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Integration of UN sustainable development goals in national hydrogen strategies: A text analysis approach

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ABSTRACT

Despite the growing recognition of hydrogen's potential role in sustainable development, there is limited understanding of how national hydrogen strategies align with the United Nations Sustainable Development Goals (SDGs). This study addresses this knowledge gap by examining the integration of the SDGs into national hydrogen strategies through text analysis. Among 66 reviewed strategic documents, only 15 explicitly reference specific SDGs, though SDG-related keywords are widespread, particularly regarding SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). Statistical analysis demonstrates a significant link between the presence of hydrogen strategies and both overall SDG performance and progress on most specific SDGs. However, countries with hydrogen strategies show lower scores for SDGs 12 (Responsible Consumption and Production) and 13, and there are no significant differences for SDGs 10 (Reduced Inequalities), 14 (Life below Water), and 15 (Life on Land). Our findings highlight the need for more explicit integration of SDGs into hydrogen strategies and better consideration of sustainability synergies and trade-offs, providing policymakers with evidence-based guidance for aligning hydrogen strategies with global sustainability objectives.

1. Introduction

Hydrogen, especially green hydrogen—produced from renewable energy sources—is gaining significant attention as a potential solution for global decarbonisation efforts [1]. With its capacity to reduce greenhouse gas emissions, promote economic growth, and enhance energy access, green hydrogen holds a particular promise for achieving the United Nations Sustainable Development Goals (SDGs) future [2–6].

The strategic importance of hydrogen in advancing the global energy transition has catalysed the development of numerous national hydrogen strategies and roadmaps. Following Japan's inaugural national hydrogen strategy in 2017, more than 65 national or regional strategies have been articulated by multiple countries across different continents (Fig. 1), demonstrating widespread policy commitment to hydrogen development [7,8]. These strategies play an essential role in shaping green energy transitions, particularly in the context of climate change mitigation and the pursuit of sustainable, low-carbon economies [9–11]. While the data indicate a global surge of interest in green hydrogen technologies, the implementation pathways are complex and vary by region [12]. Nations are developing heterogeneous strategies aligned with their distinct energy requirements, resource endowments, and long-term decarbonisation objectives [8].[1]

The spatial distribution of countries that have announced a hydrogen strategy indicates a broad interest in green hydrogen across regions (Fig. 1). The adoption of such strategies by nations at varying stages of economic development indicates the perceived strategic importance of green hydrogen across diverse socioeconomic contexts. The continued proliferation of national hydrogen strategies, as evidenced by recent policy developments in multiple countries, underscores the sustained momentum in hydrogen technologies advancement and recognition of their strategic role in energy system transformation and climate change mitigation efforts (Fig. 2).

International partnerships, such as the Africa Green Hydrogen Alliance (AGHA) and EU hydrogen initiatives, such as the Clean Hydrogen Partnership and the European Clean Hydrogen Alliance, serve as crucial mechanisms for advancing coordinated hydrogen deployment globally. In particular, the EU 2050 climate neutrality objective positions hydrogen as a cornerstone of its member states' decarbonisation

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[1] While several countries pursue a "multi-colour" approach to hydrogen deployment incorporating various production pathways, our analysis focuses specifically on green hydrogen, which [8] identifies as a priority technology supported across all national hydrogen strategies.

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frameworks. This policy emphasis manifests particularly in hard-to-abate sectors where direct electrification presents significant technical challenges [13]. The EU hydrogen strategy, adopted in July 2020, delineates a critical role of hydrogen in decarbonising four key sectors: industry, transport, power generation, and heating. Within the "Fit for 55″ package, the EU establishes quantitative targets, including 50% green hydrogen utilisation in industrial applications [14]. This commitment is further reinforced through the allocation of strategic investment priorities within the "Next Generation EU" post-COVID recovery framework [15].

The variation between countries in hydrogen strategy adoption can be attributed to multiple factors: resource constraints, divergent energy priorities, or asymmetric policy development trajectories. This heterogeneity reflects the complex interplay between technological readiness, economic capabilities, and national decarbonisation objectives [7]. A comprehensive analysis by Ref. [16] categorises the EU member states into three distinct groups—frontrunners, Developers, and Laggards—based on the implementation status of their national hydrogen strategies. The analysis identifies a critical policy gap in the absence or inadequacy of hydrogen-specific legislation across most member states, which presents significant barriers to widespread hydrogen deployment. However, this classification exhibits limitations in capturing the complete spectrum of hydrogen technology deployment. Notably, some states classified as Developers or Laggards demonstrate substantial hydrogen project implementation despite lacking formalised national hydrogen frameworks.

Examination of the potential contribution of green hydrogen to achieving the seventeen SDGs (Fig. 3) has emerged as a recent research focus, encompassing diverse applications, including transportation decarbonisation, energy storage solutions, and industrial process transformation. Recent reviews by Ref. [3–5, 59] provide systematic analyses of the hydrogen technologies' alignment with the SDGs.

In particular, green hydrogen explicitly aligns with SDG 7 (Affordable and Clean Energy) by supporting renewable energy integration, addressing intermittency challenges, and supporting rural electrification and clean cooking in underserved regions, green hydrogen [18]. In particular, advanced hydrogen storage technologies, including underground storage, can enhance energy security by providing a reliable and long-term energy supply [19]. Deployment of green hydrogen also advances progress towards SDG 13 (Climate Action) by reducing emissions in hard-to-abate sectors, including steel, heavy-duty transportation, and energy storage [20–22].

The evolution of hydrogen infrastructure and production capabilities demonstrates significant technological advancement, particularly in

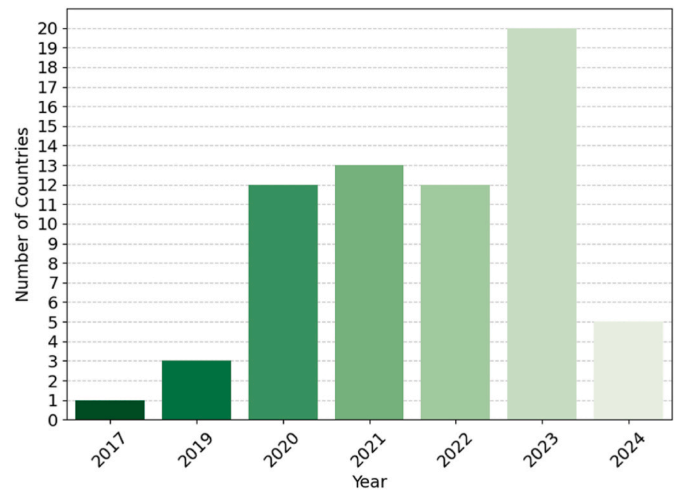

Fig. 2. Temporal distribution of national hydrogen strategy announcements. Over 80% of the announced strategies have been adopted by September 2024. Countries which declared the development of a national hydrogen strategy but have not published it (at least in the form of preliminary documentation or consultation drafts) as of September 2024 are not included.

