



Review article

Implementation factors for green hydrogen projects: A systematic literature review

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ABSTRACT

The global transition to a low-carbon economy relies on the large-scale deployment of green hydrogen as a clean energy carrier and industrial feedstock. Despite numerous project announcements worldwide, actual implementation remains limited. Accordingly, it is necessary to systematically analyse the critical factors influencing the practical deployment of green hydrogen projects. To this end, the paper conducts a systematic literature review examining the factors that determine green hydrogen project implementation success, analyzing 153 academic publications and key reports from IRENA and IEA. The systematic literature review identifies that the implementation of green hydrogen projects hinges on a complex interplay of techno-economic, site-specific resource, economic, and socio-political factors. Notably, there are significant global disparities, which are particularly evident for developing and least developed economies, often relying on international financing, technology transfer, and strategic partnerships. These disparities are also reflected in the academic landscape, where research predominantly focuses on advanced economies and major emerging markets.

Introduction

Human well-being depends on a global turnaround towards a profound and rapid reduction of greenhouse gas emissions in all sectors, according to the sixth Intergovernmental Panel on Climate Change (IPCC) [1] report. Hydrogen is recognized as one cornerstone of a decarbonized society, since the molecule can serve both as a key energy carrier and feedstock for industrial processes, while offering the potential for low-emission production and use.

Nowadays, the dominant industrial process for hydrogen production is steam cracking of fossil resources, accounting for approx. 99 % of the total production volume of 97 million tonnes (Mt) in 2023 [2]. However, steam cracking in its present form is connected to significant carbon emissions. Consequently, different hydrogen production routes are under consideration by practitioners, academics, and policymakers in pursuit of emission reduction and enhanced sustainability.

Low-carbon hydrogen encompasses both, hydrogen production using renewable energy as well as fossil sources combined with carbon capture technologies. Among these two options, only hydrogen generation based on renewable energy – also known as green hydrogen – can serve as a truly sustainable process due to its low lifecycle emissions [3].

Nations worldwide have therefore announced ambitious green hydrogen strategies, with potential exporting countries leveraging their renewable energy resources and importing countries planning to meet their decarbonization goals through hydrogen [4]. Despite rapidly expanding project announcements, recent evidence [2] suggests that there is still a significant gap between ambitions and actual project realization. Only a fraction of announced global green hydrogen projects has reached final investment decision, with several projects being cancelled or delayed in 2023. Hence, green hydrogen production remains very limited in scope, with a global volume of less than 0.1 Mt in 2023 [2].

Implementation progress also varies regionally: while different countries in Europe, Latin America, the Middle East and China could advance some of their projects to maturity or final investment decision, most projects in Africa remain in early development stage [2]. So far, the factors that lead to such differing regional capabilities to execute hydrogen projects have not been investigated comprehensively.

Researchers have approached green hydrogen project implementation from several perspectives. Techno-economic studies have examined different project configurations, focusing on factors such as production costs of different locations [5], plant scaling [6], and optimizing size

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ratios between renewable energy sources and electrolyzers [7]. Locational analyses [8–10] have evaluated site-specific conditions including water availability, land resources, and critical infrastructure access. Other studies approach green hydrogen from a political perspective and have assessed national policies’ effectiveness in promoting green hydrogen economies [11–13], while social science research has investigated public and consumer acceptance [14,15]. Additionally, broader market analyses [16–18] have explored potential risks, opportunities and barriers in different regional contexts.

Nonetheless, current research lacks a comprehensive overview, integrating these diverse aspects – technical, economic, social, and political factors – into a cohesive analysis of green hydrogen project implementation. This gap hampers political stakeholders’ and project developers’ ability to effectively plan and execute successful green hydrogen initiatives, as project success depends on the interplay of these various factors rather than any single dimension.

To address this gap, this study follows two primary objectives: (1) to create an overview of the existing literature corpus on factors impacting green hydrogen project implementation, and (2) systematically review this existing literature to identify, examine and structure these factors. Thereby this study provides stakeholders a structured approach to evaluate and improve the conditions for green hydrogen project implementation, while advancing scholarly understanding of the complex interrelationships between implementation factors.

Material and methods

Systematic literature review.

This study employs a systematic approach to literature review, inspired by Xiao and Watson [19]. The key steps of their framework are outlined in this section.

Database Selection and Search Strategy.

The first step of the framework of Xiao and Watson [19] entails the database selection and defining the search strategy. Scopus was selected for this review due to its position as the largest abstract and citation database, offering comprehensive coverage of scientific literature across various disciplines. It encompasses scientific journals, conference proceedings, and books on both global and regional levels [20,21], making it an ideal resource for this review.

To ensure a focused and relevant search, the following Boolean search string was employed: (green hydrogen OR low carbon hydrogen) AND (economy OR industry OR project) AND (challenges OR opportunities OR drivers OR barriers OR factors). This string was designed to capture literature pertinent to the research questions while maintaining a manageable scope.

To maintain consistency and accessibility, only English-language publications were included. Furthermore, the search was refined by excluding subject areas in Scopus that were clearly outside the scope of this research, such as Veterinary, Neuroscience or Psychology. The data cutoff date for this review was set at September 1, 2024 (09/01/2024).

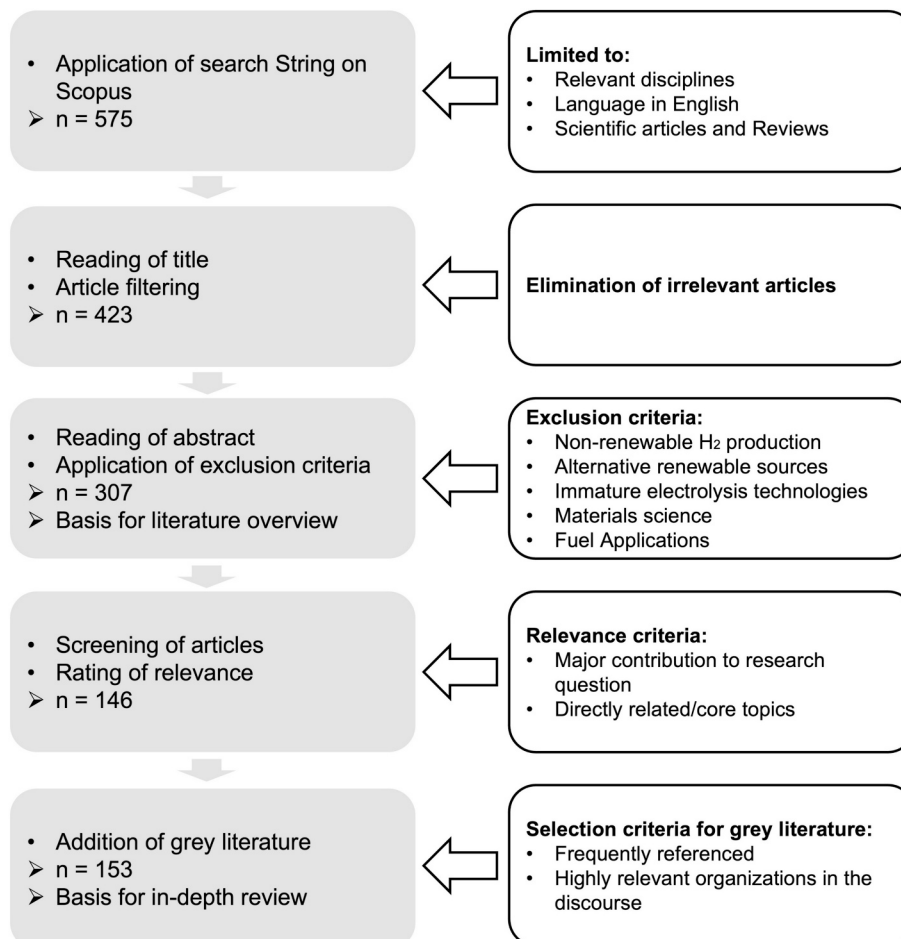


Fig. 1. Overview of the study selection process.

