Sustainability of green hydrogen technologies depends on energy mix and supply chain

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A sustainable international green hydrogen supply chain is crucial for achieving net-zero. Here, we performed a spatial-temporal prospective life cycle assessment of twenty international supply chain scenarios in 2023, 2030, 2040, and 2050 across five hydrogen production technologies (three based on water electrolysis and two on biomass conversion) in fourteen countries. The results underscore the substantial roles of the energy mix and supply chain configuration in shaping green hydrogen sustainability. In 2023, electrolysis-based systems show higher global warming impacts than biomass-based ones. Along the net-zero pathway, ecological impacts vary across scenarios. By 2050, proton exchange membrane electrolysis and dark fermentation exhibit the largest and smallest reductions in global warming impacts, respectively. The most sustainable chain involves manufacturing Proton the United States, identified using a multi-criteria decision analysis method, exchange membrane electrolysis systems in the United Kingdom, with 50% exported to that evaluates overall performance across environmental indicators.

Over the past few decades, the rise in global population and heightened energy demand have driven up the utilization of fossil fuels, resulting in phenomena such as global warming (GW) and environmental contamination[1,2]. The difficulties in lowering emissions in energy-related sectors largely arise from the global reliance on fossil fuels[3]. Depletion of fossil resources, adverse environmental effects, reliance on hydrocarbon resources, and the increasing costs of fossil fuels are the predominant reasons for concern[4]. These issues motivate governments and policymakers to develop a new framework focused on energy security and environmental conservation[5,6]. Growing worries revolve around the depletion of fossil fuel sources and the stability of the energy supply[7]. Recent studies suggest that greenhouse gas emissions are expected to rise by 50% by 2050, making it the leading and most influential driver of climate change[8]. Besides, the substantial volatility in fossil fuel prices has had a notable impact on both the energy market and industry forecasts[9]. In the pursuit of alternatives to carbon-intensive fossil fuels, hydrogen stands out as a promising option, owing to its versatility and potential as a viable solution across multiple applications[10]. At present, approximately 96% of hydrogen production is derived from fossil fuel reforming processes, including the utilization of petroleum, natural gas, and coal[11,12]. In light of the ongoing energy crisis, accelerating the introduction of green hydrogen is considered a critical strategy to reduce reliance on imported fossil fuels[13]. A key component of this initiative is the growing emphasis on renewable energy sources, which

are projected to account for around two-thirds of the global energy supply by 2050[14]. The adoption of a sustainable supply chain (SC) has become a strategic process, enabling both companies and governments to gain a competitive advantage[15]. Understanding how sustainable is the green hydrogen supply chain (GHSC) is critical because this will shape future directions of specific hydrogen technologies and how they will be produced in order to achieve the net-zero goal by 2050.

State of the art

The literature on the sustainability of hydrogen is fragmented. A literature review on research on hydrogen production methods showed that some researchers analyzed the environmental impact of electrolysis systems[16-18]. Some studies focused on biomass-based hydrogen production, life cycle assessment (LCA) to produce hydrogen, such as biomass gasification (BG)[19-22]. Different hydrogen production approaches from both fossil and renewable-based sources are compared from the environmental point of view[23]. Few studies have analyzed hydrogen technology from an international SC perspective holistically. Both fossil and nonfossil hydrogen production systems for generating blue and green hydrogen are assessed using a prospective life cycle approach to produce 500 Mt/yr of hydrogen, considering potential future SC changes[24]. The environmental impact of seven hydrogen storage and transport pathways was analyzed and grouped into three scenarios based on daily hydrogen demands and transport distances[25].

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A study considered hydrogen production, including distribution in Germany[26], however, in another study, the hydrogen SC environmental assessment in Japan is evaluated[27]. A study was conducted to assess selected environmental effects at various life cycle stages of hydrogen production pathways, with a special focus on hydrogen refueling stations[28]. Another study examined the LCA of three SC architectures for hydrogen transport and distribution[29]. A model has been developed to perform a LCA of energy consumption and greenhouse gas emissions in hydrogen SCs for fuel-cell vehicles in China[30]. Another study assessed the environmental impact of ammonia production utilizing different hydrogen SCs, taking into account different technological processes[31]. A hydrogen SC environmental assessment is conducted, considering production via water electrolysis linked to offshore wind farms, as well as transportation and storage[32]. Another study sought to assess the environmental impacts of cross-border hydrogen SCs relative to local hydrogen production operating hours and pipeline transport distances[33]. The life cycle environmental and economic impacts of alternative fuel freight transport were examined based on vehicle types and SCs, and a database was developed for key electric and hydrogen SC scenarios[34].

Some studies have examined SC factors for optimal international hydrogen and ammonia SC planning, assessing their economic viability. Life cycle optimization framework has been applied to hydrogen SC network design, incorporating both life cycle costing and assessment through a bi-objective optimization approach[35]. The implications of considering fast timescale volatility in renewable energy sources and uncertainties in demand on the design and evaluation of the international green hydrogen SC are being assessed in research done by Kim et al.[36]. The shift to green energy carriers, with green ammonia as the primary green hydrogen carrier, is examined in another study[37], which provides an overview of the current ammonia trade and develops an optimization model to assess the green ammonia value chain from production to importation. However, the prospective LCA aspect is not evaluated in these studies, leading to the lack of understanding of the sustainability of GHSC in 2050.

This study models how different international green hydrogen supply chain (IGHSC) scenarios affect the sustainability of the different hydrogen production technologies. This study introduces several innovative aspects that have been either overlooked or rarely addressed in previous research. Through a thorough literature review, it became evident that there exists a major gap in the sustainability assessment of IGHSC. While many studies have focused on evaluating and comparing different technologies or have examined local SCs, there has been a lack of attention given to holistically modeling the SC within the context of the international hydrogen economy trade. First, this study addresses this gap by encompassing the entire IGHSC, particularly focusing on its utilization within the transportation sector, thereby evaluating the environmental complexity of the global SC (involving 14 countries). Second, our models focus on multiple IGHSCs and trade, involving 20 IGHSC scenarios reflecting the interdependency of import and export in the hydrogen economy. Third, our prospective LCA models model the international SCs of the five most promising green hydrogen technologies geo-spatially across 14 countries over 27 years (from 2023 to key milestones of 2030, 2040, 2050). Besides, some studies have limited the system boundary to specific phases of the SC, whilst this study includes wider system boundary of materials extraction, feedstock production, manufacturing, storage, transportation and end use in IGHSC, representing the fourth innovative lens. Previous studies have not widely examined IGHSC scenarios involving the major countries in the hydrogen economy and their connection with the five promising green hydrogen production technologies, making this the fifth innovative aspect of the research. The 5 considered technologies in this assessment are 3 electrolysis systems (alkaline electrolysis (AE), proton exchange membrane (PEM) electrolysis, solid oxide electrolysis (SOE)) and 2 biomass technologies (BG and dark fermentation (DF)). Additionally, the use of DF technology for large-scale hydrogen production is less explored.

This study analyses the net-zero plans of the 14 countries considered, utilizing prospective LCA to forecast the sustainability of 20 IGHSC scenarios of the 5 promising green hydrogen technologies involving the 14

countries by 2030, 2040 and 2050. In addition, this study proposes an innovative approach for assessing the sustainability of IGHSC scenarios, combining spatial-temporal prospective LCA with an advanced MCDA method. Integrating the technique for order of preference by similarity to the ideal solution (TOPSIS) with a fuzzy-based methodology allows for a detailed and systematic ranking of all scenarios considered. This integrated framework effectively addresses the uncertainties and subjectivity inherent in sustainability evaluations. Through the application of this distinct methodology, our research provides an innovative approach to sustainability assessment, offering a more robust and adaptable decision-support tool for optimizing hydrogen SCs.

Table 1 summarizes the extended SC phases for all 5 green hydrogen technologies (AE1–4, PEM1–4, SOE1-4, BG1–4, and DF1–4) for the 20 IGHSC scenarios. The electrolysis systems are represented in blue, while biomass-based systems are depicted in green. The SC phases include raw material extraction, production, storage, transportation, and distribution to end use (See Supplementary Information, Hydrogen Supply Chain section). The manufacturing phase includes upstream raw materials extraction in the case of the 3 electrolysis and 2 biomass systems; and feedstock supply in the case of the 2 biomass technologies. The selection and allocation of green hydrogen production and export percentages by countries are determined through an analysis of the net-zero strategies of 14 nations. This analysis considers external factors, such as geopolitics, economic conditions, international trade, and energy policies. The operation and maintenance (O&M), storage, and end-use processes are influenced by whether the green hydrogen production technology is used domestically or exported, noting that hydrogen itself is always produced in the country of use. For the biomass technologies, the feedstock supply in the selected countries is determined based on either domestically produced or imported feedstock. In total, we model 20 IGHSC scenarios covering 14 countries (4 scenarios for each of the technologies). In each scenario, the export-import ratio of the countries involved in manufacturing, O&M, storage, and usage reflects the dynamics of the IGHSCs, which include the UK, Japan, China, France, Norway, Canada, Germany, South Korea, the USA, Austria, Ireland, Poland, Italy, and the Netherlands. The system boundaries for the SCs of all electrolysis and biomass-based green hydrogen technologies considered are illustrated in Fig. 1. Further details of each modeled SC, such as data inventories, manufacturing processes, ports for imports and exports, end-use locations, and energy and material inputs, can be found in the Supplementary Information (Supplementary Tables 1–9). The Supplementary Information also provides details of the design of IGHSC, rationale for scenario selection and export assumptions, pedigree matrix analysis of data quality, uncertainty management and future projections.