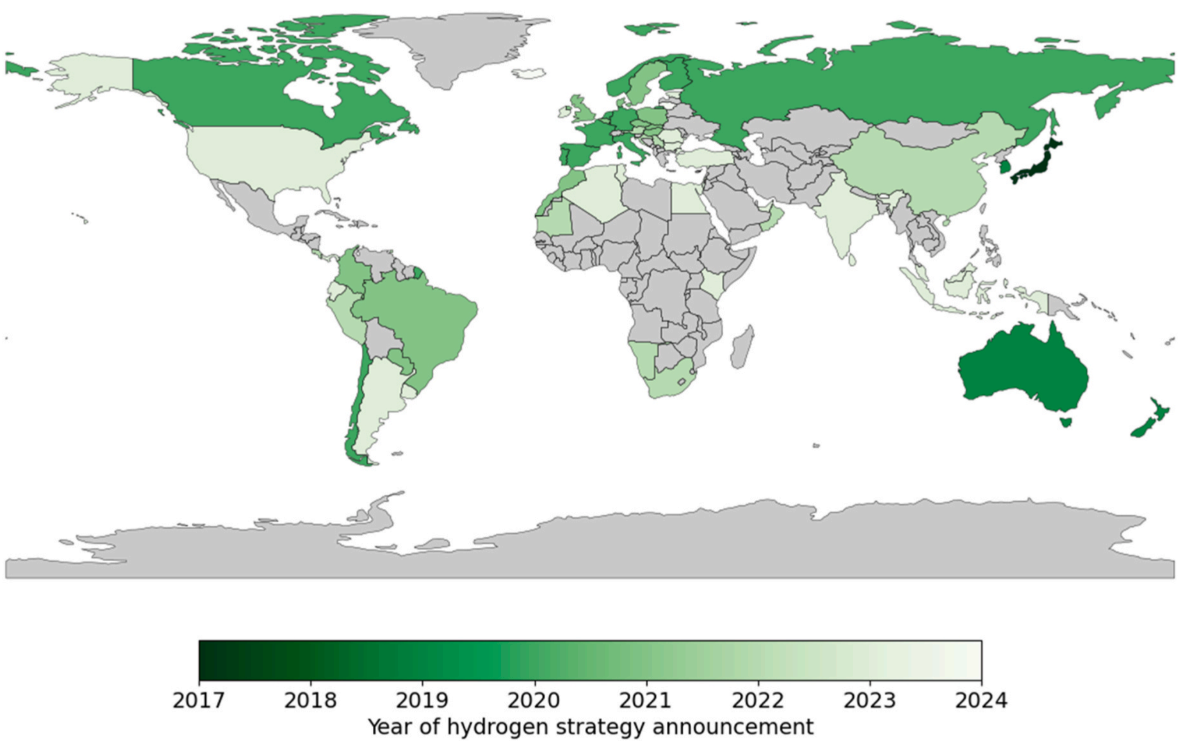

Fig. 1. Global distribution of national hydrogen strategies. Countries that have announced or developed strategies at any implementation stage are represented in varying hues of green. The saturation of the colour corresponds to the year of the strategy announcement. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 3. The sustainable development goals (SDGs) framework.

electrolysis process optimisation, thereby advancing SDG 9 (Industry, Innovation and Infrastructure) objectives [4]. The establishment of green hydrogen supply chains can contribute to regional economic transformation, cultivate export-driven growth, and create job opportunities, particularly in renewable energy and automotive sectors, These economic mechanisms align with SDG 8 (Decent Work and Economic Growth) priorities [17,23], with particular relevance for regions rich in renewable resources such as Africa and Latin America. However, this transition necessitates comprehensive workforce development strategies, specifically addressing the re-skilling requirements for workers currently employed in fossil fuel-dependent industries [24].

Green hydrogen production and utilisation also align with SDG 12 (Responsible Consumption and Production) through multiple pathways: transformation of industrial feedstock requirements, circular resource management, and optimisation of water resource use [4]. Notably, electrolysis-based production processes represent a shift toward more sustainable production paradigms than conventional fossil fuel-based systems (grey hydrogen) [25].

However, implementation challenges for green hydrogen energy systems persist across multiple interconnected dimensions. Primary barriers encompass economic constraints, with green hydrogen production costs significantly exceeding those for fossil fuel-based alternatives [26]. The economic feasibility is further constrained by infrastructural requirements, particularly in scaling up electrolysis facilities and developing storage and distribution networks [2]. Moreover, the transition faces societal barriers, including workforce development needs and limited public awareness of hydrogen technologies [3]. These challenges manifest heterogeneously across regions, reflecting variations in institutional capacity, infrastructure development, and regulatory frameworks. They are particularly evident in emerging economies where both technical expertise and supporting infrastructure may be limited [27].

Moreover, green hydrogen development can also present significant challenges for achieving certain SDGs, particularly in the medium to long term. While immediate benefits are evident for energy transition and climate action (see above), there are critical concerns regarding water scarcity trade-offs (SDG 6) [3,28], and potential threats to marine and terrestrial ecosystems (SDGs 14 and 15) through land-use changes and coastal infrastructure development [3]. The green hydrogen value chain may also compromise social targets through gender wage gaps in the hydrogen technology sector (SDG 5) [29]. Additionally, the risk of prioritising exports over domestic development in producing countries, particularly in the Global South, could hinder local progress on the SDGs [5]. These challenges underscore the need for careful strategic planning that considers not only the immediate benefits of hydrogen adoption but also its broader implications for sustainable development across different temporal and geographical scales.

The evaluation of hydrogen's contribution to sustainable development encompasses diverse methodological approaches, each offering distinct analytical perspectives. Environmental impact assessment methodologies, particularly Life Cycle Assessment (LCA), have been instrumental in comparing the sustainability profiles of various hydrogen production pathways [30,31]. Complementing these environmental analyses, Social Life Cycle Assessment (S-LCA) frameworks have illuminated the societal implications of hydrogen technology deployment, systematically evaluating both potential benefits and risks [29,32,33].

Recent methodological innovations have expanded the analytical toolkit. Bibliometric approaches have mapped research trajectories and identified knowledge gaps within the hydrogen sustainability literature [34]. SDG mapping frameworks have established systematic linkages between hydrogen technologies and specific SDG targets, providing structured evaluation criteria for challenges and opportunities [3,18]. The novel Value Chain Assessment (VCA) methodology enables the identification of both positive and negative direct and indirect impacts of the three segments (production, transportation, and end-use) of the green hydrogen value chain on the SDGs and their targets [5].

Despite this progress, a comprehensive understanding of how national hydrogen strategies translate the potential of hydrogen into concrete actions towards achieving the SDGs remains a significant research gap [5]. While many countries acknowledge the SDGs in their hydrogen strategies, a systematic analysis of how these strategies translate into specific, measurable actions towards achieving SDG targets is missing [35]. Preliminary results of a systematic review of national hydrogen strategies were presented by Ref. [36], however, they do not focus specifically on the SDGs.

Recently, the integration of Natural Language Processing (NLP) tools into SDG mapping processes has gained prominence due to the increasing need to assess alignment between policies and SDG frameworks efficiently. These tools enable automated analysis of policy documents, reducing the time and subjectivity associated with manual assessments. Recent advances in SDG mapping focus on using transformer-based models like Bidirectional Encoder Representations from Transformers (BERT). [37] introduced a BERT-based multi-label classification system to map text content to SDGs while also visualising the interlinkages between SDGs based on co-occurrence patterns. [38] applied a BERT model to map 74 European Green Deal policy documents, including the EU Hydrogen Strategy, to the SDG framework. They revealed that the analysed policies significantly align with the SDGs 7, 12, and 13. Open-source efforts in SDG mapping aim to increase the accessibility and adaptability of NLP tools. For example, the text2SDG R package [39] provides a multi-model framework to establish

SDG alignment across various text sources, while tools such as SDG Mapper [40] and OSDG [41] provide free and user-friendly options to classify multiple complex documents according to SDGs. This paper aims to bridge this gap by examining the explicit and implicit connections between national hydrogen strategies and the SDGs. It investigates how different nations articulate their hydrogen goals within the broader sustainable development framework and what concrete measures they propose to contribute to the realisation of the SDGs. Through a rigorous analysis of the text content of national hydrogen strategies, viewed through the lens of the SDGs, this paper aims to offer valuable insights into the alignment between national hydrogen ambitions and the global sustainability agenda.

2. Methods and materials

The list of currently available hydrogen strategies published by the International Renewable Energy Agency in mid-2024 [8] served as the starting point for identifying relevant documents. This list was further validated against and complemented by the CSIRO HyResource International database [42], the Global Hydrogen Review 2023 [43], the GH2 Country Portal [44], the European Hydrogen Observatory [45], and the National Hydrogen Strategies and Roadmap Tracker [46]. While most countries included in these databases have published and adopted their hydrogen strategies or roadmaps, some countries published drafts of the strategies for consultations (e.g., Romania) or published preliminary documents for the strategy (e.g., Brazil). The most recent versions were used for the countries that published an update of their hydrogen strategies (e.g., Czechia, Germany, and Japan). For the strategies published in languages other than English (i.e., Algeria, Argentina, Austria, Brazil, Bulgaria, China, Costa Rica, Ecuador, Italy, Luxembourg, Mauritania, Morocco, Panama, Portugal, Russia, Serbia, Spain, Tunisia), an online translation service was utilised, allowing for a standardised analysis. An executive summary or press release was used for countries where retrieving a full text in any language (e.g., Peru) was impossible.