Study Selection Process.

The second step is the study selection process. This process is illustrated for this study in Fig. 1. The initial search using the specified parameters yielded 575 results. A multi-stage manual screening process was then implemented to identify the most relevant literature for this review. This process began with a title screening of all 575 results. For 423 articles whose titles suggested relevance to the research question, the abstracts were read.

During this screening procedure, a set of exclusion criteria was developed and applied. In line with the recommendations of Xiao and Watson [19], these criteria were ensured to be practical, capable of effectively classifying the research, and reliably interpretable. 116 studies that met one or more of the following criteria were excluded:

- Focus on hydrogen production from non-renewable resources
- Hydrogen production methods using renewable sources other than wind and solar power. This focus reflects the current dominance of wind and solar technologies in industrial-scale green hydrogen implementation discussions and their superior cost-effectiveness, sustainability and/or availability compared to other renewable energy sources for large-scale applications [22,23]
- Studies examining water splitting technologies beyond Alkaline Electrolysis (AEL), Proton Exchange Membrane Electrolysis (PEMEL), and Solid Oxide Electrolysis (SOE). Although PEMEL, AEL, and SOE technologies are not all fully available at industrial scale, their technological readiness and suitability for industrial-scale green hydrogen projects is significantly higher than alternatives (such as thermochemical or photocatalytic water splitting).
- Detailed exploration of materials science and catalysis studies, including electrocatalyst development, membrane technologies, or novel materials for hydrogen production and storage
- Exclusive focus on hydrogen fuel applications and infrastructure such as fuel cell vehicles, aircraft fuels and/or refuelling infrastructure

The remaining 307 articles that were identified as potentially relevant were used for a broad overview analysis of the research landscape in section 3. In the next step, these articles were further screened in detail to assess their relevance to the research objectives. By excluding studies that focused exclusively on highly specific, addressed only peripherally related topics, or did not contribute significantly to the broader understanding of factors relevant to the implementation of green hydrogen projects, this further refined the selection to 146 articles. A comprehensive list of the research articles across the main phases of the study selection process is provided in Supplementary Table S1.

Although the review primarily utilized peer-reviewed research to maintain methodological standards, during the research it became evident that scholarly works frequently referenced grey literature, particularly reports from the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA). The inclusion of seven selected grey literature sources from these agencies was deemed necessary to adequately capture recent industry developments and policy considerations, despite the potential drawbacks in methodological rigor. This systematic approach resulted in the identification of 153 articles that formed the core dataset for the results section.

To provide comprehensive context for the research field, Section 3 presents a broad overview analysis of all 307 potentially relevant articles before focusing on the detailed examination of the 153 core articles in Section 4. This two-stage approach demonstrates the systematic methodology employed and helps readers understand how the final sample fits within the broader scientific discourse on green hydrogen implementation.

Structuring of factors by inductive category development

Qualitative content analysis was used on the selected articles to identify and extract factors influencing the implementation of green

hydrogen projects. To this end, MAXQDA, a scientific software allowing qualitative text analysis was utilized. This study employed an inductive category development approach [24] to organize and analyse the identified factors. Inductive category development involves a systematic process of reading through the data, identifying relevant concepts, and gradually forming these into categories and subcategories through comparison and refinement [25]. This method was chosen for its flexibility and ability to derive a structure organically from the data, rather than imposing a predetermined framework. The inductive approach allows for the emergence of themes and categories that are grounded in the specifics of the green hydrogen project context, ensuring that the results closely reflect the current state of knowledge in this field.

Overview literature corpus

Thematic analysis of literature

A broad overview analysis of all potentially relevant 307 articles was conducted to gain a comprehensive understanding of the general research landscape in green hydrogen project implementation. The analysis of the literature corpus reveals several prominent patterns in research focus and emphasis. The distribution of the primary research themes across the analysed articles is illustrated in Fig. 2.

The analysis reveals that technical and economic perspectives emerge as major themes in many publications. Approximately one-third of the reviewed literature (28 %, 87 articles) predominantly examines techno-economic aspects. Typically, these publications explore cost optimization pathways or conduct comparative cost analysis for different elements of the green hydrogen supply chain. Examples include techno-economic comparisons of production locations, green hydrogen transport and storage systems or the technical and economic viability of industrial use cases for green hydrogen.

Technical (25 %, 77 articles) and market-oriented perspectives (24 %, 73 articles) each emerge as primary foci in about a quarter of the publications of this literature review. Publications with technical orientation emphasize engineering solutions and technological processes, e.g. examining and comparing electrolysis technologies, reviewing industrial applications, and analyzing infrastructure requirements. Those studies with an economic/market focus mainly investigate market development pathways, various barriers and drivers for a green hydrogen economy, and market conditions in international, national or regional contexts. Many of these studies also touch upon technical, social or policy considerations to reflect the multidimensional nature of green hydrogen market development.

Policy considerations emerge as the major focus in 12 % (35 articles) of the publications. Typical themes identified include political strategies, regulatory frameworks and governance structures in different countries or regions as well as international relations. Environmental and sustainability considerations appear as the main theme in 8 % (25 articles) of the corpus, addressing life cycle impacts, decarbonization effects, and broader sustainability implications of green hydrogen production and applications. In some cases, these aspects are also discussed secondarily in technically focused papers.

A notable finding is the limited presence of research examining social dimensions of green hydrogen development, with only 3 % (10 articles) primarily focusing on social and socio-technical perspectives. These studies consider aspects such as public acceptance, workforce implications, and broader societal impacts of hydrogen technology adoption or green hydrogen projects.

Temporal and geographic distribution of articles

The temporal distribution of publications reveals a significant acceleration in research output, as illustrated in Fig. 3. While sporadic publications started to appear between 2006 and 2019, publication numbers increased markedly from 2020 onwards, with 125 articles

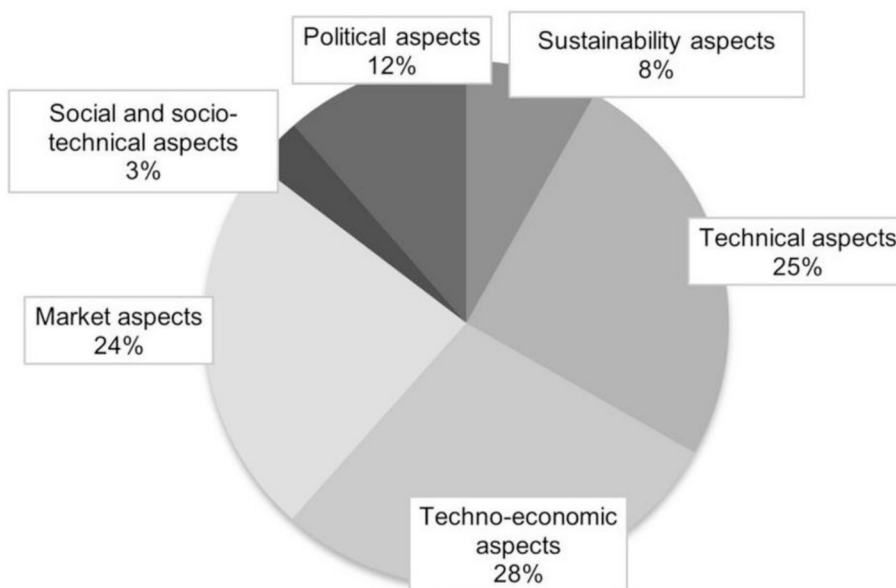


Fig. 2. Major research themes in the literature corpus.