The study reveals that in 2023, electrolysis SCs have higher (GW) impacts than biomass systems, mainly due to energy-intensive O&M phases. By 2050, PEM SCs are projected to be the most sustainable. Achieving net-zero goals will reduce environmental impacts, with fossil fuel-dependent countries seeing higher effects. As nations transition to green energy by 2050, PEM shows the lowest impact, though this varies by scenario. Biomass systems are less energy-dependent but still require sustainable feedstocks, with environmental impacts influenced by feedstock type, availability, and cultivation.

Sustainable pathways: prospective LCA of IGHSC

The impact of net-zero pathways on the international green hydrogen SC is examined through the conduct of a prospective LCA, which is based on the development of renewable resources within the energy grids of the countries under study. The main goal of this study is to conduct a spatial-temporal comparative life cycle SC assessment of five main hydrogen production technologies to generate green hydrogen. This is achieved by developing different SC scenarios that consider the 14 countries involved in technology manufacturing, feedstock production, and hydrogen usage. This study employs a prospective LCA to evaluate the temporal variation in environmental impacts across multiple time horizons, including 2023 (baseline), 2030, 2040, and 2050, in alignment with decade-specific net-zero targets.

Table 1 | Summary of the developed 20 international green hydrogen supply chain scenarios for all studied technologies

Scenario	Feedstock supply	Manufacturing	Technology export	O&M, storage and usage
AE 1	N/A	UK	50% to China	UK and China
AE 2	N/A	Japan	100% to Italy	Italy
AE 3	N/A	China	50% to Netherlands	China and Netherlands
AE 4	N/A	France	50% to USA	France and USA
PEM 1	N/A	Norway	100% to USA	USA
PEM 2	N/A	Canada	50% to UK	Canada and UK
PEM 3	N/A	China	50% to Italy	China and Italy
PEM 4	N/A	UK	50% to USA	UK and USA
SOE 1	N/A	Germany	50% to UK	Germany and UK
SOE 2	N/A	South Korea	50% to Italy	South Korea and Italy
SOE 3	N/A	UK	50% to Japan	UK and Japan
SOE 4	N/A	USA	100% to Canada	Canada
BG 1	China	Austria	100% to Japan	Japan
BG 2	Canada	Canada	50% to USA	Canada and USA
BG 3	Germany	Germany	50% to UK	Germany and UK
BG 4	China	USA	100% to South Korea	South Korea
DF 1	China	Japan	50% to China	Japan and China
DF 2	UK	Ireland	50% to UK	Ireland and UK
DF 3	China	Poland	100% to China	China
DF 4	China	Germany	50% to Netherlands	Germany and Netherlands

This table presents the import/export and geography of different phases of determined SC scenario for all technologies. Blue is related to electrolysis systems, which include AE, PEM and SOE. Green represents biomass technologies, which include BG and DF.
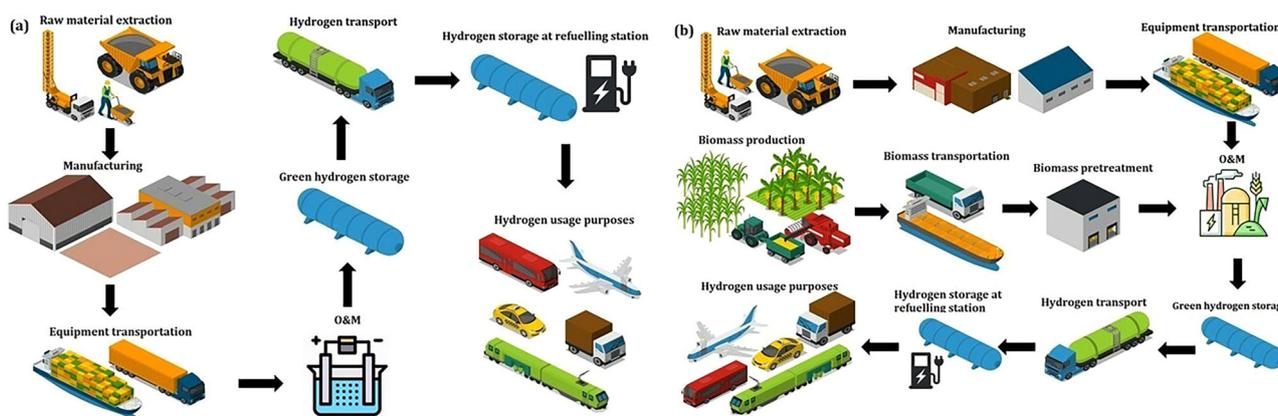

Fig. 1 | System boundary of the green hydrogen supply chain for evaluated electrolysis and biomass systems. a This diagram illustrates the system boundary for three examined electrolysis systems, encompassing raw material extraction, transportation to manufacturing sites, exportation to importer countries, installation, O&M of the systems, storage of generated green hydrogen, and transportation to refueling stations for utilization by various transportation modes. **b** This diagram delineates the system boussndary for biomass-based hydrogen production technologies, incorporating raw material extraction, transportation to manufacturing sites, exportation to importer countries, biomass and feedstock production as another key aspect of the SC, transportation to pre-treatment units, both manufactured systems and feedstock transport for the O&M phase, storage of generated green hydrogen, and subsequent transportation to refueling stations for transportation usage, constituting the final parts of the considered boundary. This figure was created by the authors using icons and the free design tool available on Icograms (https://icograms.com/designer).

The system boundary defined in this study comprises raw material extraction, manufacturing of technologies, transportation, O&M, and hydrogen storage. The results are presented for four key impact categories: GW, marine eutrophication (ME), stratospheric ozone depletion (SOD), and human toxicity (HT). These impact categories are emphasized as they encompass critical and diverse aspects of environmental health and sustainability, as determined by the normalized values. Focusing on these categories allows the study to offer a clear and comprehensive overview of the most critical impacts. The Supplementary Information includes an additional 14 midpoint impact categories, providing a broader perspective on the environmental impacts assessed in this study (Supplementary Figs. 1 and 7). The results of the evaluated scenarios for each impact category are presented as follows:

Global warming impact
The GW impact values for all scenarios and technologies are computed across all SC scenarios (Fig. 2a). These findings are derived from environmental impact assessments of the SC, rather than solely focusing on
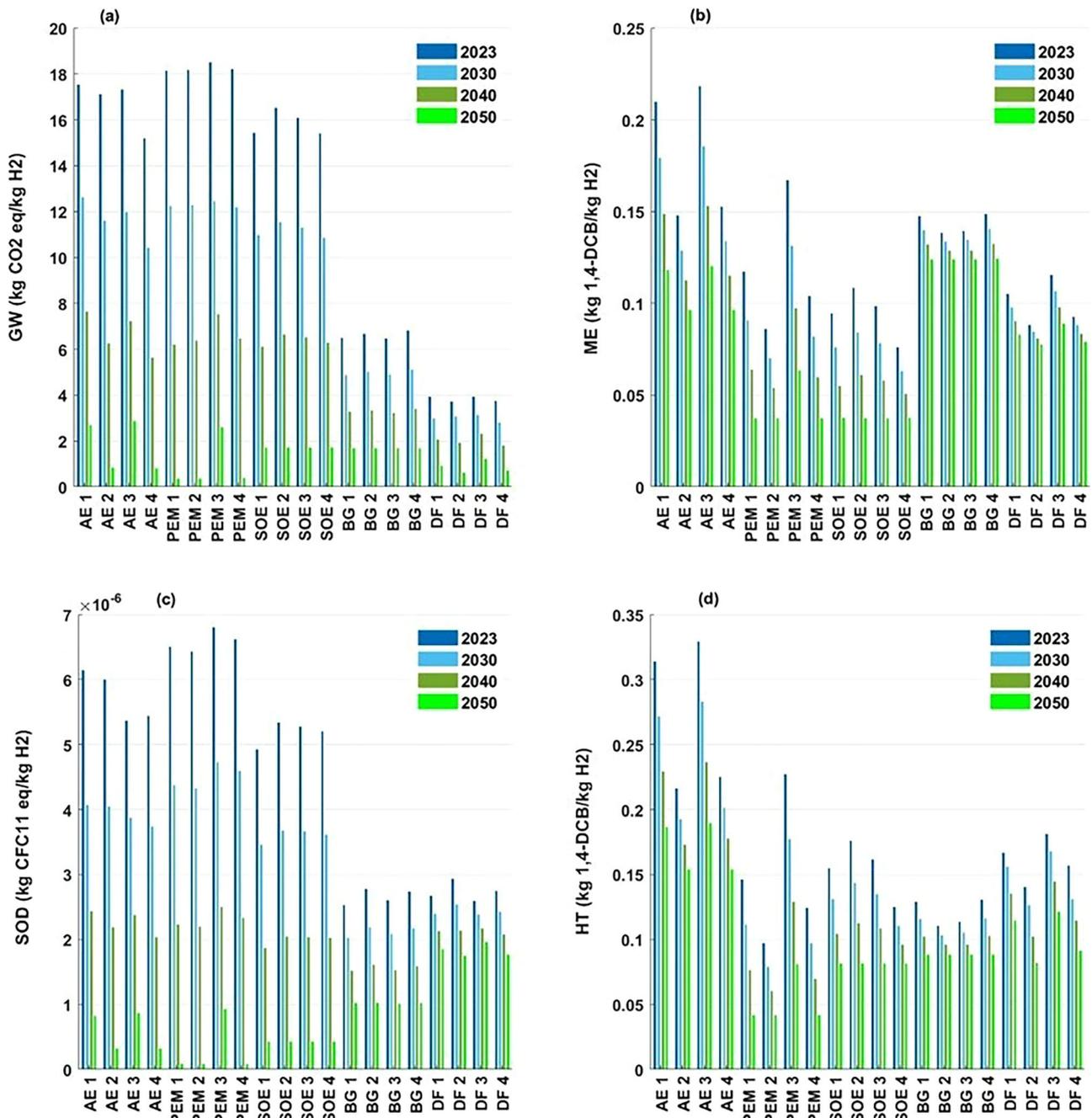
Fig. 2 | Environmental impacts in 2023, 2030, 2040 and 2050 for four selected impact categories for all considered technologies and supply chain scenarios based on prospective LCA. a This plot shows the obtained results for GW impact, **b** this graph illustrates the ME impact resulting from each scenario, **c** this plot displays the SOD impact arising from different SC scenarios, and **d** this graph shows the HT impact of all considered SC scenarios.

technological impacts. Dark blue bars represent the GW impact results for the year 2023. The analysis indicates that, in the 2023 assessment, the three electrolysis-based SCs demonstrate higher GW impacts compared to the two biomass-based systems. This elevated GW impact primarily stems from the O&M phase of electrolysis technologies, which consume more energy over their operational lifetimes. Another main contributor is the manufacturing phase, driven by the materials used and electricity consumed during the manufacturing process. Among the electrolysis technologies, PEM scenarios exhibit higher GW impacts compared to the other two, with scenario PEM3 showing the highest GW impact among all assessed scenarios and technologies. This higher GW impact is attributed to a major portion of electricity generation from oil, natural gas, and coal in these scenarios. The results indicate that DF4 ISC has the lowest GW impact

among all scenarios and systems studied in 2023, although the differences among all DF scenarios are negligible. In all scenarios, considerable reductions in GW values are observed due to the integration of renewable energy sources into the energy mix of all countries. However, the reduction trend varies across each scenario. The most substantial reduction in GW impact is observed in PEM4, decreasing from 18.21 to 0.38 kg CO_2eq per kg H_2 between 2023 and 2050, while the lowest reduction is seen in DF3, declining from 3.92 kg CO_2eq per kg H_2 in 2023 to 1.22 kg CO_2eq per kg H_2 in 2050.
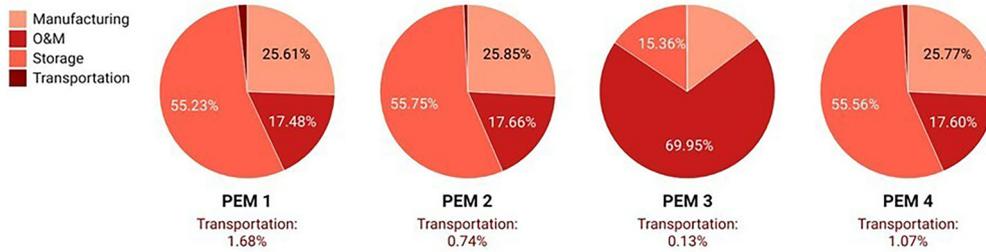
Marine eutrophication impact

The ME values for all examined technologies and scenarios are computed (Fig. 2b). The baseline cases, which depict the ME impact in 2023, revealed
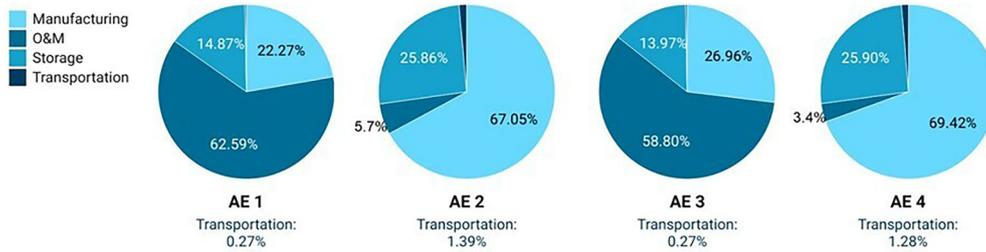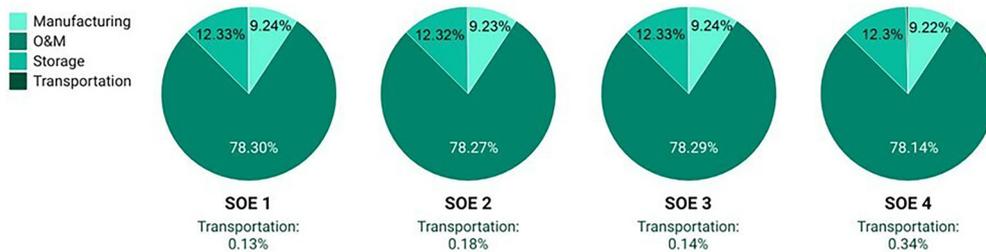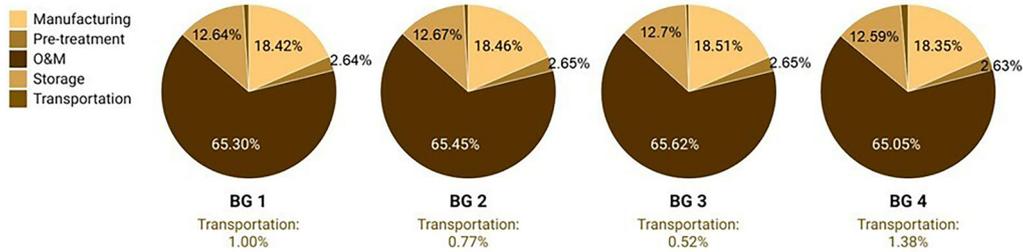
Fig. 3 | GW impact in 2050 by supply chain phases for all analyzed technologies and scenarios. These pie charts illustrate each SC phase contribution in GW potential for different developed SC and technologies based on prospective LCA for 2050. **a** These pie graphs show the results for AE SC scenarios, **b** these pie graphs display the results for PEM SC scenarios, **c** these pie graphs show the results for SOE SC scenarios, **d** these pie graphs illustrate the results for BG SC scenarios, and **e** these pie graphs show the results for DF SC scenarios.

that the highest ME impact is associated with the AE3 scenario (0.218 kg 1,4-DCB per kg H2). Following this, AE1 and PEM 3 exhibit the highest damaging ME impact. Conversely, SOE4, PEM2, and DF2 demonstrate the lowest ME impact among these scenarios (0.088 kg 1,4-DCB per kg H2). An assessment aimed at achieving net zero within different timeframes shows a declining trend in ME impacts. This decline is attributed to the increased share of renewable resources in the energy mix of all countries. However, this reduction trend is more pronounced for electrolysis technologies compared to the BG and DF scenarios. The smaller reduction in ME impacts associated with BG and DF is mainly due to their lower dependence on the energy mix during both system operation and manufacturing. In contrast, electrolysis systems require significantly more electricity during these phases, leading to greater impacts. The ecotoxicity issues of biomass systems primarily arise from cultivation, crop growth, and the associated toxicity related to feedstock production.