In total, we examined national hydrogen strategies and roadmaps of 65 countries and the supranational strategy of the European Union.[2] These countries make up 88% of the world's GDP and about two-thirds of the world's population. According to the World Bank country classification by income level, 41 of these countries belong to the high-income group, 15 countries belong to the upper-middle income group, and 9 countries – to the lower-middle income group. Some further countries declare that they are developing national hydrogen strategies but have not published them yet in any form as of September 2024 (for example, Bolivia, Greece, Saudi Arabia, Switzerland, Thailand, and others). Those countries were excluded from the analysis.

The retrieved texts of the strategic documents underwent a meticulous cleansing process to ensure a focus on substantive content. They were cleaned of auxiliary information like cover pages, tables of contents, lists of abbreviations and figures, references, acknowledgements, appendices, etc.

The pre-processed texts were then analysed with SDG Mapper, an open-source tool developed by the European Commission's Joint Research Center (JRC) for evaluating SDG content in policy documents [40]. This tool has been recognized in recent studies for its effectiveness in mapping textual content to specific SDGs ([47,48], Gunasekar et al., 2024; [48], Lathabhai et al., 2024). Our analysis consisted of two steps: first, we identified explicit mentions of the SDG framework, 2030 Agenda, and specific SDGs in the pre-processed texts of national hydrogen strategies; second, we quantified and visualised the frequency of SDG-related keywords across all strategic documents.

Additionally, we analysed the relationship between the presence of a national hydrogen strategy and the national progress on the SDGs using the database of the Sustainable Development Report 2024 [50]. We employed *independent samples t-tests* to compare the SDG Index and goal-specific scores between countries with and without a hydrogen strategy. Our null hypothesis (H_0) posited no difference in mean SDG indices between these groups, while the alternative hypothesis (H_1) suggested a significant difference between the two groups [51]. All statistical analyses were performed using Python's SciPy library. We set the significance level (α) at 0.05.

3. Results

3.1. Overview of SDG mentions in national strategies

Twenty-six countries explicitly refer to the SDGs in their national hydrogen strategies and roadmaps. However, only fifteen of these countries (Austria, Belgium, Chile, Colombia, Costa Rica, Germany, Indonesia, Kenya, Malaysia, Mauritania, Panama, Paraguay, Romania, South Africa, and Uruguay) go into more detail and specify concrete SDGs, for which progress can be made through hydrogen deployment. The other eleven countries merely mention the SDG framework or the 2030 Agenda as the context of their hydrogen strategies without specifying concrete linkages. More than half of the examined strategies refer neither to particular SDGs nor to the SDG framework or Agenda 2030 (Fig. 4). There is no clear geographical pattern, as countries from all continents (except Australia) are represented in all three groups in Fig. 4.

Fig. 5 showcases a comprehensive comparison of global engagement with the SDGs across the hydrogen strategies of various countries. SDG 7 (Affordable and Clean Energy) is mentioned in all hydrogen strategies, which mention at least one SDG, confirming a strong emphasis on energy within the context of hydrogen development. SDG 13 (Climate Action) also stands out, highlighting a shared focus on combating climate change across national hydrogen strategies. On the other hand, SDGs 14 (Life below water) and 15 (Life on land) are not mentioned in any of the reviewed strategies, while SDGs 3 (Good health and well-being), 4 (Quality education), 10 (Reduced inequalities), and 16 (Peace, justice and strong institutions) are mentioned only by one strategic document each. This may suggest a narrower focus of hydrogen strategies on direct energy and climate objectives rather than broader social and environmental goals. At the same time, as discussed in recent scientific literature, synergies and trade-offs between various SDGs can significantly impact their progress [52]. Some countries articulate this clearly, for example, Uruguay's Roadmap for Green Hydrogen and Derivatives states that green hydrogen contribution to accelerating progress on SDGs 7, 9, 11, and 13 will also indirectly contribute to progress on other goals.

Hydrogen strategies of Belgium, Kenya, and Mauritania declare engagement with multiple SDGs, indicating a potentially more holistic approach to integrating sustainable development. Hydrogen strategies of other countries, such as Austria, Germany, Indonesia, Panama, and South Africa, exhibit a more focused engagement on a smaller set of SDGs. The data suggests that while there is a consensus on the importance of energy and climate-related goals, there is a variation in the extent to which other SDGs are integrated into hydrogen strategies. The prevalence of certain SDGs may reflect the strategic priorities or the socio-economic contexts of the countries.

Below, we discuss how each SDG is referred to in the hydrogen strategies of the fifteen countries explicitly referring to particular SDGs.

SDG 1 (No poverty). Mauritania's national hydrogen strategy discusses the achievement of SDG 1 by highlighting that investment opportunities in the hydrogen sector contribute directly to this goal.

SDG 2 (Zero hunger). Mauritania's national hydrogen strategy addresses the achievement of SDG 2 by emphasising that constructing a desalination plant required for the operation of electrolysers in hydrogen production would contribute to this SDG.

[2] The full list of analysed documents is available in the Supplementary Material.

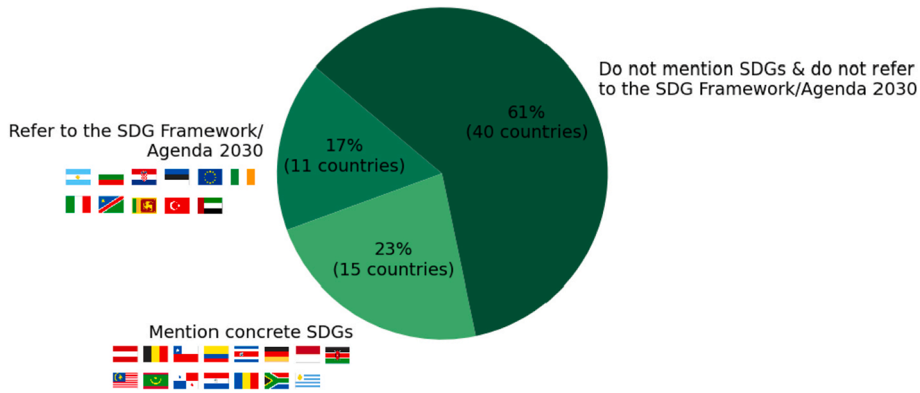

Fig. 4. Countries which explicitly refer to the SDG Framework, 2030 Agenda and concrete SDGs in their national hydrogen strategies and roadmaps.

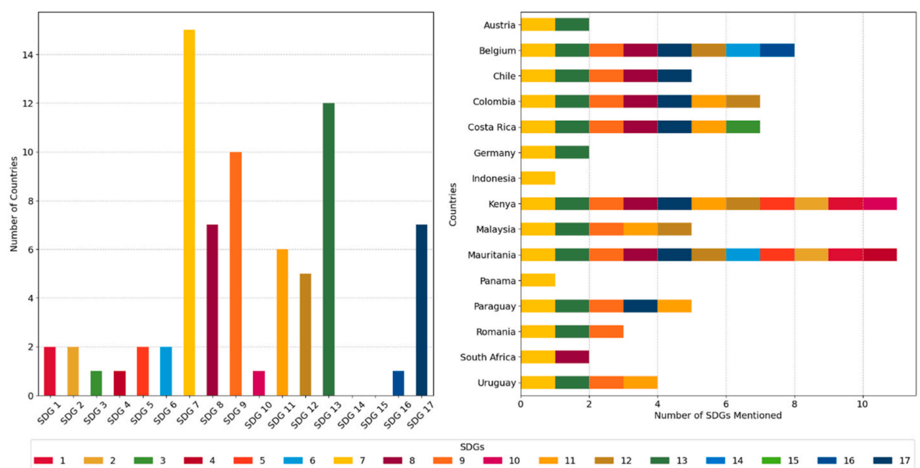

Fig. 5. Divergent engagement with the Sustainable Development Goals (SDGs) in national hydrogen strategies. Left panel: frequency of SDGs mentioned by all countries, indicating the emphasis on specific goals within hydrogen-related policies. Right panel: breakdown of SDGs mentioned within individual country strategies, reflecting the scope of sustainability considerations adopted nationally. Each SDG is colour-coded according to the official UN SDG palette. Only countries explicitly mentioning at least one SDG in their strategies are displayed. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

SDG 3 (Good health and well-being). In Costa Rica's national hydrogen strategy, green hydrogen technologies and services are recognized for their potential to contribute to SDG 3 by reducing the use of technologies that currently negatively affect the air quality of communities. Reducing pollution and improving air quality, in turn, would have a positive impact on public health.

