the green hydrogen value chain means that different segments in the chain rely on each other locally and mutually influence one another. This dynamic pair-wise interplay often involves a feedback loop and implies a close interaction between the respective segments [29]. Awareness of reciprocal interdependence between value chain segments is crucial for exploiting and optimizing possible synergies between different dimensions of sustainable development. It involves recognizing how actions and decisions in one segment of the value chain can impact other segments and, ultimately, contribute to or hinder progress on individual SDG targets. In the case of the green hydrogen value chain, reciprocal interdependence refers to the fact that the target under consideration can only be effectively influenced by simultaneously combining two or more segments. For example, SDG 2 (zero hunger) target 2.3 (double the agricultural productivity and incomes of small-scale food producers) involves reciprocal interdependence only between the transportation and end-use segments, following this explanation:

- Production + Transportation (0): While green hydrogen can have potential applications in several sectors, including agriculture, it is not a standard part of the agricultural value chain, and its transportation is generally not directly tied to agricultural productivity.

- Production + End-use (0): The production or end-use of green hydrogen in agriculture does not directly influence agricultural productivity or income in the same way as, for example, access to better seeds or farming practices.
- Transportation + End-use (1): Transportation infrastructure can influence the availability and cost-effectiveness of green hydrogen end-use for agricultural applications.

In other words, local deployment of only the transportation segment of the green hydrogen value chain does not ensure its influence on the progress of the target unless it receives effective support and collaboration from the end-use segment, and vice versa.

Green hydrogen value chain: The green hydrogen value chain consists of a series of interconnected parts and encompasses the entire process of generation, processing, storage, transportation, and utilization [30]. The value chain for any product or energy carrier can relate to sustainable practices, social aspects, and environmental considerations in each segment. In our case, we divided the green hydrogen value chain into three segments: production, transportation, and end-use. By analyzing each segment separately, we can maximize the benefits and mitigate the adverse effects of the green hydrogen value chain in promoting sustainable development. The use of green hydrogen as feedstock, such as for green ammonia production, is also taken into consideration in this study.

- *Production:* The production segment involves generating green hydrogen through electrolysis, which involves splitting water into hydrogen and oxygen using electricity from renewable energy sources such as solar or wind power [31]. Our study also considers the infrastructure required for green hydrogen production, including electricity, renewable energy sources, and water.
- *Transportation:* The transportation segment encompasses storage, transportation, and infrastructure. Storage methods include compressed hydrogen gas, liquid hydrogen, or solid-state hydrogen storage technologies. Green hydrogen can be transported through pipelines, shipping, or other means of transportation, such as trucks or trains. Infrastructure refers to the facilities and systems required for distributing and supplying green hydrogen [32].
- *End-use:* The end-use segment involves using green hydrogen in various applications, such as fuel cells for electric vehicles, power generation, industrial processes, or as feedstock for the production of synthetic fuels or chemicals [32, 33].

3.3 Limitation of analysis

The current literature predominantly focuses on the techno-economic aspects of green hydrogen, while more limited attention is given to the social and environmental aspects of its entire value chain. This raises concerns regarding the implementation of the green hydrogen value chain with all dimensions of sustainable development. When assigning either green or red flags, we choose either the one or the other qualification, based on the majority of findings reported in the reviewed articles and grey literature. As new studies are published and the deployment of the green hydrogen value chain progresses, all possible influences of the green hydrogen value chain on the SDG targets should regularly be reassessed, in order to account for new insights published in the public domain. Such reassessments may alter our green and red flag assignments. In addition to updated literature reviews, repeated analysis can also include the use of new indicators and/or revised methodologies.