Stratospheric ozone depletion impact

The impacts related to SOD for all examined scenarios are assessed (Fig. 2c). Based on the results from the base cases, PEM3, PEM4, and PEM1 exhibit the highest SOD impact in 2023, respectively. Following the PEM scenarios, AE-related scenarios show a higher SOD impact, followed by SOE technology with a slight difference. However, the SOD impact of BG and DF scenarios in 2023 is significantly lower than that of electrolysis technologies. Surprisingly, the expansion of the renewable resource share in the electricity mix of countries has a notable impact on reducing SOD-related impacts for the three electrolysis systems and their respective scenarios. However, this reduction for biomass-based technologies and scenarios is considerably lower. Interestingly, PEM scenarios, which have the highest SOD impact in 2023, have the potential to significantly reduce this impact by 2050 by achieving the net-zero goal, resulting in the lowest SOD impact. The highest reduction in SOD impact by 2050 is associated with PEM4. It should be noted that in scenarios involving China in manufacturing or O&M, the reduction trend is lower than in other scenarios. This is mainly due to the high proportion of coal and oil-based electricity generation and the longer net-zero target (2060) compared to other considered nations.

Human toxicity impact

The HT of all considered scenarios is evaluated to compare each SC route (Fig. 2d). The findings from the base cases indicate that AE3, AE1, and PEM3 exhibit the highest HT impact compared to other scenarios. The HT impact of the base cases for SOE and DF are similar to each other, while BG's HT impact is slightly lower. Among all scenarios examined, PEM2 has the lowest base case HT impact in 2023. The subsequent net-zero targets will have a remarkable impact on reducing HT impact. However, it is important to note that even in 2050, the HT impact of AE scenarios remains higher than that of other technologies and scenarios, underscoring the critical nature of this technology. This elevated toxicity issue is attributed to the materials used in the manufacturing process of the Balance of Plant and stack. Additionally, the lowest reduction percentage is observed in BG scenarios, while the highest reduction trend is seen in PEM scenarios. According to the prospective LCA results, in 2050, the lowest HT impact is associated with PEM2 (0.042 kg 1,4-DCB per kg H2), while the highest is related to AE3 (0.189 kg 1,4-DCB per kg H2). Further results for the remaining 14 other midpoint impact categories are provided in Supplementary Fig. 1 in Supplementary Information.

AE phase contributions to global warming

The distribution of phases across all analyzed technologies and SCs is depicted based on four primary impact categories in the year 2050 (Fig. 3). It is evident that the O&M phase serves as the primary contributor to GW impact in AE1 and AE3 scenarios, accounting for approximately 62.59% and 58.80%, respectively (Fig. 3a). Conversely, the manufacturing phase emerges as the main GW impact contributor in AE2 and AE4 scenarios, comprising around 67.00% and 69.42%, respectively. In scenarios where China is the manufacturer or operator of the AE system (AE1 and AE3), the

O&M phase continues to show a high GW impact. This is due to China's projected reliance on fossil-based electricity generation in 2050, which leads to an increased GW impact. This is evident from Fig. 3a, where the GW impact of AE1 and AE3 in 2050 exceeds that of AE2 and AE4 by more than threefold. The manufacturing phase also represents a major contributor to GW impact in AE1 and AE3, accounting for 22.27% and 26.96%, respectively. Additionally, the storage phase contributes to GW impact, while the transportation phase emerges as the least substantial contributor.

PEM phase contributions to global warming

The distribution of GW impact across various SC phases for PEM technology in each scenario is evaluated (Fig. 3b). The findings revealed that the storage phase accounts for approximately 55.00% of the total GW impact and serves as the primary contributor in PEM1, PEM2, and PEM4 scenarios. Manufacturing and O&M are the next notable contributors in sequence. However, in PEM3, around 70.00% of the total GW impact stems from the O&M phase, attributed to the utilization of fossil fuel-based electricity generation within China's grid network in 2050. Additionally, it is observed that transportation has a negligible impact compared to the other phases.

SOE phase contributions to global warming

For each scenario, the distribution of GW impact across different phases of the hydrogen SC for the SOE system is analyzed (Fig. 3c). The findings reveal that the O&M phase contributes approximately 78.00% of the total GW impact, primarily due to the reliance on natural gas for heating during O&M operations. This leads to a higher GW impact compared to other phases. The distribution of phases across all scenarios is largely similar, as all the countries considered in the SOE scenarios have outlined a net-zero plan for 2050, implying that renewable resources should support 100% of the energy mix. To mitigate the GW impact of O&M, the heat required for system operation should be supplied by less pollutant or renewable heat resources, which would significantly reduce environmental impact. The storage and manufacturing phases are the next two notable GW contributors, accounting for approximately 12.30% and 9.20%, respectively.

BG phase contributions to global warming

The analysis examined the contribution of each phase to the GW impact of the BG system in each scenario (Fig. 3d). According to the findings, the O&M phase accounts for the highest GW impact (approximately 65.00%), followed by the manufacturing phase at around 18.00%, and the storage phase at approximately 12.00% of the total GW impact. It is noteworthy that activities, such as biomass production, purification, gasification process, reforming, and pressure swing adsorption, are all encompassed within the O&M phase. The transportation phase has the least impact. Additionally, the pre-treatment of biomass feedstock contributes to only around 2.50% of the total GW impact.

DF phase contributions to global warming

The impact of each SC phase on the GW category for DF technologies in each scenario is depicted (Fig. 3e). It is evident that the manufacturing phase is the primary contributor to GW impact in 2050 for all scenarios. However, the contribution of the manufacturing phase varies across scenarios. DF2 shows the highest portion at 78.80% of the total GW impact, while DF3 exhibits the lowest at 41.10%. The storage phase emerged as the second main contributor to GW impact in all scenarios. However, the transportation phase exhibited a higher GW impact compared to other technologies, especially when the feedstock supplying point is distant from the importer countries. The highest GW impact attributed to transportation is observed in DF 4, accounting for 14.10% of the total GW impact. The O&M phase ranked as the third contributor to GW impact. However, since the energy required for DF operation is lower than that for other technologies, this system exhibits less dependency on the energy mix. The GW impacts by technological phase contributions for 2023, 2030 and 2040 are shown in Supplementary Figs. 2–6. These graphs depict the variations in phase portions from 2023
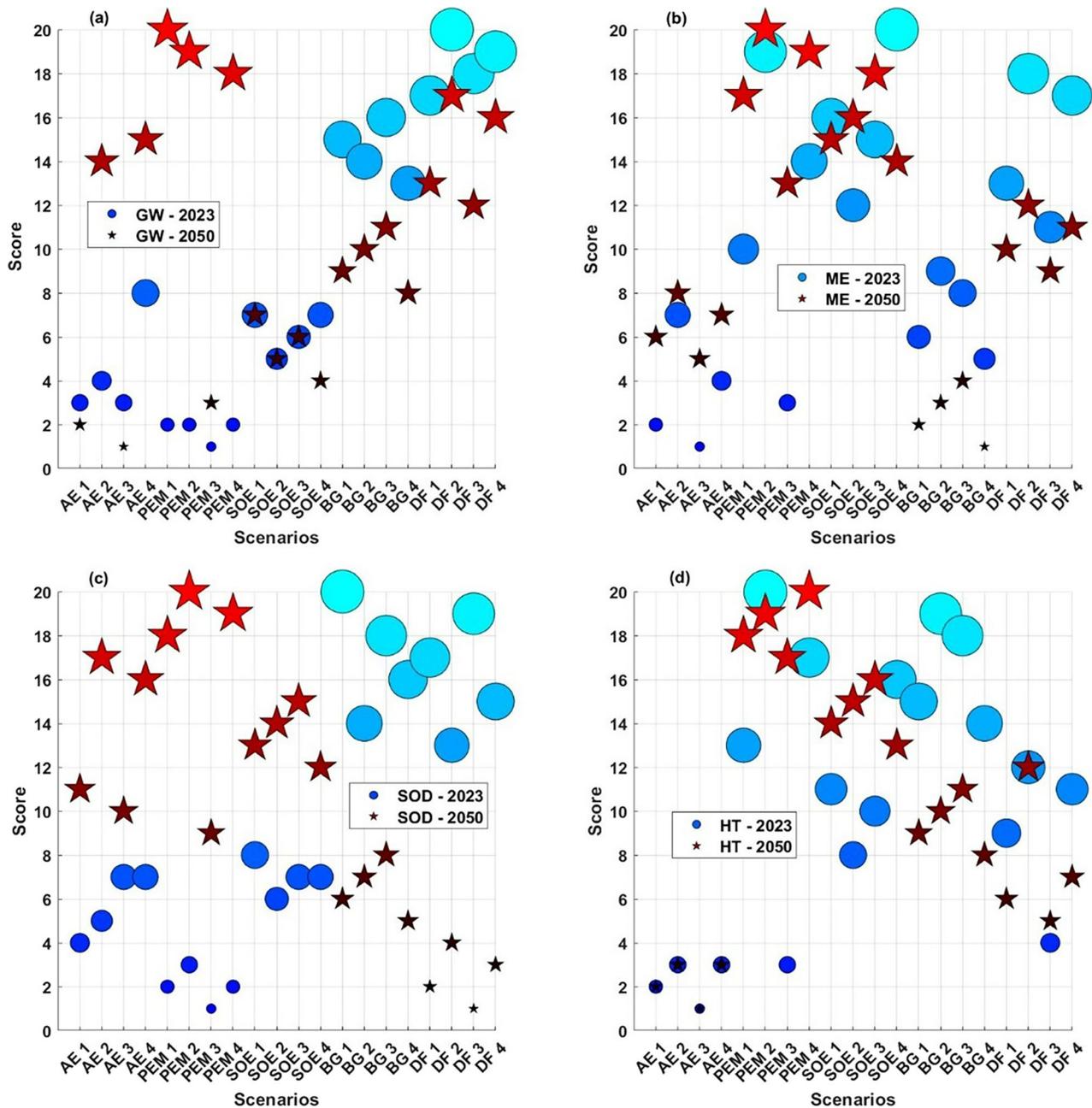
Fig. 4 | Technological supply chain sustainability ranking of all studied scenarios.
a This plot illustrates the sustainability ranking of all considered scenarios based on
GW impact, **b** this graph presents the sustainability ranking based on ME impact,
c this plot displays the sustainability scoring according to SOD impact and **d** this
graph depicts the sustainability scoring according to HT impact category. Circles
represent GW, ME, SOD and HT impacts in 2023. Pentagrams represent GW, ME,
SOD and HT impacts in 2050. The larger the size and the lighter the colors of the
pentagrams and circles, the lower the environmental impacts of the international
green hydrogen supply chains.