SDG 4 (Quality education). Mauritania's national hydrogen strategy outlines that to ensure equitable access to quality education for all and promote lifelong learning opportunities, investment opportunities in the hydrogen sector will be leveraged to create training centres and a university, ensuring the workforce has the necessary skills and education.

SDG 5 (Gender equality). Mauritania explicitly mentions SDG 5 in its hydrogen strategy. The country's roadmap for the hydrogen industry acknowledges the need for governance bodies to support gender parity as an important component of the industry's development.

SDG 6 (Clean water and sanitation). SDG 6 is acknowledged in the hydrogen strategies of Belgium and Mauritania. The Belgian hydrogen vision and strategy anticipates the contribution of hydrogen to support SDG 6, in particular, targets 6.1 (by 2030, achieve universal and equitable access to safe and affordable drinking water for all) and 6.5 (by 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate). However, it does not describe the concrete support mechanisms. Mauritania's national hydrogen strategy discusses the importance of sustainable use of water resources in the context of hydrogen production by electrolysis, which consumes water as raw material, and explicitly refers to SDG 6. For Mauritania, desalination of water from the Atlantic Ocean is identified as the most feasible solution for green hydrogen production. Obligations for purifying excess water to make it drinkable are prescribed for negotiations with project developers.

SDG 7 (Affordable and clean energy). All thirteen countries that discuss the SDGs in detail in their hydrogen strategies mention SDG 7. The Austrian hydrogen strategy strongly aligns with SDG 7 by emphasising scaling up renewable hydrogen, displacing fossil fuels, and enabling affordable clean energy access across different sectors. The Belgian hydrogen vision and strategy anticipates the contribution of hydrogen to support SDG 8, in particular, targets 7.1 (by 2030, ensure universal access to affordable, reliable and modern energy services) and 7.2 (by 2030, increase substantially the share of renewable energy in the global energy mix). However, its overall focus is more on the hydrogen industry and market rather than consumer access or affordability. The national green hydrogen of Chile explicitly refers to SDG 7. The strategy intends to leverage Chile's renewable energy resources to produce low-cost green hydrogen at scale. Colombia's hydrogen roadmap explicitly mentions SDG 7 and foresees green hydrogen to "facilitate the deployment and integration of greater FNCER generation capacity, favouring a sustainable economy, facilitating system management and enabling energy transportation and storage." The national green hydrogen strategy of Costa Rica envisages the potential of green hydrogen to replace the use of energy sources derived from polluting fossil fuels as its direct contribution to SDG 7. Mauritania's national hydrogen strategy acknowledges SDG 7 and declares that by scaling up renewable energy capacity, the hydrogen projects could contribute to more affordable clean electricity access beyond just what is needed for hydrogen electrolysis. The National Strategy for Green Hydrogen and Derivatives of Panama (ENHIVE) envisages significant progress in the transformation and modernisation of an energy matrix that is less polluting to the environment, which is in accordance with its commitment to SDG 7. The national hydrogen strategy of Romania states that its measures align with SDG 7. The Green Hydrogen Roadmap in Uruguay also explicitly references SDG 13 and advances plans for a significant expansion of renewable energy to power green hydrogen production. The Hydrogen Society Roadmap (HSRM) for South Africa commits to achieving SDG 7 by enabling a just transition to affordable and clean energy.

SDG 8 (Decent work and economic growth). Five countries emphasise SDG 8 in their hydrogen strategies. The Belgian hydrogen vision and strategy anticipates contribution of hydrogen to support SDG 8, in particular, targets 8.2 (achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors) and 8.4 (improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-Year Framework of Programmes on Sustainable Consumption and Production, with developed countries taking the lead). The strategy outlines plans to expand Belgium's leadership in hydrogen technologies through R&D funding programs and test facilities. This suggests an intention to drive innovation and technological upgrading in the hydrogen sector to enable economic growth and productivity aligned with SDG 8. Additionally, the overall goals of the strategy in terms of positioning Belgium as an import/transit hub and establishing a domestic hydrogen market indicate ambitions to develop new high-value, innovative industries, create jobs, and drive sustainable economic growth. The Chilean national green hydrogen strategy mentions SDG 8 and focuses on the expected "sophisticated and satisfactory" job creation, promotion of new sustainable industries (with hydrogen production expected to become a "new productive identity for Chile" and "catalyst for local growth"), spurring innovation and preparing workforces. Colombia's hydrogen roadmap intends to address SDG 8 by generating investments and up to 15000 new direct and indirect jobs by developing the hydrogen value chain (production, demand, and transport projects) and creating industrial clusters. The national green hydrogen strategy of Costa Rica foresees green hydrogen, coupled with the renewable energy industry, to present high employability factors that will allow new jobs to be created and have a positive impact on the economy. Mauritania's national hydrogen strategy refers to SDG 8 and foresees that the hydrogen sector will be capable of creating 380000 direct jobs by 2050. A key objective of the Hydrogen Society Roadmap (HSRM) for South Africa is to support the just labour transition by providing new green jobs and preserving jobs in transport and industry. It also aims to support "just and inclusive net-zero carbon economic growth for societal well-being by 2050".

SDG 9 (Industry, innovation and infrastructure). Strategic documents of nine countries discuss SDG 9. The Belgian hydrogen vision and strategy anticipates the contribution of hydrogen to support SDG 9, in particular, targets 9.1 (develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all) and 9.4 (by 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities). In particular, it seeks to develop transportation infrastructure like hydrogen pipelines to establish a domestic hydrogen transport network and support imports and transit. The ambition of the Belgian strategy also supports hydrogen innovation, pilot projects, and testing facilities. The Chilean national green hydrogen strategy envisages progress towards SDG 9 through infrastructure upgrades, policy adaptations toward openness and competitiveness, workforce development plans and R&D roadmaps. Colombia's hydrogen roadmap commits to fostering progress on SDG 9 through its technological development axis, with measures to build domestic innovation capabilities, including "Support national Research, Development and Innovation (R + D + I) through the financing and progress of existing workgroups" and "Evaluate the strengths of local industry in the hydrogen value chain". The national green hydrogen strategy of Costa Rica considers the hydrogen industry as "an opportunity for innovation for Costa Rica" in areas like production equipment manufacturing, such as electrolysers and fuel cells. Mauritania's national hydrogen strategy acknowledges SDG 9; the strategy intends to promote sustainable industrialisation and infrastructure development in the country by developing a new hydrogen industry, along with the associated infrastructure like renewable electricity production, water desalination facilities, pipelines, etc. The Romanian national hydrogen strategy aligns with SDG 9 by developing measures to support technological development and transferring innovations to industrial applications. The Green Hydrogen Roadmap in Uruguay also explicitly references SDG 9; it promotes mechanisms to develop research and innovation based on the Hydrogen Sector Fund.

SDG 10 (Reduced inequalities). The Green Hydrogen Strategy and Roadmap for Kenya explicitly refers to SDG 10 and declares that green hydrogen can create equitable employment and economic opportunities across the green hydrogen value chain globally by promoting participation from all countries, regardless of their level of development.

SDG 11 (Sustainable cities and communities). Five countries refer to SDG 11 in their hydrogen strategies. Colombia's hydrogen roadmap explicitly refers to SDG 11. In particular, it mentions establishing hydrogen fuelling stations in "locations that guarantee demand, such as highly populated cities with a large fleet of taxis or inter-municipal buses" and "identifying barriers for hydrogen consumption in the residential and tertiary sectors". The hydrogen strategy of Costa Rica foresees progress on SDG 11 by using green or low-carbon hydrogen in cities and communities in two ways: in mobile applications (buses, trucks, cars) and stationary applications (residential). Similarly, the Malaysian Hydrogen Technology and Economy Roadmap envisages achieving SDG 11 by applying hydrogen in mobility, heating systems and power generation to empower the Global Hydrogen Society. The Paraguayan Green Hydrogen Roadmap focuses on the application of hydrogen as a fuel for urban transport to significantly reduce emissions from vehicles in cities. The Green Hydrogen Roadmap in Uruguay also clearly mentions SDG 11; however, it does not specify the concrete ways in which hydrogen can boost progress towards it.