4 Results and discussion

Since green hydrogen is broadly recognized as a key element in achieving a low-carbon energy future, one associates it automatically with SDG 7 (affordable and clean energy). However, a wide range of direct and indirect influences exists between each green hydrogen value chain segment (production, transportation and end-use) and the remaining SDGs. These influences can involve either positive (green flag) or negative effects (red flag), and they may be subject to change as the development of the green hydrogen value chain proceeds. Figure 1 illustrates the main outcome of our analysis in which we assessed the extent to which the segments of the green hydrogen value chain influence sustainable development in terms of the 169 targets of the 17 SDGs. As one can see, based on our extensive review of the literature to date, for each of the 17 SDGs, we find at least one segment of the green hydrogen value chain that the SDG is influenced by (either directly or indirectly, positively or negatively), altogether involving 61 out of the 169 SDG targets. There are 41 SDG targets that are jointly influenced by each of the three segments of the value

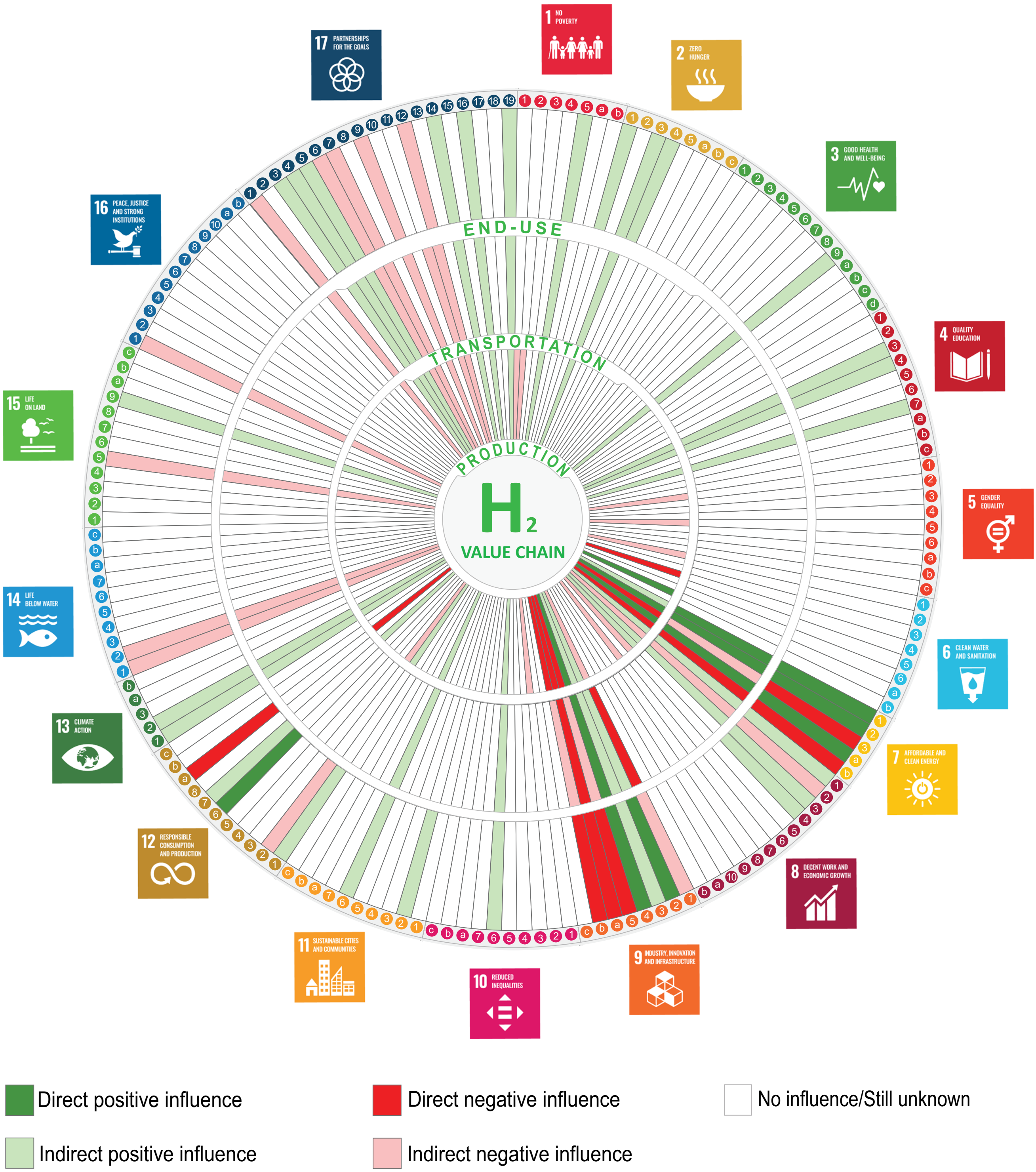

Fig. 1 The influence of the green hydrogen value chain on meeting the targets of the SDGs. Each SDG is subdivided based on the number of its targets. For each target, we conducted an assessment to determine a possible direct influence, which is either positive (in bold green) or negative (in bold red), indirect influence, which is either positive (in light green) or negative (in light red), or no influence/still unknown (indicated in white). Each assessment covers the three segments of the green hydrogen value chain: production, transportation, and end-use (viewed from the center outward) [52]

chain. In SDGs 7, 8, 9, and 17, over half of the targets are influenced by at least one segment of the green hydrogen value chain. The SDGs with the largest number of direct influences from the segments of the green hydrogen value chain are SDGs 6, 7, 9 and 12. Across the overall count of segments that have an influence on a SDG target (149 in total, with, in principle, 507 possible influences), there are about four times as many indirect influences (119) as direct ones (30), particularly the SDGs 4, 8, and 17. Given that indirect influences arise when one or more green hydrogen value chain segments function as vectors for (positive or negative) development in other sectors or fields, decision-makers should view them as potential opportunities to achieve sustainability-related outcomes.

In cases of a positive influence, we identify a correlation between the value chain segment and the SDG target, hence a commitment to sustainable practices from green hydrogen deployment. Conversely, in the case of a negative influence, we find that one has to be alert and—if possible—implement mitigation strategies to offset potential adverse effects stemming from the deployment of green hydrogen. We classify 86 influences as being positive (14 direct and 72 indirect), while the remaining 63 influences are negative (16 direct and 47 indirect). The strong green and red flags are concentrated in four main SDGs 6, 7, 9 and 12. The strong positive effects can be identified in the access to energy services, increase in the use of renewable sources, and promotion of international cooperation to align with clean energy. The high number of negative influences highlights a substantial impact of the green hydrogen value chain in the SDGs, which prompts concerns regarding the utilization of green hydrogen. These negative effects primarily concentrate on aspects such as the exploration and management of natural resources (e.g., water and raw minerals), dependence on technology transfer, development of new infrastructure, and prioritization of foreign interests over local needs. By focusing on higher energy efficiency, for example, we can enhance resource utilization, drive technological advancement, foster infrastructure development, and reduce environmental impact in the green hydrogen value chain, thus avoiding negative effects.