to 2050, illustrating the effect of the development of the share of
renewable resources in energy grids.

Hydrogen's role in energy resiliency and security

As nations strive to reduce carbon emissions and transition to sustainable
energy sources, green hydrogen production emerges as a promising solu-
tion. However, the methods used for generating green hydrogen, particu-
larly electrolysis powered by renewable energy, can significantly impact
environmental sustainability. According to the findings, the most envir-
onmentally sustainable scenario in terms of its GW impact in 2023 is DF2,
which involves Ireland and the UK (in the SC with technology manu-
facturing in Ireland and 50% of capacity exported to the UK). It's

noteworthy that this scenario maintains a low GW impact in 2050 as well,
indicating its potential to offer resilience and ensure the production of
secured clean fuel. Additionally, while the PEM1 scenario is not deemed
sustainable in 2023 (with manufacturing in Norway and 100% export to the
USA), it emerges as a resilient solution in 2050.

In terms of ME, the PEM2 scenario offers a resilient and secured energy
supply pathway for various timeframes up to 2050. This scenario presents an
SC centered around system manufacturing in Canada, with 50% of the
output exported to the UK. Moreover, based on the HT impacts, this sce-
nario also emerges as a resilient SC solution. Looking at the environmental
impact from the standpoint of SOD, PEM2 offers a pathway for a resilient
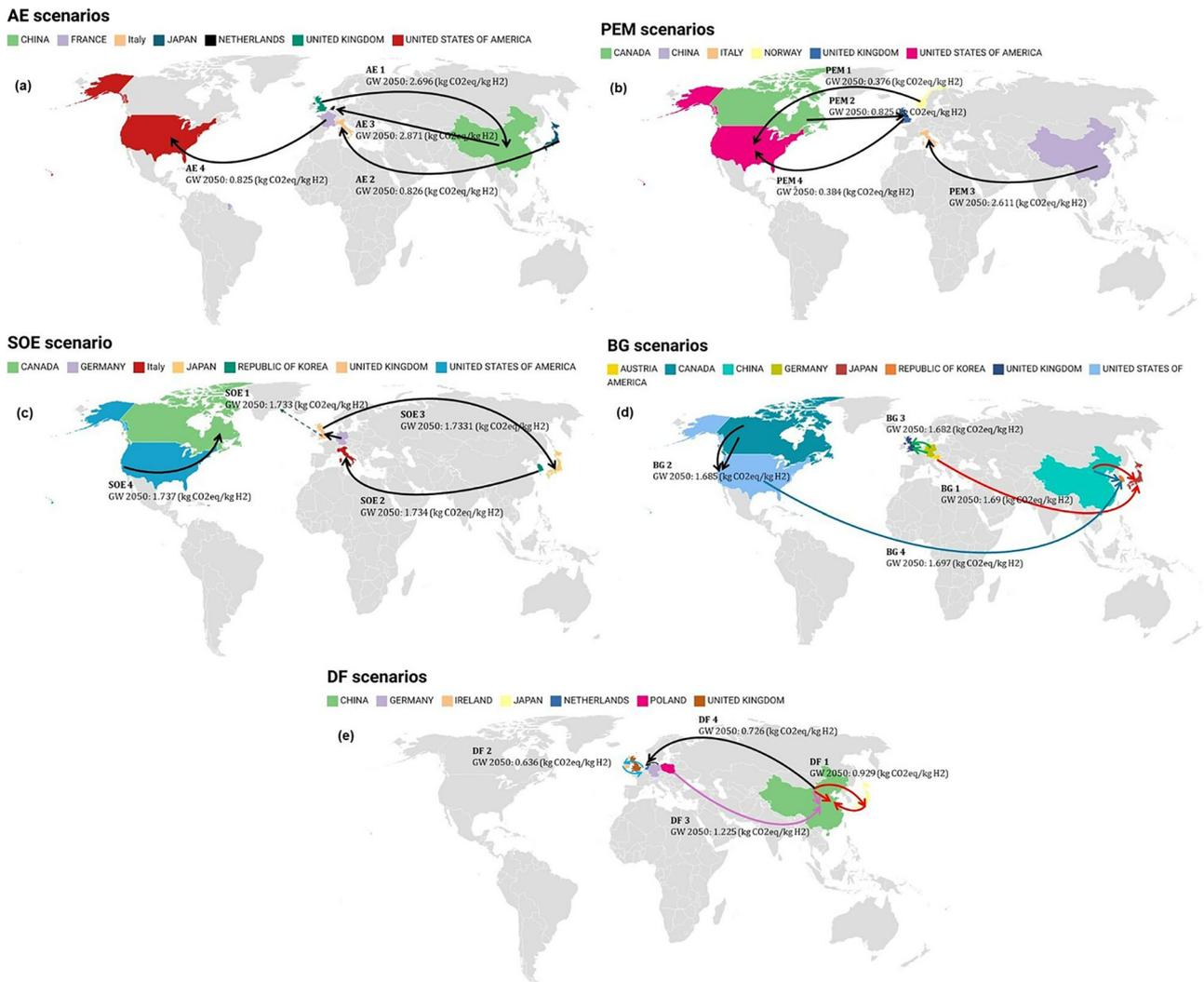and secured energy SC, despite its current unsustainable status. Another

Fig. 5 | International supply chain maps illustrating green hydrogen import and export for all 5 technologies and 20 scenarios of the 14 countries, highlighting their GW 2050 outlook. a This map illustrates the developed supply chain scenarios for AE technology. **b** This figure shows the expanded supply chain for PEM. **c** This map displays the defined supply chain for SOE. **d** This figure shows the determined supply chains for BG system. **e** This map represents the designed supply chains for DF technology. Both systems and feedstocks are shown in maps related to BG and DF SCs. The GW impact value in 2050 for all SC scenarios is shown in all maps.

option is BG1, which involves Austria and Japan. In 2023, BG1 presents a secured SC from the perspective of SOD impact. However, over time, the resilience of this scenario diminishes in terms of sustainability compared to other scenarios.

Overall, the most sustainable IGHSC by 2050 is PEM4, which involves manufacturing in the UK with 50% of the system exported to the USA. This IGHSC route is considered the most resilient and sustainable for the UK. Whilst the environmental impacts of PEM, as demonstrated in their relatively low GW, ME, SOD, and HT in 2050, PEM4 exhibited the highest reduction in GW impact, with around 97.00% decline from 2023 to 2050. PEM3 manufacturing exhibits a consistently lower GW impact compared to the current AE1 scenario, with 2023 values already favoring PEM3 (17.51 vs. 17.55 kg CO_2eq per kg H_2). This suggests that the UK could start phasing in PEM manufacture immediately without increasing environmental impact. The lowest reduction is seen in DF3, with 69.00% reduction, which involves manufacturing in Poland with 100% export to China. Regarding hydrogen production from biomass, the DF4 scenario demonstrates a lower GW impact than DF3 throughout the period analyzed (3.76 vs. 3.93 kg CO_2eq per kg H_2 in 2023, declining to 0.73 vs 1.22 kg CO_2eq per kg H_2 in 2050). Consequently, phasing out hydrogen production via the

DF3 pathway in favor of DF4 should commence as soon as possible to maximize environmental benefits.