SDG 12 (Responsible consumption and production). Hydrogen strategies of four countries discuss SDG 12. The Belgian hydrogen vision and strategy anticipates the contribution of hydrogen to support SDG 12, in particular, target 12.2 (by 2030, achieve the sustainable management and efficient use of natural resources). It claims that producing, transporting, storing and using hydrogen should take into account impacts on climate and the environment. Colombia's hydrogen roadmap also explicitly refers to SDG 12, in particular, by enabling fair transition and conversion of hydrocarbon industries. The Malaysian Hydrogen Technology and Economy Roadmap considers the hydrogen economy capable of increasing economic growth with revenues of more than USD 2.5 trillion/year as an economic driver to achieve SDG 12. Mauritania's national hydrogen strategy foresees investment opportunities in the hydrogen sector that will contribute to establishing sustainable consumption and production patterns.

SDG 13 (Climate action). Ten countries refer to SDG 13 in their strategies and roadmaps. The Austrian hydrogen strategy directly addresses SDG 13, advocating for producing renewable hydrogen and targeted use in selected sectors to close decarbonisation gaps. It also plans to substitute 80% of fossil-based hydrogen consumption in energy-intensive industries with climate-neutral hydrogen by 2030 and suggests establishing strict sustainability criteria for renewable hydrogen, in particular, for Sustainable Aviation Fuels. The Belgian hydrogen vision and strategy refers to SDG 13, particularly to target 13.1 (strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries). The overall context of the strategy foresees renewable hydrogen as an important pillar in enabling Belgium's transition away from fossil fuels to renewable energy and achieving climate neutrality by 2050. The national green hydrogen of Chile explicitly refers to SDG 13. It aims to develop green hydrogen as part of an "efficient pathway to a net-zero country" alongside energy efficiency and other solutions. Exporting green hydrogen and its derivatives will allow Chile to help other countries reduce their emissions to combat climate change. Colombia's hydrogen roadmap intends to address SDG 13 by using low-carbon hydrogen and its derivatives to decarbonise the economy and reduce CO2 emissions by 2.5–3 million tons by 2030 by using low-carbon hydrogen for transportation and industry. As the national green hydrogen strategy of Costa Rica refers to SDG 13, one of its main strategic axes is focused on decarbonisation of the transport and industry sectors through green hydrogen and its derivatives. Mauritania's national hydrogen strategy aims to contribute to SDG 13 by displacing fossil fuel usage and enabling greater renewable energy production to significantly reduce greenhouse gas emissions. The Romanian national hydrogen strategy aligns its measures with SDG 13 by promoting green hydrogen production and use as contributions to climate actions. The Green Hydrogen Roadmap in Uruguay also explicitly references SDG 13, striving to displace fossil fuel usage with green hydrogen and its derivatives both locally and for export.

SDG 14 (Life below water) and **SDG 15 (Life on land).** None of the analysed national hydrogen strategies explicitly refers to these SDGs.

SDG 16 (Peace, justice, and strong institutions). SDG 16 is acknowledged in the Belgian hydrogen vision and strategy, which mentions, in particular, targets 16.5 (substantially reduce corruption and bribery in all their forms) and 16.7 (ensure responsive, inclusive, participatory and representative decision-making at all levels). However, it does not provide specific details or plans for how hydrogen deployment aims to address SDG 16.

SDG 17 (Partnerships for the Goals). Six countries refer to SDG 17 in their hydrogen-related strategic policy documents. The Belgian hydrogen vision and strategy anticipates contribution of hydrogen to support SDG 17, in particular, targets 17.6 (enhance North-South, South-South and triangular regional and international cooperation on and access to science, technology and innovation and enhance knowledge sharing on mutually agreed terms, including through improved coordination among existing mechanisms, in particular at the United Nations level, and through a global technology facilitation mechanism) and 17.7 (promote the development, transfer, dissemination and diffusion of environmentally sound technologies to developing countries on favourable terms, including on concessional and preferential terms, as mutually agreed). In particular, Belgium seeks energy partnerships globally to position itself as a renewable hydrogen import/transit hub. The strategy emphasises cooperation within Belgium, across Europe, and globally to achieve strategy goals. The Chilean national green hydrogen strategy embraces the SDG 17 underlying premise of multi-stakeholder partnerships across industry, government, civil society and international borders as crucial for scaling up green hydrogen sustainably. It backs this up with specific planned actions on knowledge sharing and collaborative policies and explicitly acknowledges "openness to the world" and "green hydrogen diplomacy". Colombia's hydrogen roadmap intends to address SDG 17 by pursuing international cooperation for technology access and investment, exploring collaboration agreements with other countries, leveraging foreign affairs relationships and trade networks, and fostering public-private consortiums with foreign partners. The national green hydrogen strategy of Costa Rica emphasises the importance of collaborations to achieve the SDGs, referring, in particular, to the NAMA project [53]. Mauritania's national hydrogen strategy mentions SDG 17 in the context of academic, technological, and economic bilateral agreements with other countries.

3.2. Frequency analysis of SDG-related keywords

While more than three-quarters of the reviewed national hydrogen strategies do not explicitly mention particular SDGs, they often use SDG-relevant keywords. Our analysis of the full texts reveals various patterns of such keywords prevalence across countries and SDGs. It enables a more comprehensive understanding of how nations integrate the SDGs into their hydrogen strategies beyond direct citations.

Analysis of the frequency of keywords associated with the SDGs in national hydrogen strategies yields several key insights (Fig. 6). Similar to explicit SDG references, there is a major focus on SDGs 7 (Affordable and Clean Energy) and 13 (Climate Action), emphasising a strong commitment to developing sustainable energy solutions and the anticipated critical role of low-carbon hydrogen in climate change mitigation efforts, correspondingly. The significance of SDG 4 (Quality Education) highlights the recognition of education and skill development as foundational for advancing sustainable energy technologies.

Furthermore, the emphasis on SDGs 8 (Decent Work and Economic Growth) and 9 (Industry, Innovation, and Infrastructure) suggests that the hydrogen strategies are also geared towards fostering economic growth and employment as well as promoting industrial innovation and building robust infrastructure for sustainable development. Additionally, SDGs 11 (Sustainable Cities and Communities) and 12 (Responsible Consumption and Production), while less represented, indicate efforts towards enhancing urban sustainability and fostering responsible consumption patterns within the broader context of hydrogen energy development.

Analysis of the frequency of SDG-associated keywords in national hydrogen strategies reveals a strong emphasis on terms like "clean," "renewable," "energy," "climate change," and "decarbonisation" (Fig. 7). These terms align closely with SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), reinforcing the prioritisation of these goals observed in Figs. 5 and 6, with national policies targeting

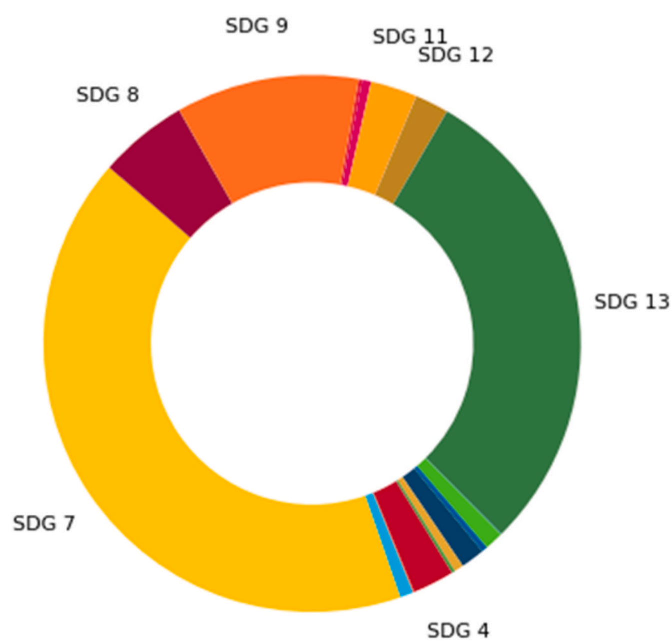

Fig. 6. Distribution of SDG-associated keywords in national hydrogen strategies. Wedge sizes denote the weights of SDG-associated keywords in the strategies. Only SDGs with a weight larger than 2% are annotated.