By integrating our analysis of direct and indirect influences with that of positive and negative effects, we identify in the three following paragraphs some benefits and challenges that each segment of the green hydrogen value chain presents for meeting the SDGs:

- *Production:* Green hydrogen production either directly or indirectly influences all 17 SDGs, involving 57 of the 169 targets. The production segment is responsible for influencing 4 targets in a direct positive, 25 in an indirect positive, 7 in a direct negative, and 21 in an indirect negative way. Green hydrogen production can boost investments in renewable energy, thereby contributing to the immediate progress of SDG 7, especially in developing countries [12]. However, potential conflicts, such as those related to land acquisition and a lack of strategies for reinvesting project revenues within the local community, must be resolved and mitigated prior to the deployment of renewable energy projects (SDGs 15, 16) [34]. Dependence on critical minerals, such as platinum and iridium, can impact the scaling up of electrolysis, while also posing risks associated with land exploitation (SDGs 7, 9, and 15) [35–37]. Green hydrogen production can spur investments, create funding opportunities and partnerships, and stimulate diplomatic efforts (SDG 17) [38, 39]. In addition, collaborations (North–South, South-South, and triangular) may bolster capacity-building for integrating climate mitigation measures into the energy policies of developing nations (SDGs 13 and 17) [38, 40]. There is a risk that importing countries may simply externalize their carbon-intensive activities to exporting nations, for example (SDG 13) [24]. Green hydrogen producing countries must invest in local technology development and education to mitigate the risk of losing out on domestic economic benefits, including opportunities for local job growth and addressing possible gender wage gaps (SDGs 1, 4, 5, 8, and 10) [22, 41]. Additional risks associated with green hydrogen production center around water demand and security (SDG 6) [42, 43].
- *Transportation:* Green hydrogen transportation either directly or indirectly influences 14 SDGs, involving 42 of the 169 targets. The transportation segment influences 4 targets in a direct positive, 21 in an indirect positive, 3 in a direct negative and 14 in an indirect negative fashion. Green hydrogen transportation can benefit the energy system by enabling seasonal storage and addressing the intermittency challenges of renewable energy sources (SDG 7) [44]. However, it requires a robust infrastructure, involving significant investments in pipelines, storage facilities, and transportation networks (SDG 9) [39, 45]. Besides that, the infrastructure directly influences the local and cross-border production and end-use of green hydrogen, and green hydrogen transportation still requires a sustainable and robust infrastructure, with significant investments in pipelines, storage facilities, and transportation networks. The deployment, maintenance, and upgrading of infrastructure also play a key role in diversifying trade, stimulating international cooperation, and integrating different energy sectors (SDGs 7, 9, and 17) [39, 46]. Nevertheless, a significant concern arises in the context of determining the boundaries for emissions accountability and the possibility of fugitive emissions, mainly during the transportation phase of green hydrogen (SDGs 13, 14, and 17) [47].