Technology and SC developments

Technology development consists of several aspects and edges. It can be discussed from different views. One of the main challenges would be material utilization over the manufacturing process, which causes some main environmental issues, such as GW, corrosiveness, toxicity, and acidity. It is necessary to enhance the efficiency of promising methods to compete economically with existing hydrogen production techniques reliant on fossil fuels.

Technological advancements can aid in achieving greater resilience and security in SCs and hydrogen production. The findings indicated that scenarios related to BG and DF are less reliant on the grid network due to lower energy consumption during system operation and manufacturing. However, there's a need to enhance the resilience of feedstock production and the technological processes involved in production. To ensure competitiveness from an environmental standpoint and enable large-scale application in hydrogen production, it is essential to prioritize the production of sustainable and less polluting feedstock for biomass-based systems. This becomes particularly crucial for mitigating impacts on HT, ME,

and SOD, as the results suggest a slower decrease in these impacts for DF and BG SCs compared to electrolysis-based scenarios for hydrogen production.

A major environmental impact of DF SCs arises from the transportation phase, which exhibited a notably higher impact compared to other SCs. PEM SCs demonstrated a higher impact compared to the two other electrolysis-based scenarios. This highlights the urgent need for technical advancements through the use of more sustainable and innovative materials while reducing energy consumption during system operation. This enhancement is essential for improving resilience and ensuring the production of secure hydrogen fuel.

The broadening of the circular economy through innovative technological strategies aligning with regulatory policies aims to guarantee the safe and environmentally sustainable operation of the entire SC[38].

Technological SC sustainability ranking

An integrated TOPSIS and fuzzy approach is used to perform the sustainability ranking. A sustainability ranking of the analyzed scenarios is performed using the results from four impact categories in 2023 and 2050 (Fig. 4). Larger markers and lighter colors indicate a more environmentally friendly SC. In essence, a higher score signifies that the SC pathway is less polluting compared to others.

Results reveal that scenario PEM4 (UK manufacturing with 50% export to the USA) emerges as the most sustainable international SC by 2050. This outcome is supported by the UK's projected full decarbonization of its electricity grid by 2050 and the relatively clean energy mix and infrastructure in the USA, which together lead to substantial reductions across all impact categories—particularly GW (−97.90%), HT, and SOD.

However, this top-ranking scenario must be interpreted in light of practical trade-offs. PEM systems, while environmentally promising, involve high upfront costs, resource-intensive materials, and technological maturity constraints compared to AE. Moreover, the geopolitical feasibility of transatlantic trade between the UK and the USA may be influenced by regulatory, trade, and infrastructure coordination challenges.

Technology-specific patterns also emerge. Electrolysis technologies (PEM, AE, and SOE) demonstrate the highest sustainability improvement over time, driven by their strong dependency on the electricity grid—which benefits significantly from decarbonization. For example, PEM4 improved from score 2 (2023) to score 20 (2050) in GW impact. In contrast, BG and DF technologies exhibit more gradual and consistent changes, as their impacts are primarily driven by feedstock production and are less influenced by improvements in the energy mix.

Regional insights are also evident. Scenarios involving China in manufacturing or O&M (e.g., AE3, PEM3, DF3) consistently perform poorly across multiple categories even in 2050, primarily due to the country's slower projected decarbonization (net-zero by 2060) and reliance on coal- and oil-based electricity. This underlines the importance of aligning hydrogen SC planning with national net-zero trajectories.

Impact category differences further influence the rankings. While PEM4 excels in reducing GW and SOD impacts, DF2 and PEM2 perform better in HT, suggesting that no single scenario dominates across all environmental criteria. This reinforces the need for context-specific decision-making, where technology selection and trade partnerships are based on a balance of environmental, economic, and geopolitical factors.

These findings underscore that sustainable hydrogen SCs cannot be universally prescribed but must be tailored to technology type, regional decarbonization pathways, infrastructure readiness, policy alignment, export-import feasibility and long-term decarbonization commitments. Rankings across the remaining 14 impacts categories for 2023 and 2050 are illustrated in Supplementary Fig. 7. Figure 5 maps the green hydrogen SCs, detailing import-export flows across 14 countries and 20 scenarios in 2050.

Implications of the results

The managerial implications of the spatial-temporal prospective LCA in this study on the IGHSC are considerable. Policymakers and decision-makers can utilize the study's findings to make informed strategic sustainable

decisions about investments for green hydrogen production and its export potential, optimizing SCs for minimal environmental impact. The insights from the 20 IGHSC scenarios help identify the most sustainable and efficient routes for producing, importing, and exporting green hydrogen. Additionally, they highlight optimal transportation strategies, enhancing SC resilience and reducing emissions. Additionally, the study provides a framework to ensure compliance with international environmental regulations and net-zero targets, avoiding potential legal and compliance issues.

From a practical or operational perspective, this study illustrates the hotspots in the green hydrogen SC phases, enabling companies to adopt more sustainable practices for reducing the environmental impact of hydrogen production and transportation. It guides policymakers and industry leaders to consider the longer-term impact in 2030, 2040, and 2050 to meet the net-zero goal through a sustainable route, as indicated in the findings from the IGHSC scenarios as part of the transition to decarbonize the energy grids and to achieve energy independence of the 14 countries. The results highlighted the benefits of certain green hydrogen technologies, informing the selection of the most effective and environmentally sustainable options.

Theoretically, this study contributes to the advancement of spatial-temporal prospective LCA methodologies specifically for IGHSCs. It integrates insights from net-zero goals and energy policies with the economic and trade dynamics of import and export across various SC phases, including raw materials, manufacturing, storage, transport, and end use, for 14 countries. Additionally, it incorporates technological advancements in five green hydrogen technologies. This comprehensive approach enables the emulation of geopolitical, economic, trade, and resource flow scenarios for 20 designed IGHSC scenarios from 2023 to 2050, covering key milestone years, such as 2030 and 2040. This study contributes to sustainability models and fosters interdisciplinary research by connecting environmental science, SC management, and sustainability studies. These contributions and implications collectively emphasize the study's relevance to academic, policy, and industry stakeholders, providing actionable insights and advancing theoretical frameworks in IGHSCs.

The key findings of this study indicate that, in 2023, the three electrolysis-based SC scenarios exhibited higher global warming impacts compared to the two biomass-based systems. This difference is primarily attributed to the energy-intensive O&M phases, as well as the manufacturing processes associated with electrolysis technologies. By 2050, PEM SC scenarios are projected to be the most environmentally sustainable option. Additionally, aligning with net-zero plans by 2050 will lead to substantial reductions in environmental impacts across all countries, though the magnitude of this reduction will vary depending on the scenario.

The energy mix significantly affects the environmental impact of the IGHSC, with countries relying more on fossil fuels for electricity, resulting in higher ecological impacts. In a similar context, PEM SC exhibits a lower environmental impact compared to the other technologies examined when nations transition to green power in 2050. However, the environmental impact varies significantly across different scenarios, influenced by factors such as the energy mix of specific countries, transportation distances, O&M, and storage conditions.

Environmental impact values vary across different impact categories and are influenced by distinct SC phases. The transportation phase has a minimal impact compared to other phases of the SC for electrolysis systems, but it has a more substantial effect in biomass-based systems. Energy and material inputs are the main contributors that influence the extent of the environmental sustainability of IGHSCs. However, biomass-based systems' SC are less dependent on the energy mix compared to electrolysis systems due to their lower energy requirements for manufacturing and operation; but the use of sustainable feedstocks and treatment processes is crucial. The feedstock type, including its availability, abundance, and cultivation location, significantly influences the environmental impact of biomass-based hydrogen SCs.