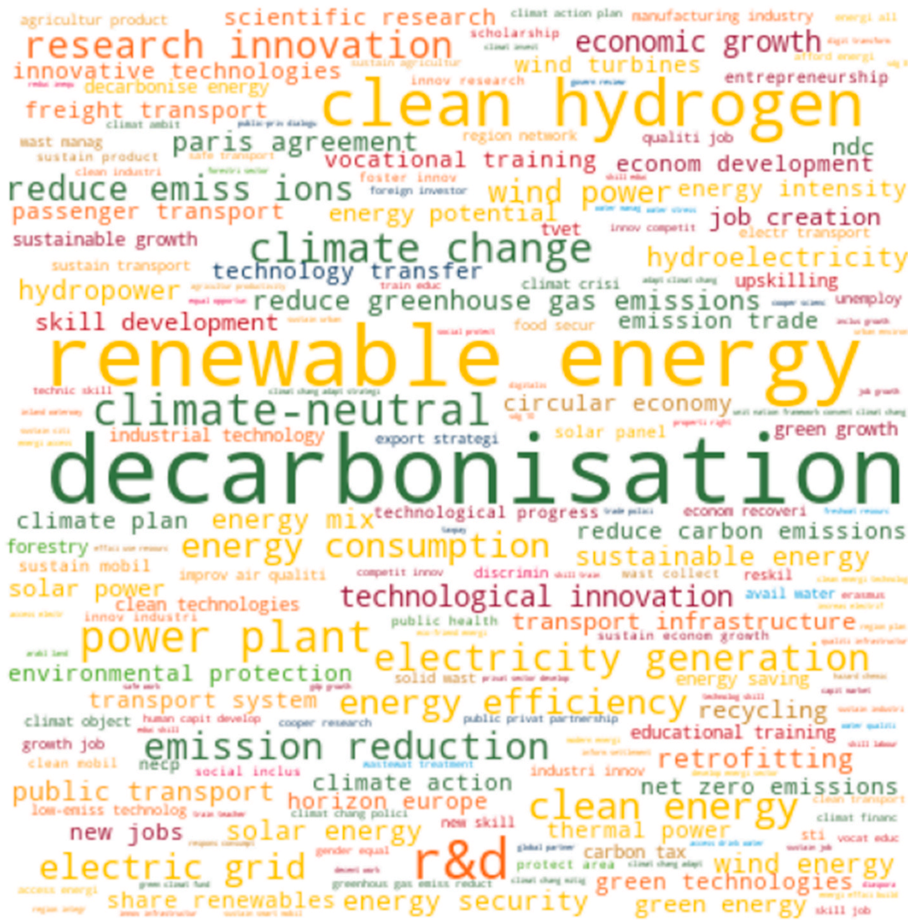

Fig. 7. Word cloud representing the frequency and thematic focus of terms within national hydrogen strategies. The size of each term corresponds to its relative frequency. The colour denotes the association of terms with their respective SDGs, with each hue matching the official SDG colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

carbon emission reductions and a transition to climate neutrality. The prominence of terms like "research and development (R&D)", "innovation," and "technology" suggests a strategic focus on innovative and sustainable hydrogen technologies and acknowledges the role of scientific research and technological advancement. The presence of these terms points to the emphasis of the strategies on knowledge creation, technological transfer, and innovation, indicating robust support for SDG 9 (Industry, Innovation, and Infrastructure). Further, the prominence of terms such as "skill development," "job creation," and "economic growth" corresponds to SDGs 4 (Quality Education) and 8 (Decent Work and Economic Growth), respectively. It highlights the dual focus of the strategies on building a skilled workforce and fostering economic development through the hydrogen economy. This suggests that the strategies are not only environmentally oriented but also seek to address educational and economic dimensions of sustainable development.

3.3. Country-specific analysis

Country-specific analysis of the SDG-associated keywords frequencies confirms the outcomes of the analysis of explicit mentions of SDGs in national strategies and overall distribution of the SDG-related keywords in Figs. 7 and 8, i.e., the strategic discourse of most of the examined strategies contains the keywords related to SDGs 7 and 13, followed by SDGs 9, 8, 12 and 11 (Fig. 8). On the one hand, the strategies which do not refer to specific SDGs in their national strategies still comprehensively cover the corresponding areas of energy availability (with notable exceptions of France and Ireland) and climate action (with notable exceptions of China, South Korea, and Tunisia[3]). On the other hand, the national hydrogen strategies of several countries, such as Belgium, Kenya, and Mauritania, which explicitly refer to multiple SDGs, contain few corresponding keywords. For instance, Belgium's strategy mentions, among others, SDGs 6, 8, 16, and 17 but lacks keywords related to these SDGs. These strategies, therefore, typically contain little detail on how exactly the declared SDGs can be achieved through the deployment of hydrogen projects. Finally, the keyword analysis can point to "hotspots" where strategies of certain countries discuss SDGs which are not commonly addressed by other countries. For example, the role of SDG 4 in the strategies of Namibia and South Africa is quite prominent, i.e., the Hydrogen Society Roadmap of South Africa includes a dedicated section on human capital development. The Hydrogen Economy Roadmap of Korea discusses the topic of SDG 11 (i.e., improving urban transportation) without explicitly mentioning this SDG. The hydrogen strategies of Mauritania, Hong Kong, Poland, and Uruguay implicitly address concepts of SDG 15 despite no explicit mention. Finally, the topics related to SDGs 7, 8, 9, and 13 are extensively discussed in numerous strategies without formally acknowledging these SDGs.

[3] Strategic documents of China, France, and Tunisia were machine-translated into English before the keyword analysis, which might affect the mapping results; therefore, these conclusions should be taken with caution.