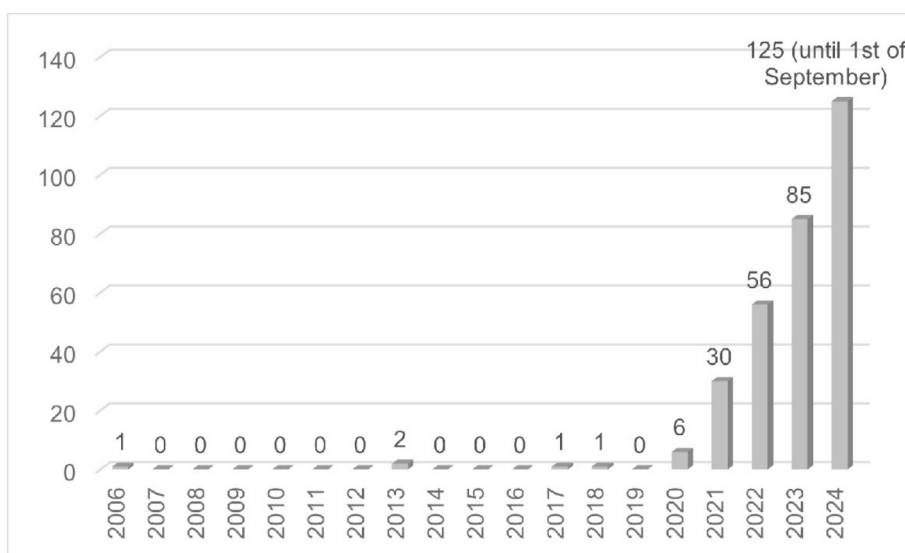


Fig. 3. Temporal distribution of the literature corpus.

published in the first eight months of 2024, compared to 85 in 2023 and 56 in 2022.

The examined literature corpus shows a global distribution of research focus as seen in Fig. 4, with a notable regional emphasis on Asia & Pacific (17 %) and Europe (18 %), followed by the Middle East and North Africa (MENA) region (9 %) and Latin America (5 %). Remarkably, only 3 studies (1 %) focusing solely on North American countries were published. Approximately 4 % of the studies in this review took a cross-regional and 43 % a global perspective (or results of the study were deemed relevant globally).

At the country level, Australia and China led with 5 % of the studies addressing each of the two countries, followed by India (4 %), Germany (3 %), the United Kingdom (UK) (2 %) and Brazil (2 %). Table 1 shows the distribution of studies across the 14 most examined countries.

As presented in Table 2, this analysis also reveals that studies specifically focused on emerging markets and developing economies (29.6 %) exceed those on advanced economies (19.5 %). However, there is a notably limited representation of Least Developed Countries (LDCs) in

the literature corpus with only one study each, comprising green hydrogen development in LDCs in the context of the Western African and Southern African region. Other studies within the emerging markets and developing economies group focus primarily on more economically advanced nations like China, India, Brazil, Chile or Saudi Arabia.

Results

Overview of identified factors.

This section presents an overview of project implementation factors, identified through the in-depth review of 153 articles. Fig. 5 illustrates these factors across two levels and five dimensions, with the hydrogen project level positioned at the center of the illustration and the project environment level surrounding it. The hydrogen project level focuses on the techno-economic dimension of hydrogen production, while the project environment level encompasses the site-specific resource, economic, public acceptance, and the political dimensions.

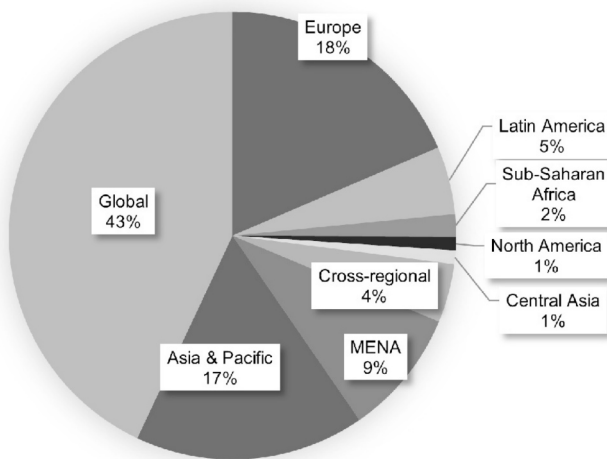


Fig. 4. Spatial distribution of research focus.

Table 1
Distribution of research focus across countries.

#	Country	Studies	%
1	Australia	16	5 %
2	China	16	5 %
3	India	11	4 %
4	Germany	10	3 %
5	United Kingdom	7	2 %
6	Brazil	5	2 %
7	Chile	4	1 %
8	Oman	3	1 %
9	Saudi Arabia	3	1 %
10	Spain	3	1 %
11	South Korea	3	1 %
12	Turkey	3	1 %
13	Portugal	3	1 %
14	Colombia	3	1 %
15	Rest of the world	217	71 %

Table 2
Distribution of studies across economic groups.

Category	Studies	Percent
Advanced Economies	60	19,5%
Emerging/Developing	91	29,6%
Across Economies / Global	156	50,8%

This analysis reveals that the techno-economic dimension fundamentally determines project viability, with production costs varying substantially based on technological choices and plant design. Key factors include hybridization of solar and wind energy, connection of the hydrogen production facility to the electricity grid, choice of electrolyser technology, scaling effects, and sizing ratios between renewable energy and electrolyser capacity. Furthermore, project implementation hinges on decreasing costs of the electrolysers and renewable energy equipment.

Regarding the project environment, the site-specific resource dimension incorporates several factors, emphasized by literature: The capacity factors of renewable energy sources, water availability, land requirements, underground storage options, and mineral resource deposits for value-added products such as green steel.

Considering the economic dimension, project implementation is significantly influenced by the distance to hydrogen offtakers, access to existing infrastructure such as natural gas pipelines and industry know-how. In terms of public acceptance projects depend on local communities' institutional trust, perceived risks and benefits, and consideration

of regional and local identity, necessitating public participation mechanisms.

Furthermore, the literature demonstrates that project success relies heavily on political and regulatory frameworks. National hydrogen strategies, implemented as concrete policies – in particularly market creation measures, tax credits and grants, and broader decarbonization efforts promoting fossil resource phase-out – emerge as essential factors. The reviewed studies emphasize the importance of international financing mechanisms, as projects in the Global South face distinct challenges due to higher financing costs and lower fiscal budgets. Project implementation also requires legal certainty, streamlined permitting processes, and harmonized standards across countries.