- *End-use:* Green hydrogen end-use either directly or indirectly influences 14 SDGs, involving 50 of the 169 targets. The end-use influences 6 targets in a direct positive, 26 in an indirect positive, 6 in a direct negative, and 12 in an indirect negative manner. Green hydrogen end-use and its use as feedstock have the positive potential to enhance agricultural productivity, decrease the reliance on food and fertilizer imports, enhance land quality, avoid soil degradation, and facilitate the adoption of local sustainable agricultural practices (SDGs 2, 12, and 15) [48, 49]. Also, the use of green hydrogen can be an optimal strategy for decarbonizing hard-to-abate emissions in certain sectors, such as the steel industry and heavy transport (SDGs 3, 7, 9, and 11) [18]. Green hydrogen can not only make a significant contribution to climate change mitigation, but also improve air quality in cities through governmental strategies aiming at increasing sustainability (SDGs 3, 11, and 13) [50]. Green hydrogen can also directly and positively influence the residential sector by substituting fossil fuels in cooking and heating applications (SDG 7) [12, 51]. Hydrogen production and transportation segments can yield direct benefits, especially in facilitating sustainable energy services for the end-user. However, challenges related to a new infrastructure and public acceptance may become negative factors if not addressed effectively.

The urgent need for immediate actions to reach the SDGs by 2030 has spurred numerous studies dedicated to developing methodologies for tracking and evaluating their implementation [2]. However, we argue that this short-term perspective needs to be complemented by a view with a horizon deeper into the future. Developing also medium- and long-term pathways for attaining the SDGs is essential not only for guiding decision-makers and explaining to the public, but also for enabling sustained action that ensures the ultimate achievement of sustainable development in its entirety, especially when some SDGs prove unreachable in the short-term. In the case of the green hydrogen value chain, direct and indirect influences with positive or negative effects on long-term sustainability may emerge, for instance depending on the pre-existing socio-economic context, geographical scale, and the local implementation of either specific segments or the entire value chain [13]. In Fig. 2, with our analysis we find that, for 47 of the 61 selected targets, green hydrogen deployment can influence the progress of sustainable development when taking a short-term perspective (i.e. over the period ≤ 2030), while an additional 14 targets are influenced when taking a medium- to long-term view (> 2030). Our findings demonstrate the timing of when the green hydrogen value chain may possibly influence the progress of any given SDG target. In terms of the segments of the green hydrogen value chain, in the short-term 20% of the influences are direct and 80% are indirect, while in the medium- to long-term 15% are direct and 85% indirect (See the numbers