The study demonstrates that the sustainability performance of IGHSCs is not fixed but evolves over time with changes in energy mix, technology

maturity, and SC configurations. For instance, while electrolysis-based systems generally show higher GW impacts in 2023, some scenarios like PEM4 achieve massive reductions by 2050 due to cleaner electricity and optimized supply routes. This temporal variation implies that optimum scenarios shift over time, requiring countries to adopt adaptive and forward-looking strategies. Aligning national hydrogen plans with these evolving optimum IGHSCs is practical in principle but challenging in practice, particularly given the uncertainty of future net-zero commitments, policy continuity, and the pace of energy transitions. Such uncertainties may affect infrastructure investment decisions, trade negotiations, and international cooperation. Therefore, flexible policy frameworks, continuous monitoring of technological and geopolitical developments, and dynamic updates to hydrogen strategies are essential. For example, the UK, projected to perform best in PEM4 by 2050, would benefit from early investment in manufacturing capacity and grid decarbonization, while China's strong role in biomass-based scenarios highlights the importance of domestic feedstock access and resilient trade channels. Overall, alignment is feasible but must be supported by governance structures that account for long-term uncertainty. Pedigree matrix analysis of data quality and Monte Carlo simulation-based uncertainty analysis results (including error bars) are shown in Supplementary Table 4 and Supplementary Fig. 8, respectively.

The study's findings demonstrate that achieving a sustainable IGHSC by 2050 requires not only a net-zero energy mix but also the use of sustainable materials, a greener transportation system, and the promotion and optimization of production techniques to mitigate impacts across all categories.

Discussion

This study provides a comprehensive sustainability evaluation of 20 international green hydrogen SC scenarios involving 14 countries and 5 production technologies, using a spatial-temporal prospective LCA from 2023 to 2050. A key contribution is the shift from merely assessing production technologies to systematically analyzing how international SC design influences environmental outcomes. This approach identifies leverage points for reducing impacts and improving sustainability within global hydrogen trade systems.

Compared to prior LCA studies that generally report environmental impacts for individual hydrogen production technologies or national contexts[16,18,19], our study reveals considerable variation in sustainability outcomes driven by international SC design and regional energy grid trajectories. For example, previous studies[18] highlighted the importance of electricity mix on electrolysis impacts, while our results quantify how this effect varies across countries with different decarbonization timelines, showing that scenarios involving countries like China exhibit higher long-term environmental burdens due to slower grid decarbonization. Unlike previous biomass-based hydrogen LCAs[19,20], which mainly emphasize feedstock impacts, our findings expose that biomass pathways are comparatively less sensitive to grid decarbonization but contribute more to land-use and ecotoxicity concerns along extended SCs, especially when biomass cultivation and transport distances increase internationally.

Furthermore, while earlier studies[24] reported potential environmental benefits of renewable hydrogen at a large scale, our spatial-temporal approach uncovers critical trade-offs between electrolysis and biomass routes that are masked in static models, particularly under future grid and technology scenarios. Electrolysis technologies show the greatest improvement by 2050 in global warming and HT, but remain vulnerable to current regional grid carbon intensities and material-related toxicities during manufacturing. Specifically, across the 20 scenarios, the GW potential of electrolysis-based pathways declines by 55–70% between 2023 and 2050, compared to a 20–30% reduction for biomass-based pathways. Among electrolysis systems, PEM and AE show the highest decarbonization responsiveness, improving their normalized sustainability scores by up to 0.25 points (TOPSIS ranking scale 0–1) by 2050. The integration of MCDA highlights how sustainability rankings of hydrogen SCs change when considering uncertainty and multiple environmental impact categories

simultaneously—an outcome not typically addressed in prior LCAs[23,33]. Notably, despite variations in weightings and uncertainty ranges, the top-ranked scenarios (e.g., AE–UK and PEM–Norway) remained stable across 90% of the sensitivity cases, confirming the robustness of policy insights regarding the importance of clean electricity and regional manufacturing. This reveals the importance of combining quantitative LCA with expert judgment for robust policy decisions.

One of the most critical findings is the clear interdependency between technological choice and spatial SC design. While all technologies benefit from cleaner energy grids by 2050, electrolysis-based systems (especially AE, PEM) show the greatest environmental performance improvements, particularly in global warming and HT categories. This is due to their higher sensitivity to the electricity mix during both manufacturing and operation phases. In contrast, biomass-based technologies (BG and DF) are less sensitive to grid decarbonization but raise concerns around feedstock production-related ecotoxicity and land-use impacts.

This highlights an important trade-off: electrolysis technologies offer greater long-term decarbonization potential, especially when integrated into countries with aggressive net-zero targets and renewable expansion plans, but are more vulnerable to current grid carbon intensities and material toxicity in manufacturing. In contrast, biomass systems, while less energy-intensive during operation, bring other sustainability burdens related to agricultural practices and transportation distances, particularly in DF scenarios.

Geographical variation further shapes these trade-offs. For example, scenarios involving China in manufacturing or O&M phases (e.g., AE3, PEM3, DF3) tend to underperform in 2050 due to the projected slower decarbonization of its grid (targeting net-zero by 2060), compared to countries like the UK or Norway. By 2050, the average GW potential for Chinese-involved scenarios remains 40–50% higher than equivalent European configurations, while HT and metal depletion indicators are up to 30% greater due to the manufacturing material mix. Countries with cleaner future grids and strong policy frameworks (e.g., UK) are better suited as production or manufacturing hubs, especially for electrolysis technologies, in line with the EU hydrogen strategy and national net-zero roadmaps. This implies that aligning international green hydrogen SC configurations with national energy transitions is essential.

From a policy perspective, this suggests that international hydrogen trade agreements and technology partnerships must consider more than economic cost—they must be sustainability-informed. Quantitatively, optimizing supply chain configuration (e.g., shifting manufacturing to low-carbon electricity regions) can reduce total life cycle GW by up to 45% and HT by 35% compared to baseline international scenarios, highlighting the importance of integrating environmental metrics into trade and investment decisions. Countries should incentivize local production only if their energy infrastructure and SC practices support low-impact hydrogen generation. Furthermore, targeted investments in clean manufacturing, renewable heat sources (especially for SOE), and low-impact biomass cultivation can alleviate specific bottlenecks identified in the phase-level impact analysis.

An additional contribution of this work is its use of an integrated TOPSIS-fuzzy MCDA framework to support robust decision-making under uncertainty. This approach allows policymakers and planners to systematically rank and prioritize international green hydrogen SC scenarios by incorporating both quantitative LCA outputs and subjective expert criteria. Given the evolving nature of technology maturity, grid decarbonization trajectories, and international collaboration, such decision tools are essential for adaptive long-term hydrogen planning.

Sensitivity to key variables, such as energy mix evolution, technological efficiency improvements, and regional feedstock availability, should be acknowledged in interpreting the results. While 2050 projections are based on current net-zero commitments, any delay in policy implementation or disruption in renewable energy deployment could significantly shift the relative sustainability of SC options.

The 14 countries studied were selected based on their current and projected involvement in the international green hydrogen economy, which

have declared national hydrogen strategies or net-zero targets; significant roles as exporters, importers, or users of green hydrogen; and relevance to trade routes that are technically and economically feasible by 2050. Future research can expand to other regions like MENA, Australia, and South America (e.g., Brazil), representing emerging hydrogen hubs. In addition, future research can build from this integrated spatial-temporal prospective LCA framework with TOPSIS-fuzzy MCDA to consider prospective multi-objective optimization of cost and environment of the international green hydrogen SC.

In conclusion, this study found a more sustainable and resilient international green hydrogen SC by 2050 will depend on:

- Strategic alignment of technology selection with regional decarbonization trajectories.
- Holistic SC planning beyond national borders.
- Proactive management of technology-specific and phase-specific environmental burdens.
- Application of multi-criteria sustainability frameworks that integrate LCA with decision-making tools.

By enabling such integrated thinking, this study offers a foundation for guiding governments, industries, and international organizations toward evidence-based, globally coordinated hydrogen economy strategies that meet both climate and energy security objectives.

This study focuses on individual technology pathways (AE, PEM, SOEC, BG, and DF) to ensure clear attribution of impacts and methodological consistency. Hybrid configurations (where multiple hydrogen production technologies are integrated) were excluded to avoid introducing additional layers of uncertainty and allocation complexity. While this simplification limits the ability to capture potential system synergies and integrated operation efficiencies, it does not critically affect the comparative conclusions, as the goal of this study is to assess the relative sustainability performance of each technology under harmonized boundary conditions.

Methods

Life cycle assessment

When it comes to gauging environmental sustainability, LCA methodologies are increasingly dominant, especially within the realm of SC management[39]. LCA is commonly employed to inform choices regarding transformative approaches, such as reducing carbon emissions in energy systems, promoting circular economy practices, and encouraging sustainable consumption patterns[40]. LCA serves as a standardized instrument for measuring environmental impacts across the entire life cycle of a product or process[11,41,42]. Utilizing the LCA framework enables the recognition of routes to production processes linked with extensive energy and resource consumption, pollution, and greenhouse gas emissions. This identification facilitates the development and implementation of appropriate sets of intervention options and strategies aimed at mitigating these issues[43]. Its objective is to offer direction to decision-makers to lessen environmental repercussions[44]. LCA offers a structured approach for businesses to analyze the consequences of their product choices and SC operations[45]. In addition, prospective LCA offers a tool that is applicable to new products and technologies as they emerge[46]. The methodology used in LCA is comprehensively outlined in the International Organization for Standardization (ISO) 14040/14044 standards[47,48]. The OpenLCA software is utilized to calculate the environmental impacts in this study. A spatial-temporal approach is integrated into the prospective LCA to model the geographical distribution of international SCs and project future environmental impacts on a decade-by-decade basis.