Project level: Techno-economic dimension of hydrogen production

Techno-economic aspects of the green hydrogen production process are subject to multiple studies of the examined literature corpus, since high production costs pose a significant barrier to green hydrogen project implementation. Primary cost drivers include capital expenditures (CAPEX) for renewable energy infrastructure and electrolysers, as well as operational energy costs [26,27]. The reviewed techno-economic studies reveal a wide range of Levelized Cost of Hydrogen (LCOH), currently spanning from 2.1 \$/kg [28] to 15 \$/kg [29]. The substantial variation of costs underscores the critical impact of plant and process design on economic viability.

The comparative analysis of Nasser et al. [26] on different renewable energy technologies found that LCOH varies in a wide range for wind and solar photovoltaic (PV), with slight economic advantages of solar powered systems over wind powered systems. However, it is important to note the optimal choice highly depends on the capacity factors of the renewable energy source at a given project location (see details in section 4.3.1.1.). Notably, hybrid use of solar and wind energy can enhance electrolyser utilization by providing more consistent energy supply [30,31]. Specific cost advantages of hybrid systems depend on various factors, including solar irradiance and wind speeds at specific locations, and the relative costs of solar, wind, and grid electricity [27].

Hydrogen production systems can be either off-grid (using only energy generated on-site) or on-grid (connected to the electricity grid). Grid connection offers several advantages: Facilities can sell excess renewable energy for additional revenue, cut costs due to better utilization of the electrolysers and the reduction of the installed renewable energy capacity [32], and operate electrolysers more continuously to extend their lifespan [33]. The economic benefits of grid imports depend heavily on electricity prices and purchasing agreements [34]. Grid-connected facilities can also leverage dynamic electricity pricing by producing hydrogen when electricity is cheap and exporting power (either from renewable energy plants or by generating power by utilizing hydrogen) during peak demand, thereby contributing to grid stability and flexibility as renewable energy adoption increases [35,36]. However, it needs to be ensured that electrolysers operate at least 5,000 full load hours per year to be economically viable [37].

The environmental impact of grid-supported hydrogen production depends significantly on the grid's emission factors, an aspect often overlooked in practical assessments, as highlighted by Garud et al. [32]. The potential utilization of grid electricity for hydrogen production is further influenced by regulations (such as the European Union (EU) Renewable Energy Directive), offtaker requirements and the evolution of certification schemes, particularly in their approach to carbon accounting. These factors collectively determine the framework conditions under which grid electricity can be employed in hydrogen production processes.

Regarding electrolyser technology, the reviewed literature identifies AEL and PEMEL as the dominant technologies, currently accounting for 60 % and 30 % of global capacity respectively [38]. AEL shows lower CAPEX compared to PEMEL, though PEMEL is projected to reach cost parity within the next decade [39]. Techno-economic studies of the

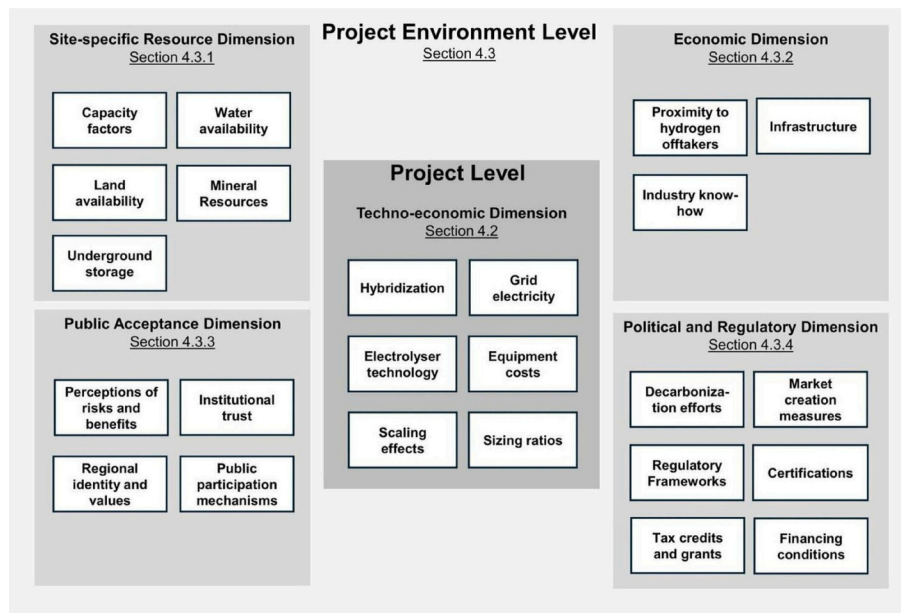


Fig. 5. Overview of project implementation factors.

literature corpus confirm this temporarily existing price advantage of AEL. For instance, Shin et al. [40] and Velasquez-Jaramillo et al. [41] report a lower LCOH for AEL in comparison to PEMEL for hydrogen production on the basis of onshore wind, offshore wind and solar PV.

Several studies of the reviewed literature [6,29,42] have demonstrated significant cost reductions associated with scaling up green hydrogen production. A study for Queensland, Australia [43], showed that LCOH could decrease by 49 % (from \$6.1/kg to \$3.1/kg) when scaling a PV-based plant from 10 megawatt (MW) to 1 GW (GW). Similarly, for wind-based plants, a 36 % reduction (from \$5.8/kg to \$3.7/kg) was observed for the same scale increase.

Furthermore, Marocco et al. [7] highlight the importance of optimal sizing ratios between renewable energy and electrolyser capacity. These ratios would vary in different locations based on local capacity factors, with areas of higher and more consistent renewable generation likely requiring less oversizing. The oversizing of renewable capacity is necessary to balance two competing factors: ensuring sufficient electrolyser utilization to justify its high capital costs, while maintaining efficient use of the renewable resources. Their scenario for Italy [7] indicates optimal ratios of 2.2 for PV plants, 2.8 for wind plants, and 1.6 for hybrid systems (for both wind and PV) relative to electrolyser capacity. The authors expect these ratios to decrease in the future due to projected reductions in electrolyser investment costs.

The economic viability of green hydrogen projects is intrinsically linked to the cost dynamics of key technologies, particularly electrolysers and renewable energy. Reviewed studies [38,44,45] project significant cost reductions for renewable energy and electrolyser technologies in the coming years due to technological advancements, economies of scale, and supportive policies. These declining costs are crucial for the widespread implementation of green hydrogen projects. The effects of economies of scale are evident in electrolyser manufacturing. Kenny et al. [27] indicate substantial price impacts, with the Levelized Cost of Hydrogen (LCOH) potentially reducing from 6.40 \$/kg to 1.37 \$/kg as manufacturing scales up and technological improvements are made. Conversely, the realization of these cost reductions depends substantially on the broader adoption of green hydrogen.

Project environment level

Site-specific resource dimension

Capacity factors of renewable energy resources. Critical determinants of economic viability are the capacity factors of the renewable energy sources [41,46]. Those factors are directly influenced by the consistency and intensity of wind or solar resources of the geographical locations of a project [28,47]. Higher capacity factors enable more efficient electrolyser operation and reduce idle time, thereby improving overall project economics [5].