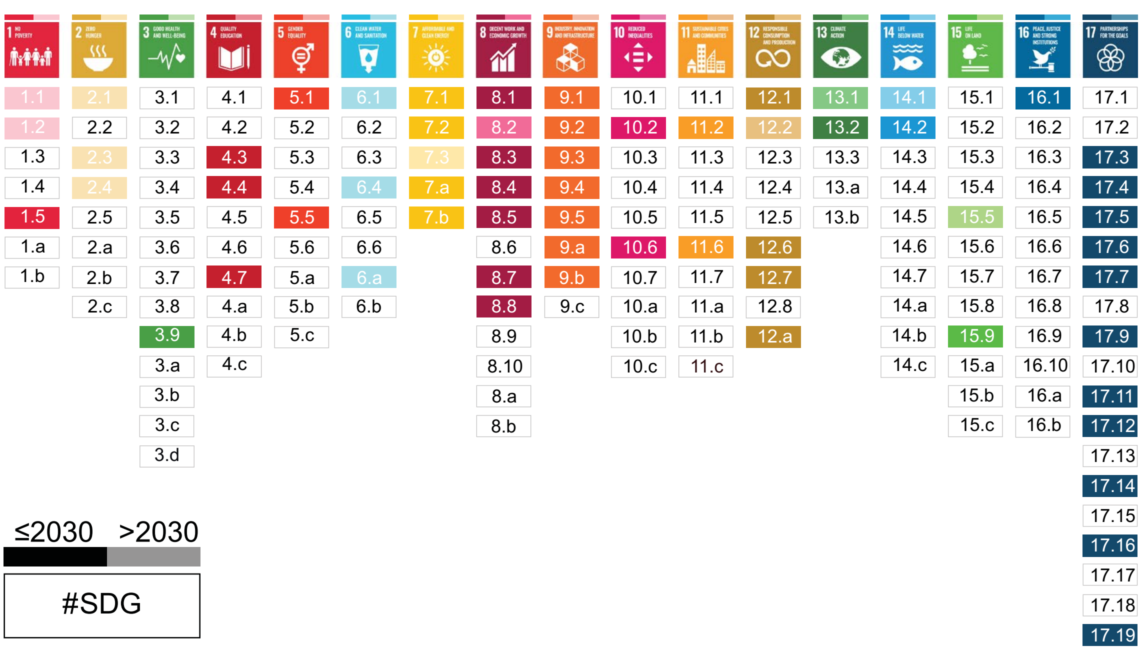

Fig. 2 Dimensions of temporality of the influences on the SDG targets from the green hydrogen value chain. The numbers refer to the respective SDG targets, while short-term influences are indicated in bold, and medium- to long-term ones in light colors. Short-term refers to ≤ 2030, and medium- to long-term corresponds to > 2030 [52]

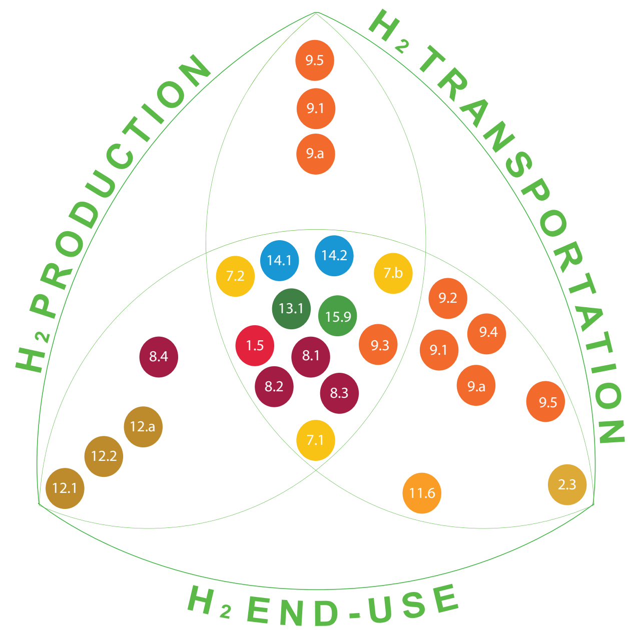

Fig. 3 Reciprocal interdependences between the segments of the green hydrogen value chain in relation to SDG targets. Three kinds of pairs of segments exist: production + transportation, production + end-use, and transportation + end-use

in the Supplementary Material, T4). Whereas positive effects represent the majority in the short-term (66% positive and 34% negative), negative influences become more evident in the medium- to long-term (33% positive and 67% negative).