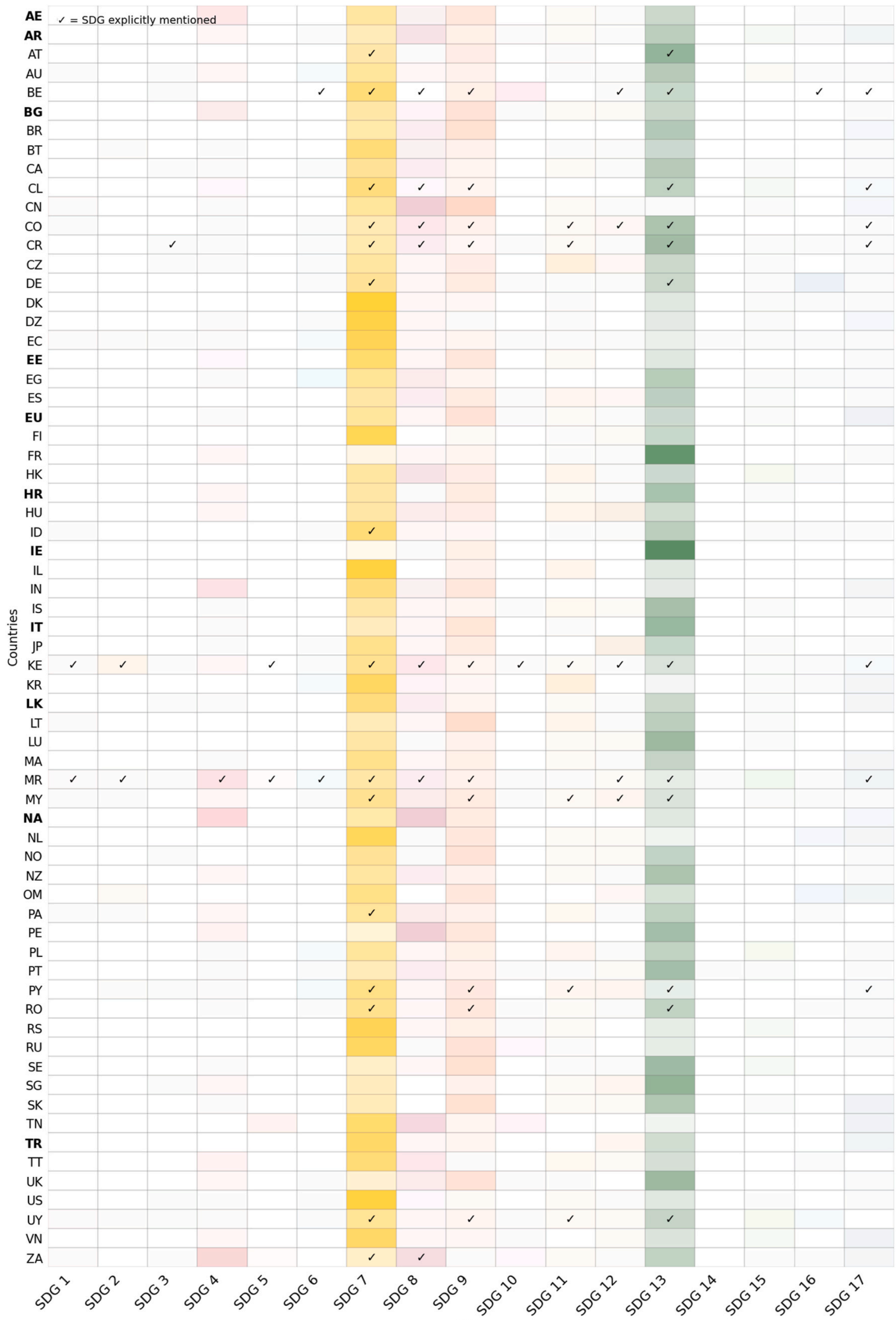

Fig. 8. Frequency of SDG-related keywords in national hydrogen strategies. The colours correspond to the official colours of the SDG framework. The saturation of the colours corresponds to the frequency of the keywords related to each SDG in each national hydrogen strategy. The ticks represent SDGs explicitly referenced in the strategies; strategies of countries highlighted in **bold** refer to the SDG framework or 2030 agenda without mentioning particular SDGs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.4. A link between the presence of a national hydrogen strategy and the national progress on the SDGs

Countries with a hydrogen strategy tend to have a higher rank in the SDG ranking in the Sustainable Development Report 2024 [50], i.e., countries with a hydrogen strategy have an average SDG Index Rank of approximately 48, while countries without a hydrogen strategy have an average SDG Index Rank of approximately 103 (out of 167 countries; a higher rank denotes a better outcome). An independent samples *t*-test revealed a statistically significant difference between the mean SDG Index Scores of countries with and without a hydrogen strategy ($t = 8.07, p < 0.001$). The analysis demonstrated that countries with a hydrogen strategy exhibited significantly higher mean SDG Index Scores than those without a hydrogen strategy (Fig. 9).

There are also statistically significant differences in the goal-specific scores between countries with and without a hydrogen strategy for most SDGs. These include SDGs 1 (No Poverty), 2 (Zero Hunger), 3 (Good Health and Well-being), 4 (Quality Education), 5 (Gender Equality), 6 (Clean Water and Sanitation), 7 (Affordable and Clean Energy), 8 (Decent Work and Economic Growth), 9 (Industry, Innovation and Infrastructure), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production), 13 (Climate Action), 16 (Peace, Justice, and Strong Institutions), and 17 (Partnerships for the Goals). Notably, the mean scores for SDGs 1–9, 11 and 16–17 are significantly higher in countries with a hydrogen strategy.

SDG 9 (Industry, Innovation and Infrastructure) demonstrated the highest statistical significance and positive difference in favour of countries with a hydrogen strategy (Fig. 9, upper right panel). In contrast, the mean scores for SDGs 12 (Responsible Consumption and Production) and 13 (Climate Action) are significantly lower in countries with a hydrogen strategy (Fig. 9, lower left panel). This suggests that countries with hydrogen strategies might be performing worse in these areas, potentially due to the current state of hydrogen technology and its environmental impact (i.e., the predominant use of grey hydrogen). Green hydrogen presents an opportunity to decrease emissions and shift to resource-efficient industrial processes in these countries. Finally, the mean scores for SDGs 10 (Reduced Inequalities), 14 (Life Below Water), and 15 (Life on Land) do not exhibit significant differences between the two groups of countries (Fig. 9, lower right panel). This suggests that the presence of a hydrogen strategy might not be strongly related to these specific goals. Interestingly, SDGs 14 and 15 are the only ones not referred to by any strategies that discuss specific SDGs (see Fig. 5).

4. Discussion

The findings from our analysis reveal that while many countries have embraced hydrogen strategies as part of their energy transition agenda, the explicit integration of SDGs into these strategies remains inconsistent [5]. While many countries recognise their importance, only a few clearly identify specific SDGs in their strategies that hydrogen can help achieve. This can be partially attributed to the fact that national hydrogen strategic documents vary substantially in content and depth, lacking a standardised international framework [8].

The dominant focal points of the reviewed national hydrogen strategies are SDGs 7 (Affordable and Clean Energy) and 13 (Climate Action). This aligns with the global emphasis on decarbonising energy

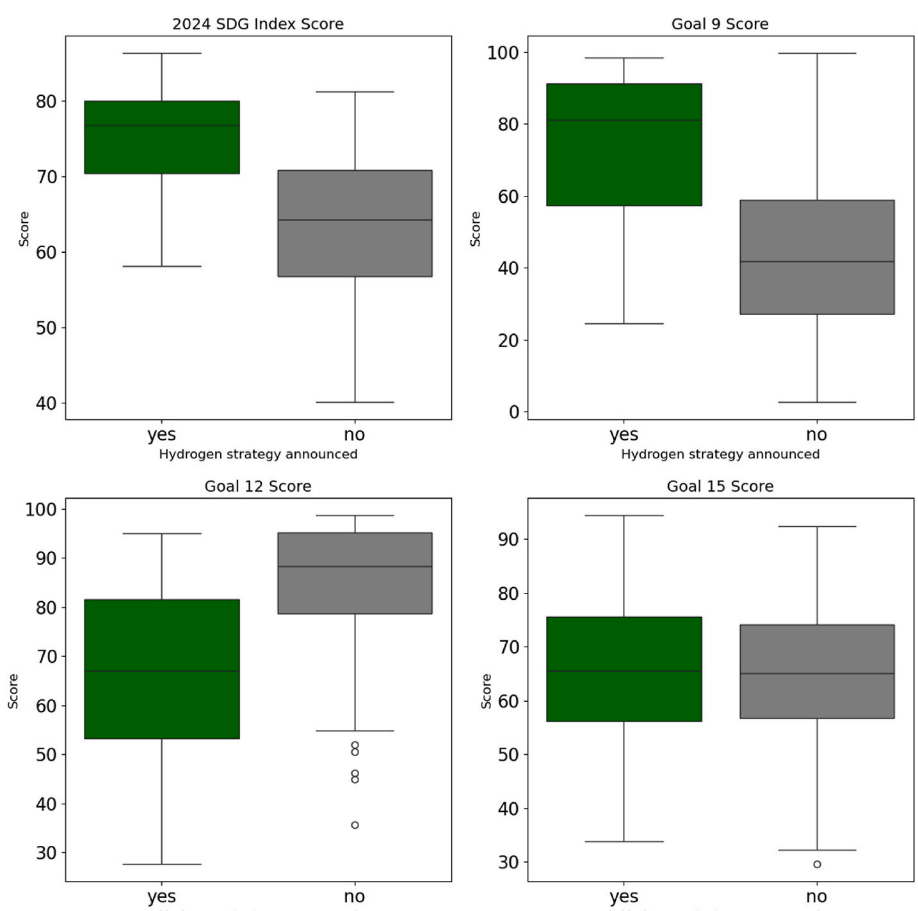

Fig. 9. Comparative Analysis of 2024 SDG Index Scores for countries with and without announced hydrogen strategies for the overall SDG Index Score (upper left panel) and for scores for separate goals illustrating either a statistically significant difference between countries with and without a hydrogen strategy (lower left and upper right panels) and a lack of statistically significant difference (lower right panel). The data source for the SDG Scores: [50].

systems and the potential of green hydrogen in the decarbonisation of energy systems [4]. The prominence of these SDGs likely stems from the urgency of climate change mitigation and the need for clean energy solutions. The integration of SDGs 8 (Decent Work and Economic Growth) and 9 (Industry Innovation and Infrastructure) indicates that hydrogen strategies consider broader economic prospects and technological advancements alongside climate mitigation. This commitment is evident in the frequent references to job creation, innovation, and infrastructure development, signalling that the hydrogen economy is envisioned as a catalyst for industrial growth and economic diversification.