This analysis shows that substantial variability in capacity factors has been observed across different sites. The reviewed literature reveals that variations in capacity factors can have substantial price implications to produce green hydrogen, observable at national [41,48,49], macroregional [47], and intercontinental [5,28] levels. For instance, Gomez et al. [28] found that production costs by 2030 could vary substantially between potential major exporters, ranging from 2.8 to 4.5 \$/kg in Chile to 4.1–4.9 \$/kg in Colombia, with variations primarily driven by electrolyser utilization rates and specific investment costs.

Water Availability. Multiple studies [8,9,30] of the reviewed literature have identified water as a critical factor, serving as a feedstock for electrolysis and as a process aid throughout the hydrogen production chain. Potential water sources include surface water (e.g., rivers, lakes, and reservoirs), groundwater, seawater, and wastewater [9]. Current electrolysers necessitate water purification regardless of the source, as impurities may cause irreversible cell damage [50].

From a techno-economic perspective, the costs associated with water purification and treatment processes such as desalination are negligible relative to overall hydrogen production costs, suggesting that the water source is not a significant economic factor. However, some scholars [8,9] indicate that proximity to a water source is an important economic consideration for green hydrogen projects, as long-distance water transport is deemed economically unfeasible. Specifically, Amrani et al. [9] established in their multi-criteria analysis of Morocco's Eastern region that areas beyond 150 km from the Mediterranean Sea were considered unsuitable for photovoltaic-powered hydrogen production units due to the economic constraints of long-distance water transport.

Water availability also impacts the sustainability of green hydrogen

projects since it may exacerbate water stress in arid and semi-arid regions. In the context of climate change and population growth, green hydrogen projects could potentially intensify resource competition among industry, agriculture, and local communities [51,52]. Over 70 % of global electrolyser capacity could be located in water-stressed areas, with 85 % of projects potentially relying on desalination plants for water supply [53].

Land availability. Land availability emerges as a critical determinant in the reviewed literature for hydrogen production, particularly concerning large-scale production facilities integrated with renewable energy infrastructure [51]. The land requirements of such facilities generate potential competition with alternative land uses, including agricultural activities and conservation zones.

This issue is especially pertinent in densely populated regions where land is already at a premium, such as in parts of India, Southeast Asia, Europe, Japan or South Korea [51]. Scholars [9,51] also highlight geographic and topographical limitations, specifically steep terrain gradients, which can render locations technically unsuitable for green hydrogen production facilities. Such spatial constraints can have significant practical implications for the global hydrogen economy [51], potentially necessitating the development of international trade relationships between regions with low land-availability and countries with comparatively high land availability.

Some authors [8,54] propose desert regions as potentially advantageous locations for large-scale hydrogen projects, offering both abundant solar resources and sparsely populated areas. However, historical precedents indicate that desert regions have frequently been subject to oversimplified characterizations as unoccupied territories, leading to inadequate consideration of indigenous rights and local ecological systems. Therefore, the implementation of extensive renewable energy infrastructure in these environmentally sensitive or deemed inhabited areas necessitates thorough evaluation of potential impacts on local ecosystems and communities as highlighted by [55,56].

Mineral resources. Mineral resources, such as iron ore, bauxite, and mineral sands, have been identified as potentially relevant factors in the literature for project implementation. Dagnachew et al. [52] suggest that the co-occurrence of mineral deposits with areas of high renewable energy potential may create advantageous conditions for green hydrogen production and industrial development. This could potentially facilitate the integration of green hydrogen production with mineral processing facilities. The literature [53,57] posits that such co-occurrence could offer logistical benefits and enhance value creation opportunities.

Examination of the literature corpus also reveals that hydrogen production equipment such as electrolysers, wind turbines or solar panels requires substantial amounts of critical minerals [58]. Current mineral extraction rates cannot meet projected electrolyser demand, with supply shortages expected as early as 2025 and growing more severe through 2050 [59]. This is particularly severe for PEMEL electrolysers, while alkaline electrolysers face comparatively less critical constraints due to their ability to use non-precious metals and greater flexibility in material substitutions.

Besides potential supply shortages, Eikeng et al. [59] highlight that a few countries dominate the supply of the necessary critical materials. For instance, South Africa emerges as a crucial supplier for PEMEL electrolysers, controlling 75 % of global platinum production, 82 % of iridium, 92 % of ruthenium, and 85 % of rhodium production. Hence, PEMEL electrolyser production will be dependent on one major supplier with limited alternatives in the near term. Other important exporters of critical minerals include China, Indonesia, Congo, Russia and Canada [59]. However, the examined literature corpus lacks evidence on how such dependencies and geopolitical supply dynamics might influence green hydrogen projects in certain locations.

Underground Storage Infrastructure. Underground geological formations, particularly salt caverns, depleted oil and gas reservoirs, and aquifers, present significant potential for large-scale hydrogen storage. Among these options, Quintos et al. [60] highlight salt caverns, demonstrating superior characteristics, including lower investment costs compared with other underground storage options, flexible withdrawal with minimal cushion gas requirements, exceptional impermeability, and rock salt's inert properties. Additionally, existing experience with natural gas storage in these formations can provide valuable operational insights.

The reviewed literature [61,62] shows that availability of suitable geological structures can significantly influence green hydrogen project viability, as underground storage represents the most economically viable solution for large-scale hydrogen storage, potentially reducing levelized costs through effective supply-demand management. For example, the techno-economic study from Schwartz and Menefee [63] reveals that the returns on revenue of wind farms can increase from approx. 8 % over a 30-year project lifetime to over 15 % when coupled with hydrogen production and underground storage.

However, the reviewed literature also shows that implementation challenges persist, including substantial infrastructure investment and the need for comprehensive technical, environmental, and socio-economic assessment as well as continued research and development for enhancing the feasibility of underground hydrogen storage [60,64].

Economic dimension

Proximity to hydrogen offtakers. This literature analysis reveals that proximity between green hydrogen production facilities and offtakers significantly influences project viability through its impact on transport mode selection and associated costs.

Hydrogen poses technical challenges for transportation and storage due to its relatively low volumetric energy density and low liquefaction temperature [65]. Consequently, hydrogen typically requires transformation into a carrier form through compression, liquefaction, conversion, or chemical/physical bonding to facilitate effective transportation and storage [66–68]. Additionally, hydrogen requires special safety measures due to its properties: it is odorless and colorless, has a wide flammability range (4–75 vol%), and a low ignition energy (0.02 millijoules) [62,69,70]. These properties render hydrogen more challenging and costly to handle compared to conventional fossil fuels.

Pipeline transport of compressed hydrogen represents the most cost-effective solution for very large quantities of green hydrogen, with an optimal operating range up to 4,000 km [71]. However, pipeline transport of hydrogen over longer distances is considered economically challenging, as hydrogen transport through pipelines requires approximately four times more energy than natural gas, which affects efficiency and costs [72,73]. Therefore, for distances exceeding 4,000 km, maritime transport might become necessary, requiring either hydrogen liquefaction or conversion into derivatives such as ammonia or methanol, followed by reconversion at destination (if derivatives are not appropriate for further processing).