Green hydrogen can primarily impact the progress of the SDGs 7, 8, 9, 12, and 17 in the short-term. Integrating different sectors, the green hydrogen value chain can provide a more diversified trade and sustainable industrialization route. Additionally, this value chain can directly promote the development of sustainable business models and incentivize companies to invest in clean technologies and practices. While the green hydrogen value chain is underway, its development tends to be prioritized with a focus on the hydrogen economy. This stagnates the possible progress that can be made on sustainable development, despite the potential of the green hydrogen value chain to contribute. In the short-term, with well-targeted investments and policies from the outset of the deployment of the green hydrogen value chain, SDGs related to education, gender and equality can be strongly impacted. In the medium- to long-term, two SDGs stand out as having negative effects: SDGs 1 and 6. SDG 1 is highly influenced by the progress made in other SDGs. For example, the positive development of SDGs 7, 8, 9, and 12 can directly impact poverty reduction efforts by creating economic benefits and job opportunities domestically. In the case of SDG 6, water availability remains a critical concern for some green hydrogen-producing countries. Countries exporting large-scale green hydrogen need to develop strategic water management plans and implement measures to mitigate the potential negative ecological impacts of water use in the medium- to long-term [53].

We introduce the concept 'reciprocal interdependence' to express that often close pair-wise interconnections exist between segments of the green hydrogen value chain that contribute to meeting SDGs. This term is used to describe a scenario in which a pair of segments jointly influences a specific SDG target. Efficiently managing such reciprocal interdependences can be particularly instrumental for accelerating progress on reaching SDGs. The reciprocal interdependence may vary depending on specific circumstances, such as the regional context, or the strategy employed by a country to develop the green hydrogen value chain. This analysis underscores the importance of countries being considerate of the potential impact when deploying individual segments of the green hydrogen value chain to achieve specific SDG targets. As can be seen in Fig. 3, 12 targets require the reciprocal interdependence of three pairs of segments for progress towards the corresponding SDG. The pair of segments consisting of production and end-use is the most frequently present among the targets (46 times) and exhibits 16 instances of reciprocal interdependence between the segments in the pairs. The segments production and transportation are present 42 times and need to be linked 15 times in a reciprocal interdependence in order to influence the corresponding targets, while transportation and end-use are observed 41 times, and need to be connected 19 times in order to have a SDG effect. SDGs 7 and 8 include the highest number of targets with reciprocal interdependence between all three pairs of segments, while SDGs 9 and 12 present the highest number of targets with reciprocal interdependence between only one or two pairs of segments. These four SDGs (7, 8, 9, and 12) jointly constitute some of the most urgent challenges confronting the development of the green hydrogen value chain, which we consider require immediate action. Many of the countries with the potential for large-scale green hydrogen production are situated in the global south, and they are often prioritizing exports over domestic end-use of green hydrogen. Such exports only become meaningful if domestic green hydrogen production is matched by demand for it in countries in the global north, which demonstrates the importance of international coordination and collaboration. Also, deploying just one or two segments of the green hydrogen value chain can negatively impact the progress of individual SDG targets, which underscores the importance of considering value chain segments collectively when planning strategies or formulating policies.

Our analysis provides directions for how to unlock the green hydrogen value chain for sustainable development. Depending on where and how green hydrogen is developed, it could yield both beneficial and adverse impacts on sustainable development that need to be investigated further. Implementing value chains, for example in the field of energy, may appear as linear processes, but in fact, there are much more intricate phenomena in reality. Each value chain is singular and demonstrates varying degrees of complexity [29]. Economic factors have thus far predominantly driven the implementation of the green hydrogen value chain, whereas environmental and social aspects have been marginalized in essentially all of its three segments. Figure 4 presents a concise strategic framework that indicates instances when the segments of the green hydrogen value chain are strongly linked to the dimensions of sustainable development. These thus demand special attention. This guide provides directions for stakeholders and decision-makers to assist them in