Despite the rather limited explicit mention of SDGs, keyword analysis reveals a more nuanced picture. Even in strategies without explicit SDG references, keywords related to SDGs 7 and 13 frequently appear, suggesting an inherent focus on energy access and climate action. This finding is corroborated by a bibliometric analysis of academic research on green hydrogen [6]. The prevalence of keywords related to SDG 4 (Quality Education) further suggests the importance of education and skill development in supporting a transition to sustainable energy technologies. This emphasis on human capital aligns with findings from existing literature that highlight the need for a skilled workforce to drive the hydrogen economy [3]. Nevertheless, the absence of explicit references to the SDGs may hinder the ability to track progress effectively and coordinate actions with broader international sustainability objectives.

A notable finding of our analysis is the statistically significant difference in SDG performance between countries with and without national hydrogen strategies, as evidenced by their 2024 SDG Index rankings. This suggests that hydrogen strategies might contribute to the overall progress of these countries towards the SDGs. However, it is crucial to interpret these results with caution, as statistical association does not imply causation. The observed relationship could be influenced by various confounding factors, including countries' overall commitment to sustainable development, economic capacity, and technological readiness, rather than solely by the presence and implementation of hydrogen strategies. The strongest statistical significance for SDG 9 suggests that countries with national hydrogen strategies typically have more robust innovation ecosystems and industrial infrastructure. This aligns with the findings of [3], who identified the importance of improved infrastructure and research and development efforts for the transition to a hydrogen economy. Our counterintuitive finding of the significantly lower scores for SDGs 12 (Responsible Consumption and Production) and 13 (Climate Action) in countries with hydrogen strategies likely reflects the current reliance of these countries on fossil fuels (including grey hydrogen production), which raises concerns about environmental sustainability [54]. This highlights the need for a shift towards green hydrogen production methods to ensure that the hydrogen economy contributes positively to climate action and responsible consumption and production patterns.

In this vein, it is important to admit the environmental footprint of hydrogen production varies considerably depending on the chosen production method and its associated emissions. While green hydrogen can contribute to reducing greenhouse gas emissions, the energy intensity of the electrolysis process and resource demands like water consumption still pose challenges [3,4,17] argue the infrastructure requirements and high production costs can be significant barriers to scaling green hydrogen technologies, particularly in developing regions. Blue hydrogen, which relies on carbon capture and storage (CCS), is cheaper in production than green hydrogen and has lower emissions than grey hydrogen but still depends on fossil fuels [55], which complicates its contribution to achieving SDG 13 (Climate Action).

A critical consideration in advancing global hydrogen adoption is addressing technological, economic, institutional and social barriers [8]. As countries' ability to develop hydrogen economies is significantly influenced by their existing renewable energy capacity, water resources, industrial infrastructure, and human capacity, a key challenge is the uneven distribution of these assets across nations [2]. In particular, due to limited infrastructure and resources and inadequate institutional framework, many developing countries face substantial barriers to transitioning to a hydrogen economy [56,57]. These challenges align with the observed differences in SDG performance between countries with and without hydrogen strategies (Fig. 9), suggesting that existing socio-economic disparities may influence a nation's capacity to develop and implement hydrogen strategies. Addressing these inequalities requires enhanced international collaboration, technology transfer, and targeted support for developing nations in building necessary infrastructure and capabilities [11]. This support would be crucial not only for achieving SDG 17 (Partnerships for the Goals) but also for ensuring that the benefits of green hydrogen contribute equitably to sustainable development across all regions [11].

It is also essential to acknowledge synergies and trade-offs between various SDGs, as progress towards a specific goal or target may impede other goals and targets [3,5]. For instance, while green hydrogen production is generally considered beneficial for climate action (SDG 13), its potential adverse impact on water and land resources (SDGs 14 and 15) requires careful consideration and mitigation strategies. Similarly, promoting green hydrogen for economic growth (SDG 8) should go hand in hand with ensuring decent work conditions and addressing potential social risks in the hydrogen supply chain [32]. A detailed analysis of synergies and trade-offs of hydrogen and SDG on a target level has been recently conducted by Ref. [3,5]. However, these studies based their analysis on academic and grey literature evidence rather than systematically assessing national hydrogen strategies.

We acknowledge certain limitations of our approach. Focusing primarily on the textual content of national hydrogen strategies, it lacks a quantitative assessment of targets, investments, and timelines to provide a more robust evaluation of the ambition and potential impact of implementing the national hydrogen strategies in advancing towards the SDGs. For instance, while we have identified the prominence of SDG 7 in national strategies, a quantitative analysis of investment allocations towards renewable energy deployment for hydrogen production would provide a clearer picture of countries' commitment to green hydrogen. Similarly, while our study highlights the significance of SDG 9, examining the specific policy instruments, such as subsidies, incentives, and regulations, aimed at fostering innovation in the hydrogen sector would further strengthen the analysis. Future research employing a more quantitative approach—including an assessment of investments, policy instruments, and regional cooperation—could provide a clearer picture of how hydrogen strategies are being implemented and their actual impact on advancing the SDGs. While we identified mere mentions of SDGs in national hydrogen strategies, strategic documents may discuss not only the benefits of hydrogen development towards the SDGs but also the barriers. Finally, in the interest of brevity, we conducted our analysis on the level of goals rather than on the level of targets.

Another methodological limitation relates to handling multilingual source documents and associated translation challenges. Using online translation services for strategies published in languages other than English may introduce potential terminological inconsistencies. As [58] demonstrated in their analysis of EU energy policy documents, translation challenges can affect the precision of automated text analysis, particularly for domain-specific vocabulary that shows subtle variations across languages. The automated translation process may have affected our keyword analysis accuracy, especially for technical terms and SDG-specific terminology.

To address potential bias from using a single SDG mapping tool, future work could explore ensemble modelling approaches that combine multiple SDG labelling systems [39]. Such approaches can improve the robustness of the mapping while reducing susceptibility to individual system biases [49].

Despite these limitations, our study offers valuable insights for policymakers, industry stakeholders, and researchers. By identifying the areas of convergence and divergence between national hydrogen strategies and the SDGs, we underscore the need for greater ambition, tangible action plans, and international collaboration to fully leverage the potential of hydrogen for sustainable development and achieving the SDGs.

5. Conclusion

Integrating SDGs into national hydrogen strategies is essential to aligning energy policies with global sustainability objectives. However, less than one-third of national hydrogen strategies and roadmaps explicitly mention SDGs, reflecting a gap between aspirations towards sustainable development and its formal recognition in policy documents. Despite this, the implicit alignment with SDGs, as evidenced through keyword analysis, indicates that hydrogen strategies are inherently linked to sustainability objectives, particularly those related to clean energy, climate action, economic growth, and industrial innovation. Expanding this alignment to include other goals such as education, social equity, and environmental protection could render hydrogen policies more comprehensive and effective in promoting sustainable development.

Our findings suggest that hydrogen has the potential to play a significant role in advancing multiple SDGs, but realising this potential will require a more explicit, coordinated, and holistic approach. Future hydrogen strategies should, therefore, aim to explicitly articulate their contributions to the SDGs, fostering greater transparency and accountability. By encompassing a wider array of SDGs beyond energy- and climate-related, national hydrogen strategies could contribute more comprehensively to social equity, education, and responsible consumption. Such an approach would not only support national development goals but also contribute to the collective global effort to achieve the 2030 Agenda for Sustainable Development.

CRediT authorship contribution statement

Nikita Strelkovskii: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nadejda Komendantova:** Writing – review & editing, Validation, Supervision, Conceptualization.

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 AI model to improve the readability of the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2025.01.134.

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