Data from the IEA [38] on planned hydrogen projects provides insights into current industry preferences for long-distance hydrogen transport: on major future hydrogen trade routes connecting Australia, Europe, Asia, America and Latin America, maritime transportation of ammonia is likely to be the prevalent option, with around 80 % of announced projects focusing on using ammonia for hydrogen delivery. However, when pure hydrogen is required, ammonia must be decomposed (cracked) into hydrogen and nitrogen [74]. This is particularly important for end-use applications such as fuel cell vehicles (FCVs), which require high hydrogen purity, as traces of ammonia can poison fuel cell catalysts.

Ammonia cracking is an endothermic and energy-intensive process that requires high temperatures and pressures to split the ammonia

molecule into its constituent nitrogen and hydrogen [61]. The commercialization of large-scale ammonia decomposition processes and subsequent hydrogen separation and purification remains challenging due to the lack of established commercial processes. [75]. The overall energy efficiency is significantly affected, with only about 30 % of the original renewable energy remaining when hydrogen is the desired energy vector [74,76]. These additional conversion processes considerably increase delivery costs [77], potentially disadvantaging countries beyond pipeline range from major importers.

The co-location of production facilities with industries that might use green hydrogen in the future, such as iron and steel manufacturing, chemical production, and refining generates operational synergies through shared infrastructure utilization and development, as reflected by Wang et al. [57] and Ersoy et al. [30]. On-site hydrogen usage for synthesizing decarbonized products can minimize logistical inefficiencies by leveraging existing trade ecosystems and infrastructure [78]. However, Ausfelder et al. [79] note that transitioning from conventional feedstocks to green hydrogen may require significant modifications to existing industrial configurations and infrastructure, warranting consideration in project planning.

Logistic and energy grid infrastructure. Insufficient infrastructure for hydrogen transport and storage represents a significant barrier to project implementation [80,81]. When the necessary infrastructure is lacking or requires development from scratch, this results in substantial CAPEX [82] and extended development timelines. For instance, the development of entirely new energy infrastructure like port terminals and pipelines is a time-intensive and complex process, typically requiring between 6 and 12 years from conception to completion according to the IEA [38].

Hence, the utilization of existing infrastructure for the transportation of green hydrogen has been a recurring theme in the reviewed literature due to its potential to reduce costs and improve economic viability of projects, accelerate deployment, and overcome the substantial challenges associated with developing entirely new hydrogen-specific infrastructure. Gordon et al. [64] and Sadik-Zata [4] discuss the potential for repurposing natural gas pipelines for hydrogen transport. The authors note that existing gas networks may be adapted to carry hydrogen blends or pure hydrogen, potentially leading to cost savings of around 50 % compared to newly built hydrogen pipelines. In accordance with those findings, IRENA [71] highlights that the bridgeable pipeline distance increases from 4,000 km for newly built pipelines to over 8,000 km for repurposed natural gas pipelines.

However, the economic and technical viability of using repurposed pipelines depends on several factors such as the end use cases or technical details of the pipeline [64], including material compatibility with hydrogen. Hydrogen's interaction with certain metals can cause embrittlement and infrastructure integrity issues, which can affect the feasibility of leveraging existing pipeline infrastructure for hydrogen projects [72,83]. Studies examining the feasibility of using natural gas pipelines for hydrogen transportation have produced mixed results. The literature [75,84] indicates that current understanding remains preliminary, requiring additional research to comprehensively assess the technical and economic feasibility of pipeline repurposing.

This review also shows that projects relying on maritime transport depend on sea access and existing port infrastructure for both importers and exporters. Required dedicated port infrastructure includes access to deep-water infrastructure and facilities to convert hydrogen into hydrogen carriers at the exporting port and facilities for reconversion back to hydrogen at the importing port. Therefore, Khan and Al-Ghamdi [85] highlight existing port infrastructure as a potential asset for hydrogen-related activities and emphasize the role of ports in potential hydrogen export scenarios. Khan et al. [8] also emphasize the importance of considering port facilities when evaluating potential sites for green hydrogen production. Other potentially relevant transport

infrastructure are roads and railways to transport equipment, workers and low quantities of hydrogen or derivatives via tube trailers [8].

The role of electricity grid infrastructure in facilitating grid-supported hydrogen production has as well been examined in the reviewed literature. Grid connection of production facilities can provide economic advantages, however, several technical challenges need careful consideration. Research [86] shows that optimal placement of power-to-hydrogen facilities requires balancing multiple factors: proximity to renewable sources, grid stability constraints, and voltage security requirements. While hydrogen production plants can act as flexible loads and provide grid balancing services during high renewable generation periods [87,88], their operation must be carefully coordinated with grid capacity limits and security constraints [86]. Ausfelder et al. [79] highlight that existing grids, primarily designed for centralized power generation, may require increased efficiency and flexibility to accommodate substantial shares of renewable energy necessary for low-emission hydrogen production.

Industry know-how for the implementation of green hydrogen projects. This literature analysis shows that the successful implementation of green hydrogen projects requires technical expertise and industry know-how, which is currently concentrated among specific countries and industry players. Patent and research and development activities in hydrogen technologies as well as manufacturing capacities for major components such as solar PV cells, wind turbines, and electrolyzers are predominantly controlled by industrial countries in the Global North and China [4,89,90].

Hunt and Tilsted [91] reveal that industry expertise for producing and handling green hydrogen is particularly concentrated among incumbent firms from the fossil fuel and chemical sectors. These companies possess valuable experience in operating large chemical facilities, handling explosive gases, and managing related safety protocols. Renewable energy companies are also increasingly entering the sector; however, they often lack the specific chemical and industrial expertise needed for hydrogen production and handling [91]. The literature identifies organizational effectiveness as the primary criterion for green hydrogen investments, highlighting the importance of established operational capabilities in project success [92].

The transition to a green hydrogen economy may leverage existing workforce capabilities from related sectors, as professionals such as plumbers, gas fitters, technicians, and engineers possess potentially transferable skills applicable to hydrogen infrastructure and operations [85,90]. However, industry perspectives, as captured by the reviewed literature [93–95], indicate that while training and skill development for jobs within the green hydrogen supply chain are perceived as crucial, they are currently considered insufficient across the sector. Barriers to education and training include a lack of hydrogen expertise and trainers, funding and resource constraints, intellectual property issues and a lack of leadership [93].

To address these disparities, Harichandan et al. [96] suggest developing a broader knowledge base on green hydrogen among students through academia-industry collaborations. The authors also discuss the establishment of a dedicated skill council to develop a workforce capable of working with green hydrogen technologies across various industries. The reviewed literature [93,96] also highlights a need for strategic planning and coordinated efforts across education and academia, politics, and industry with governments required to take a leadership role.

Additionally, the concentration of know-how in specific regions and among certain industry players has important implications for the global development of green hydrogen projects. International knowledge sharing and technology transfer are considered essential with organizations such as UNIDO, IRENA, IEA, and the World Bank contributing to knowledge dissemination and capacity building [90]. Despite the criticality of this topic, this analysis reveals that the examined body of

literature exhibits a notable gap regarding research on cross-border knowledge dissemination and technology transfer mechanisms specific to green hydrogen production.

Public acceptance dimension

Green hydrogen projects' success hinges significantly on the acceptance of local communities and the broader public, as negative perceptions and mistrust can impede their implementation. However, this literature review reveals that research on social acceptance of green hydrogen projects remains limited in scope. Due to the nascent stage of deployment and the consequent scarcity of existing implementation projects, Häußermann [14] reasons that studies predominantly focus on general public attitudes rather than examining real-world projects with tangible impacts.