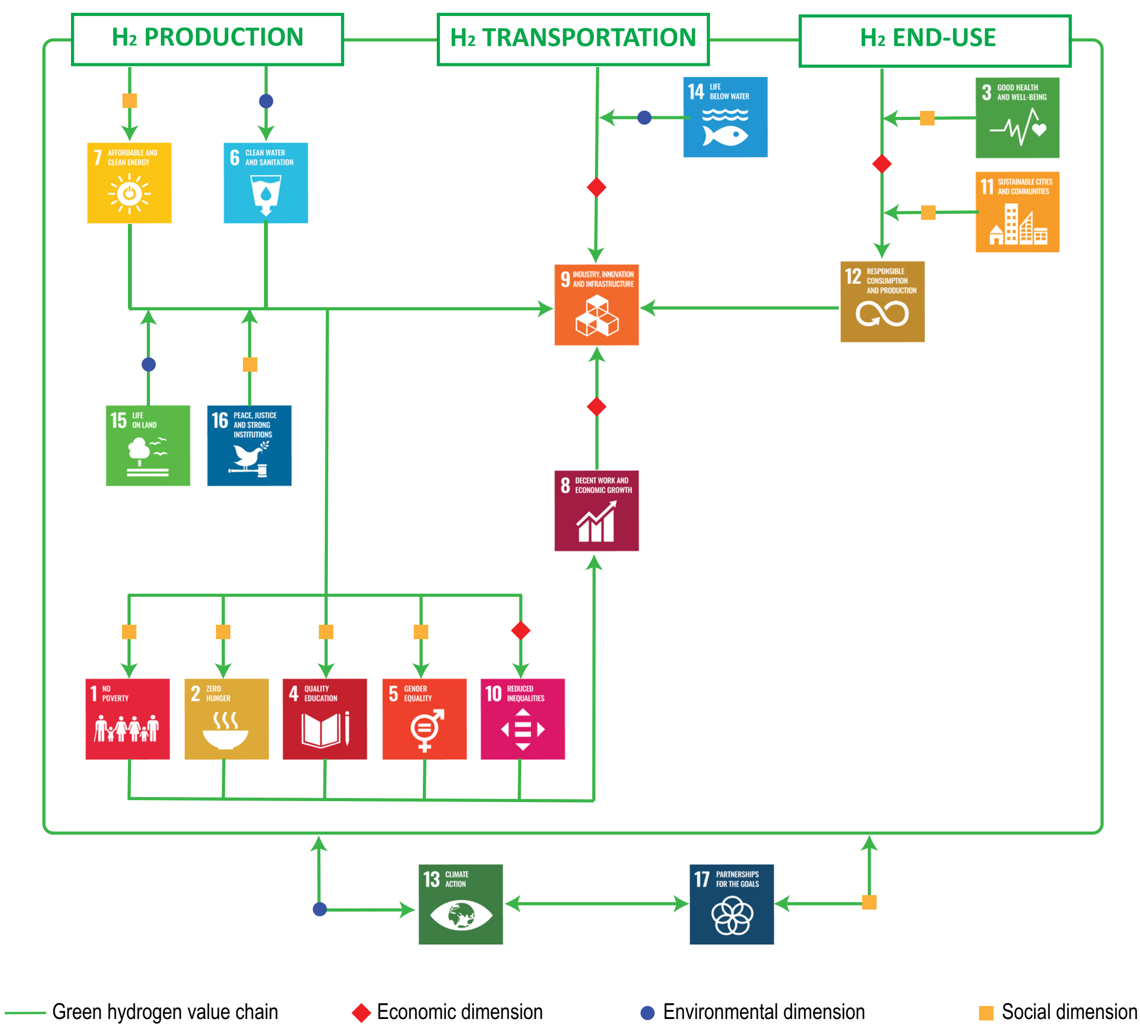

Fig. 4 A strategic framework to unlock the green hydrogen value chain for sustainable development. The red symbols represent the economic dimension, the blue ones the environmental dimension, and the yellow ones the social dimension. The connection between the green hydrogen value chain segments and the SDGs are denoted by green lines [52]

comprehending how to optimize—segment by segment—the green hydrogen value chain to meet sustainable development, guided by the 17 SDGs.