Goal and scope definition

The first phase of an LCA study is goal and scope determination[49]. The primary objective of this study is to conduct a spatial-temporal prospective life cycle SC assessment of 5 major hydrogen production technologies for generating green hydrogen. This involves developing 20 SC scenarios that account for 14 countries involved in technology manufacturing, feedstock

production, and hydrogen utilization. The study's system boundary includes raw material extraction, technology manufacturing, transportation, O&M, and hydrogen storage. The chosen functional unit for all studied technologies is 1 kg of produced hydrogen by the system, which is a suitable functional unit to compare all the different technologies. The energy mix conditions of each country considered are incorporated into the manufacturing and other phases of the SC. All the countries included in the study have set 2050 as their target year for achieving net-zero emissions, except for China, which has set its target for 2060. It is assumed that by 2050, a small portion of the energy mix will still be derived from fossil fuels. Therefore, the energy mix for electricity generation reflects both the current conditions and the anticipated future scenarios in each country. Technological advancements and improvements in production efficiencies have not been included in the prospective LCA. The assessment does not account for the substitution of novel materials. The primary focus is on the net-zero targets of different countries for generating electricity and the required power across various phases of the hydrogen SC. It is assumed that all technologies are capable of scaling up to meet future demand projections. Additionally, it is assumed that all technologies will adhere to current and anticipated environmental regulations.

Life cycle data inventory

The process of acquiring data plays a pivotal role in LCA, serving as a fundamental and crucial step in collecting essential information necessary for evaluating the environmental impacts throughout the life cycle of a product or system[50]. A fundamental stage within the LCA process involves constructing the life cycle inventory (LCI)[51]. Several references and literature are applied to gather the required data for this study. The applied data for each technology is collected from different references (AE[52,53], PEM[52,53], SOE[52,53], BG[19,53–55], and DF[53,56,57]). Furthermore, various databases, including Ecoinvent and environmental footprint (EF), are considered to address gaps in data and ensure completeness in the assessment process. The Ecoinvent database offers thoroughly documented LCI process information for a wide array of materials and products, encompassing major environmental aspects[58]. The data on the energy mix contributions of the considered countries are sourced from the International Energy Agency database[59]. Values of materials and energy usage were utilized from the cited references and databases. However, it is important to note that using different databases or making varying assumptions about processes can lead to different results. This variability underscores the need for transparency in the choice of data sources and assumptions, as these factors can influence the outcomes of the environmental impact assessment. The LCI for this study is presented in the Supplementary Information (Supplementary Tables 1–9).

Impact assessment approach

The LCA assessment stage connects emissions and resource consumption to environmental effects using characterization factors[60]. In this phase, the LCI elementary flows, such as emissions and natural resource use, are converted into potential impacts using a set of characterization factors[61]. The ReCiPe 2016 midpoint method is utilized to evaluate the environmental repercussions of systems, aiming to offer a deeper comprehension of the underlying processes and pinpoint areas where more focused efforts can be made to reduce environmental impacts. A total of 18 potential environmental impact categories were considered to ensure a thorough assessment of the EF throughout the lifespan of a specific product.

Interpretation

Interpretation is the last phase of LCA evaluation[62]. Recognizing the phases within the life cycle that exert the greatest environmental influence is commonly known as pinpointing hotspots, and these can differ based on the specific product or process under evaluation. The interpretive phase involves a comprehensive assessment of the results obtained from an LCA study, covering both the inventory and impact assessment stages, in accordance with the defined objectives and scope of the research[63,64]. According to ISO 14044, interpretation involves three main aspects:

identifying substantial issues based on LCI and life cycle impact assessment results, conducting evaluations for completeness, sensitivity, and consistency, and offering conclusions, limitations, and recommendations[47].

Scoring and decision-making approaches

In this study, we employed the TOPSIS method integrated with fuzzy approach to rank various scenarios. TOPSIS has served as the foundation for numerous promising methods and comparative analyses, establishing itself as one of the core techniques in multi-attribute decision-making (MADM)[65]. The TOPSIS method operates on the principle that the best-performing alternative has the smallest geometric distance to the ideal solution. In contrast, the worst-performing alternative is closest to the negative-ideal solution. It leverages the complete information from a decision matrix and a vector of criteria weights to comprehensively rank all evaluated options[66]. The optimal alternative is the one that is closest to the positive ideal solution (PIS) while being farthest from the negative ideal solution (NIS). The PIS represents a hypothetical alternative with the best possible values for all attributes, whereas the NIS represents a hypothetical alternative with the worst possible values for the attributes under consideration[67]. However, in this study, an integrated fuzzy and TOPSIS is applied to rank the scenarios. The integration of fuzzy logic with MCDA techniques has gained considerable attention among researchers in the decision science community. The efficiency of the fuzzy inference system has further contributed to the advancement of various MCDA-based methods. Among these, the TOPSIS is recognized as one of the most effective approaches for addressing complex MCDA problems[68]. The methodology employs linguistic data to represent the decision-maker's opinions. These linguistic values are then utilized to construct both the fuzzy decision matrix and the normalized fuzzy decision matrix. Next, the fuzzy positive and fuzzy NISs are determined by assigning appropriate weights to each output criterion. Finally, the distances of each alternative from these ideal solutions are computed, leading to the establishment of a preference ranking for the alternatives[68].

This method is utilized to assess the impact categories examined across all devised scenarios and technologies. This method seeks to ascertain the sustainability performance of each scenario by evaluating the impact category values across various timeframes. Each scenario is assigned a score ranging from 1 to 20, with 20 indicating the most sustainable SC scenario and 1 representing the least sustainable one. The ranking process involves comparing the values of all scenarios, dividing them into various categories and ranges based on the outcomes obtained. A subjective weight is assigned based on the acquired results and their comparison with other calculated values according to subjective judgment. This ranking elucidates the disparities among each SC scenario in terms of sustainability performance. Here is a summary of the applied method[69,70]:

1) Defining the decision-making problem:.

- Evaluating and ranking the sustainability of various SC scenarios for green hydrogen production, emphasizing several impact categories for the years 2023, 2030, 2040 and 2050.
- Each scenario is assessed using LCA results and evaluated over multiple time periods.

2) Constructing a fuzzy decision matrix:.

- For each SC scenario and impact category, evaluate the performance using fuzzy numbers to account for uncertainty in the assessment.
- Fill the decision matrix with fuzzy evaluations for each impact category, considering the years 2023, 2030, 2040 and 2050.

3) Assigning subjective weights to impact categories:.

- Assigning subjective weights to each impact category based on the normalized results and their relative importance in the overall assessment.

- These weights represent the perceived importance of each impact category in relation to sustainability, considering their comparison with other values.

4) Normalizing the fuzzy decision matrix:.

- Normalizing the fuzzy decision matrix involves standardizing the performance values across all scenarios and impact categories.
- Applying a defuzzification process to convert fuzzy numbers into crisp values, thereby making them suitable for comparison.

5) Identify the ideal and anti-ideal solutions:.

- Determining the ideal solution (the best performance for each impact category) and the anti-ideal solution (the worst performance) for each scenario.
- These solutions are derived from the normalized and defuzzified values in the decision matrix.

6) Computing the distance to the ideal and anti-ideal solutions:.

- Calculating the Euclidean distance (or other suitable distance measures) for each SC scenario to both the ideal and anti-ideal solutions in each impact category.

7) Calculating the relative sustainability score:.

- Calculating the relative sustainability score using the below formula for each scenario[69]:

$$C_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{1}$$

Here, d_i^+ is the distance to the anti-ideal solution, and d_i^- is the distance to the ideal solution.

8) Ranking the scenarios:.

- Ranking all SC scenarios from 1 to 20, with 20 indicating the most sustainable scenario and 1 representing the least sustainable one.
- The ranking process involves comparing all scenarios based on their relative sustainability scores and categorizing them according to the outcome of the ranking.

9) Interpreting the sustainability ranking:.

- The final ranking elucidates the sustainability performance of each scenario.

Data availability

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Author contributions

M.S. initiated and designed the research, gathered data, did the LCA analysis, and wrote the first draft. S.C.L.K. conceptualized the research, provided additional assessments, validated the results, edited the first draft, and provided comments and feedback on the text.

Competing interests

The authors declare no competing interests.

Additional information

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