Moreover, the research landscape is geographically skewed, with studies of the reviewed literature concentrating on industrialized countries in the Global North, particularly the UK [97], Germany [14] and Australia [98], indicating a significant gap in our understanding of the global perspective on green hydrogen acceptance. This geographic concentration of social acceptance research represents a significant limitation, as potential hydrogen-exporting regions in the Global South may have fundamentally different cultural, economic, and political contexts that shape public acceptance patterns. The lack of regionally grounded, context-specific studies in these areas might represent a critical barrier to developing globally viable hydrogen trade relationships, as successful implementation depends on social acceptance in both importing and exporting regions.

Acceptance is strongly correlated with the public perception of risks and benefits [97]. Individuals and communities need to see clear advantages of new energy technologies and green hydrogen outweighing potential risks and costs. These benefits include community-level gains such as job security and industrial reinvigoration, as well as environmental improvements, which have been shown to be particularly influential in shaping public acceptance in the UK [97].

Institutional trust significantly influences acceptance of green hydrogen, with particular emphasis on trust in scientific institutions, governmental bodies, media, and entities responsible for ensuring distributive justice of benefits and costs [14]. Successful implementation appears to benefit from consideration of regional identity and values. Evidence from this review [14,15,55] also suggests that public participation mechanisms may help address potential conflicts while supporting alignment with such community priorities. This involves early and ongoing dialogue, providing accessible information, actively addressing concerns, and ensuring marginalized groups have a voice.

Political and regulatory dimension

A major theme in the reviewed literature is the pivotal role of political and regulatory frameworks to enable and accelerate the development and implementation of green hydrogen projects. A supportive political framework is meant to address cost disparities with grey hydrogen [4], mitigate investment risks for stakeholders [91], create demand through mandates and incentives [64], and foster technological innovation [96]. This framework is also essential for establishing a clear regulatory environment [99], promoting harmonized standards [90], streamlining permitting processes, and ensuring a just and equitable transition to a green hydrogen economy [64].

Developing a political framework typically involves several steps according to IRENA [100]: initiating R&D programs to lay the technological groundwork, creating a long-term vision document, devising a roadmap to outline specific goals, and ultimately evolving into a comprehensive national hydrogen strategy.

Scholars [11,101] emphasize the importance of a clear vision and concrete deployment targets in national hydrogen strategies. Studies [64,102,103] also confirm the results of the previous sections of this literature analysis and highlight that strategies should consider specific national, regional and local circumstances, including factors such as

renewable resource availability, industrial structure, existing infrastructure, and public acceptance, to develop tailored approaches for hydrogen deployment.

Policies to enable green hydrogen projects. National hydrogen strategies need to be translated into tangible policies and regulations to foster the implementation of green hydrogen projects [104]. The reviewed literature discusses various policy mechanisms for scaling up the hydrogen economy, from financial incentives to market creation measures.

Sadik-Zada [4] and Yap and McLellan [81] highlight the necessity of addressing market barriers and providing financial support to overcome cost challenges associated with green hydrogen technologies. Tax credits and grants can be applied at different stages of the hydrogen value chain to foster hydrogen adoption and stimulate both supply and demand [13,17]. Another approach to financial subsidies is a Contract for Difference (CfD) scheme. These long-term agreements, typically spanning 10–15 years, between hydrogen producers and government entities guarantee fixed prices for produced hydrogen, reducing market risks and thereby making projects more attractive to investors [65,103,105]. Similarly, Carbon Contracts for Difference, as used in Germany and Japan, support the phase-out of fossil fuels in energy-intensive industries [17].

Measures to support market creation and stimulate demand are likewise important in driving green hydrogen adoption [106]. Governments can implement quotas and mandates that establish minimum shares of green hydrogen usage in specific sectors or applications [96,107]. Public procurement strategies that prioritize green products like hydrogen, steel, and ammonia over fossil alternatives can also support the creation of initial market demand [101].

Special economic zones can provide beneficial regulatory and political environments for green hydrogen projects such as fast-track permitting, tax incentives, infrastructure support, and export facilitations [30,108].

The adoption of green hydrogen is intrinsically linked to broader efforts to reduce carbon emissions [85]. Carbon pricing mechanisms, such as carbon taxes, cap-and-trade systems and border measures such as the EU Carbon Border Adjustment Mechanism (CBAM) can significantly impact the competitiveness of green hydrogen and incentivize the shift from fossil fuels to green alternatives [109]. However, as of 2023, only about 25 % of global greenhouse gas emissions were covered by carbon pricing schemes and existing carbon prices are generally too low to achieve cost parity between green hydrogen and fossil alternatives, indicating a need for more robust carbon pricing policies [38].

This analysis confirms the statement of Moura and Soares [13] that there is limited evidence regarding the efficacy of hydrogen public policies, potentially due to the novelty of the subject. Some authors have analysed the effectiveness of political instruments in specific countries or regions such as in Germany [110] or the UK [99]. However, Tholen et al. [110] posit that policy design is contingent upon national contexts and extant challenges. They advocate for a multifaceted policy approach, emphasizing that no one-size-fits-all solution exists. Optimal outcomes necessitate well-coordinated instruments, particularly concerning the temporal implementation. As the green hydrogen market transitions from niche to mainstream, policy priorities will likely shift, requiring ongoing assessment and adjustment [100].

Policy approaches for projects in the Global South. Projects in the Global South face more challenging financing conditions due to higher costs of capital, as credit agencies typically assign higher risk premiums to these investments [91,111]. Techno-economic studies of this review confirm that regions with strong renewable energy potential such as at locations in Colombia [41,48] or Brazil [112] may still face competitive disadvantages due to these higher capital costs, potentially making projects less competitive than in the Global North. This underlines that financing conditions, particularly in terms of interest rates and associated risk

premiums, play a crucial role in determining project viability in the Global South despite often superior renewable resources.

These challenging financing conditions are further compounded by the fact that most nations of the Global South face constraints in their financial capacity to support green energy and hydrogen projects through government subsidies or other support mechanisms. Consequently, researchers [52,113] emphasize the central role of advanced economies in providing financial resources for emerging markets and developing countries. International financing mechanisms, including grants, concessional loans, equity investments and competitive bidding schemes can bridge cost gaps, de-risk investments, and enhance project bankability to attract private sector investment to hydrogen projects in the Global South.

This literature analysis reveals that while these financing mechanisms aim to enable green hydrogen development in the Global South, their implementation raises concerns among scholars [56,114,115], warning that the current financing approaches for green hydrogen in the Global South may perpetuate colonial-style resource extraction and deepen external debt vulnerabilities. Therefore, to ensure both project viability and equitable outcomes, governments hosting projects should combine strategic public ownership of hydrogen infrastructure with institutions capable of enforcing technology transfer requirements on foreign investors, enabling domestic firms to develop their own technological capabilities rather than relying solely on derisking mechanisms that often primarily serve foreign investor interests.

Regulations for green hydrogen projects. The reviewed literature also highlights the necessity of a well-defined regulatory framework that addresses issues such as hydrogen certification, safety and technical regulations, and market design to facilitate efficient hydrogen trading [38,64,106]. Regulatory frameworks for infrastructure development also play vital roles in facilitating green hydrogen adoption [116]. Streamlining permitting and approval processes for green hydrogen plants and infrastructure is essential to avoid bottlenecks in project implementation [95].