Despite cost competitiveness being a determinant factor in the selection of suppliers for green hydrogen production, the principal challenges to sustainable development lie in the environmental and social spheres in the case of the production segment. In the case of investments and policies for green hydrogen production in developing countries, interests from foreign entities may be prioritized over those of local communities, which could worsen inequalities and hinder poverty reduction efforts [24, 34]. Countries with significant potential for green hydrogen production ideally establish robust connections with all possible SDG dimensions at the local scale, including e.g. investments in the domestic market and technological innovation [39]. As hydrogen production levels advance, it is crucial to also consider environmental factors, especially water availability and usage; this holds particular significance for countries with large renewable energy potential but constrained access to water. Challenges may arise when water used for the production of green hydrogen competes with that employed in other sectors, especially in regions facing water scarcity or stress [53, 54].

The transportation segment of the green hydrogen value chain is intricately linked to both economic and environmental dimensions, requiring sustainable infrastructure. Transnational maritime commerce for green hydrogen has the potential to redefine the landscape of global energy trade and fundamentally transform geopolitical dynamics [19, 55]. Green hydrogen value chain certification can also avoid certain geopolitical uncertainties [33]. In both the segments of transportation and end-use, green hydrogen has sustainability impacts on urban infrastructure [50]. The segment of green hydrogen end-use is closely tied to both economic and social dimensions of sustainable development, since it necessitates the adoption of sustainable practices throughout society. Economic growth is intrinsically linked to increasing job opportunities and expanding access to education. However, deploying a new or only one segment of the green hydrogen value chain can give rise to social risks, such as an increase in child labor or a widening of the gender wage gap, mainly in developing countries [24]. Further investigation is required regarding consumer acceptance of green hydrogen, particularly in the context of deploying large-scale infrastructures for each segment of the green hydrogen value chain [56].

All sustainable development dimensions are inherently connected, and their interrelation must be internalized when implementing each segment or even the entire green hydrogen value chain in different locations. As we show in this work, to accelerate progress on achieving the SDGs and, at the same time, promote the sustainable development of the green hydrogen value chain, the latter needs to be inspected with careful attention to the singularities of each segment. The presence of reciprocal interdependences confirms this observation, as they may serve as catalysts for the promotion of sustainable development at the local level. Internalizing reciprocal interdependences enables maximizing synergies between the green hydrogen value chain and sustainable development while minimizing possible trade-offs throughout the entire value chain.

5 Conclusions

In conclusion, green hydrogen can have a relevant role in the progress of the SDGs and, in some cases, accelerate the progress of specific SDG targets, mainly to 2030. However, as with any new value chain, green hydrogen can face challenges and negative effects, particularly regarding its medium- to long-term sustainability. New investments, financial support, public policies, or other incentives provided by governments or companies for green hydrogen deployment can foster collaborative efforts to meet the SDGs. This highlights that the sustainable implementation of the green hydrogen value chain demands investments and policies that are synchronized over space and time. Additionally, each segment of the green hydrogen value chain introduces local complexities related to meeting the SDGs, and their deployment requires strategic planning to ensure optimal integration and effectiveness within the broader sustainability framework.

The VCA methodology identifies the complexity of the emerging green hydrogen value chain and can serve as an instrument for aiding in reaching the SDGs. In addition, this methodology can provide mitigation strategies by segment to offset potential adverse effects arising from the implementation of the green hydrogen value chain. The main outcomes of applying this methodology can support policymakers and stakeholders in addressing the uncertainties associated with the sustainability of the green hydrogen value chain, and contribute to meeting the targets of the SDGs. Establishing this new value chain offers a unique opportunity to build a more sustainable future, which contrasts starkly with the way in which fossil fuels were launched into the world economy since the Industrial Revolution. The massive diffusion of the use of fossil fuels constitutes an important lesson from history, the pervasive negative consequences of which should not be repeated.

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Data availability The data supporting the findings reported in this study can be found in the Supplementary Material (T1, T2, T3 and T4).

Declarations

Competing interests The authors declare no competing interests.

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