Another factor identified in this literature review is the lack of harmonized policies and regulations across countries, hindering the development of a global green hydrogen market and hence the implementation of green hydrogen projects [64]. Governments worldwide are implementing regulatory frameworks and certification systems to address the ecological impact of green hydrogen. These frameworks share some similarities but also differ in scope, system boundaries, and assessment criteria [38]. As of 2023, seven national and supranational entities have established frameworks, with six more announced [38]. These frameworks share some similarities but also differ in scope, system boundaries, and assessment criteria [84,117,118]. This heterogeneity increases transaction costs for project developers, particularly those involved in international projects who must navigate multiple certification systems. International cooperation is therefore crucial to ensure interoperability between different regulations and certifications. While the IEA [38] considers full harmonization of certification systems and regulatory frameworks currently unfeasible, enabling mutual recognition among certification schemes could serve as a first step to reduce market fragmentation.

Furthermore, specific methodologies to assess project compliance are still partly undefined up to date. Hence, the development of international standards for assessing the impact of green hydrogen is critical for its widespread adoption. Current efforts are primarily focused on carbon life cycle accounting of greenhouse gas emissions for hydrogen and its derivatives [117]. However, to ensure the sustainability of green hydrogen projects, efforts should prioritize environmental, social and governance aspects of the green hydrogen value chain [55,119].

Additionally, the development of green hydrogen projects and value chains depends on comprehensive international standards focusing on safety, technology compatibility, and operational issues [120].

Discussion and Conclusion

Implementation dynamics for green hydrogen projects

This systematic review has explored the multidimensional factors discussed in the literature corpus, influencing green hydrogen project implementation. At the project level, the reviewed literature focuses on techno-economic aspects, showing that implementation success is determined by process and plant configurations. However, this analysis indicates that decisions upon these factors cannot be viewed in isolation, as they are intrinsically linked to the project environment level. Site-specific resources, existing infrastructure, and economic, political and social conditions create a unique implementation landscape for each project. The reviewed studies further demonstrate that green hydrogen projects are also embedded within global market and political dynamics. Concentrated technical capabilities among specific countries and industry players, reveal dependencies of other countries with less expertise. International capital markets influence the economic viability of projects and emerging international standardization efforts, and certification protocols further affect project implementation.

Through this systematic literature review, it becomes apparent how these factors are connected. Linkages can be exemplified by various examples: While the reviewed techno-economic studies demonstrate significant cost reductions through increased project size, it is evident that such scaling necessitates proportionally greater demands on land resources, water availability, infrastructure capacity, and capital requirements. The economic viability of grid-connected projects depends on both, physical grid infrastructure and regulatory frameworks governing on-grid hydrogen production. Cost reductions of electrolyzers and renewable energy rely on economies of scale and learning effects through aggregate market growth beyond any single project's scope.

This systematic literature review provides a better understanding of the multifaceted nature of green hydrogen project implementation. It offers a holistic view of influencing factors, from project-level technical decisions to the global context of green hydrogen markets.

Project developers have several options to optimize the cost-effectiveness of hydrogen production and logistics, but this highly depends on the immediate environment in which projects are planned. While these factors are external to the project itself and hydrogen project developers have limited direct influence, they can exert some degree of control through stakeholder management and strategic decision-making, particularly in site selection.

Looking forward, these findings suggest that successful green hydrogen implementation will require greater coordination between different stakeholder groups and policy domains. The complex interdependencies identified indicate that siloed approaches to project development are unlikely to succeed. Instead, integrated strategies that address multiple implementation factors simultaneously while considering local contexts may prove more effective.

Regional disparities for green hydrogen project implementation

This systematic review highlights that countries and regions differ in their starting positions to host green hydrogen projects. Some countries might offer abundant renewable resources but lack technological know-how, a skilled workforce, an infrastructural and industrial basis, and political and regulatory support, potentially putting them at a competitive disadvantage. These countries will likely have limited attractiveness for green hydrogen projects despite their renewable resource endowment and will heavily rely on international financing, technology transfer, and international partnerships to exploit their renewable energy resources. Conversely, emerging and industrialized economies offering suitable locations with high-capacity factors, existing infrastructure, strong political support, advanced regulatory frameworks, and developed industrial sectors with existing hydrogen industries and potential offtakers might provide a beneficial environment

to attract investments and host green hydrogen projects. Other countries might offer the suitable industrial and infrastructural base but rely on imports due to a lack of land or low renewable energy capacity factors.

The research landscape itself reflects these disparities, with a predominant focus on studies in developed nations and larger emerging economies like Brazil, China, and India. This bias in research attention potentially reinforces existing inequalities by limiting our understanding of implementation challenges, particularly in developing nations.

These findings indicate that successful global hydrogen market development may require reconsidering current approaches to international cooperation and technology transfer. The complex interdependencies between resource availability, technical capabilities, and financing conditions confirm that purely market-driven approaches are insufficient to ensure equitable opportunities for project implementation and participation in the emerging hydrogen economy.

Limitations of the study

Several limitations need to be acknowledged regarding the methodology and scope of this systematic review. The first limitation concerns language restrictions. The literature search was confined to English-language publications, which may have resulted in exclusion of relevant studies published in other languages from the analysis. The search strategy could have incorporated additional terms such as “clean hydrogen” or “enablers” to generate a more comprehensive literature base. Furthermore, the review’s focus on green hydrogen resulted in the exclusion of literature addressing developments of fossil-based hydrogen with and without carbon capture technologies. This constraint is significant due to the interconnected nature of green and fossil-based hydrogen markets, which exhibit both competitive dynamics and potential synergies within the broader energy transition context. The fourth limitation pertains to source selection criteria and the inclusion of select grey literature sources to adequately capture recent industry developments and policy considerations, despite potential variations in methodological rigor.

Future research

Future research could build upon this review in several ways. Investigating tangible green hydrogen projects and analysing stakeholder perspectives on the importance of the factors derived from this literature review. This approach could also shed light on factors or considerations that may have been overlooked in the current literature, particularly in the areas of commercial structure, financing, and stakeholder engagement.

The findings from this study could be operationalized to conduct comparative analyses of different regions’ attractiveness for green hydrogen projects. Such research could provide valuable insights for project developers, policymakers and investors by quantifying and weighing the various factors identified in this review.

Furthermore, the literature analysis identifies several research gaps. While the technical and economic dimensions have received substantial scholarly attention, multiple areas remain insufficiently investigated. One such area concerns workforce development and knowledge transfer mechanisms for green hydrogen projects. Evidence on effective financing mechanisms for green hydrogen projects is notably limited. Therefore, research into innovative financing mechanisms and international cooperation models could help address the significant investment gap in emerging markets and developing countries. Additional understudied areas include the comparative efficacy of policy instruments across jurisdictions. Furthermore, project implementation experiences in developing economies could improve the scholarly understanding of their specific implementation challenges.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Claude 3.5 Sonnet in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Alexander Leuthold: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Julia Terrapon-Pfaff:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Peter Viebahn:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.seta.2025.104555>.

Data availability

I have shared my data as [supplementary file](#)

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