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Ethical and social dimensions of Green Hydrogen: insights from systems thinking and stakeholder engagement between the Global North and the South

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Abstract

Background Green hydrogen is widely promoted as a cornerstone of the global low-carbon transition. Yet, while its technical and economic potential has been extensively studied, the ethical, social, and governance dimensions remain underexplored. The increase in Green Hydrogen deployment across diverse contexts, particularly through the Global North-South supply chains, risks reproducing the existing inequalities, extractivist practices, and governance challenges. Addressing these risks is necessary to ensure that Green Hydrogen not only contributes to climate change mitigation but also to socially just, sustainable development.

Results This paper integrates a systematic literature review, an exploratory stakeholder survey, and systems thinking through causal loop diagrams (CLDs) to examine the justice implications of Green Hydrogen transitions. The literature review identifies that there is a gap in region-specific and theoretically-grounded analysis of social and ethical impacts of Green Hydrogen production. The survey results highlight high energy intensity, land-use conflicts, investment costs, and fossil fuel job displacement as key challenges in the Green Hydrogen sector. The CLD analysis highlight that reinforcing and balancing feedback loops that link production, community well-being, and governance structures, as revealing leverage points for more equitable transitions. This study is among the first to explicitly integrate energy justice frameworks, stakeholder perceptions, and systems thinking through CLDs in the context of Green Hydrogen transitions, thus offering an original interdisciplinary contribution to the literature.

Conclusions The findings demonstrate that Green Hydrogen transitions are not purely technical or economic but also involve socio-ethical transformations. This study emphasises the importance for embedding distributive, procedural, and recognition justice across the Green Hydrogen value chain to avoid reinforcing inequalities. Participatory, transparent, and inclusive policy mechanisms are necessary to enhance social legitimacy. By bridging social science insights, stakeholder perspectives, and systems analysis, the paper contributes to ongoing debates on how hydrogen can serve not only as a decarbonisation tool but also as a pathway toward just and sustainable energy futures.

Keywords Green Hydrogen (GH) · Ethical and social impacts · Causal loop diagrams · Stakeholder engagement · Just transition · Global North–South dynamics

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Background

The world is moving towards decarbonising the energy sector, and as a result, clean hydrogen emerges as a key component not only to replace fossil fuels but also to meet climate targets while achieving energy security [1]. Many countries are increasing renewable electricity shares and introducing green hydrogen [2]. Some countries that already have fully established hydrogen infrastructure find GH to have significant potential in the industrial and transport sectors, such as Australia and Japan [3]. Meanwhile, scholars argue that countries in regions like Southern Africa have not identified their potential in producing and usage of GH [4]. According to [5], one of the many reasons for countries to navigate towards GH energy in various sectors is its potential to meet specific sustainability criteria, which mark GH as an alternative source of clean energy. These dynamics in GH development emphasises its growing role in the global energy transition.

Producing Hydrogen can be through multiple pathways but those pathways could differ significantly based on their environmental impacts. Hydrogen can be produced through fossil-based or renewable pathways, such as Grey Hydrogen which generated from fossil fuels and highly carbon intensive. Although Blue Hydrogen incorporates carbon capture and storage it continues to depend on fossil fuel extraction. By contrast, only green hydrogen (GH), which is produced via electrolysis using renewable electricity, offers a near-zero carbon option. While GH is widely recognised as the cleanest hydrogen pathway, its large-scale deployment faces challenges of cost, infrastructure, and social acceptance [6]. The widespread adoption of hydrogen as an alternative fuel includes high production cost, underdeveloped value chains and infrastructure issues [6].

Despite rapid policy momentum, current research on hydrogen has predominantly focused on technological feasibility and environmental performance. The social, ethical, and governance dimensions remain comparatively underexplored [7]. Moreover, scaling production and optimising value chains have become the priority in policy and industry dialogues, while social considerations are becoming secondary.

Social aspects of the hydrogen sector have been studied, but gaps remain in socio-political, geopolitical, and well-being dimensions associated with the Hydrogen energy sector [7]. Moreover, according to [7], among the three dimensions of sustainability, current non-renewable sources such as fossil fuels have mostly been compared against the economic and environmental aspects of hydrogen. For instance, through carbon footprint indicators. But socio-economic and especially ethical aspects of the Green Hydrogen (GH) energy sector still lack research attention.

As GH production is anticipated to increase by 57% annually by 2030 [8], overlooking socio-economic and ethical aspects risks reinforcing injustices in energy transitions [9]. This study addresses that gap by exploring stakeholder perceptions and mapping ethical and social challenges through a multi-method approach, contributing both to the energy justice literature and to policy debates on equitable hydrogen transitions.

Hence, this study provides an essential contribution to the GH energy literature with in-depth perceptions of stakeholders who are currently engaged in the GH industry (at any level) about environmental, economic, and ethical aspects of GH and existing barriers towards an equitable energy transition to GH. Further, the findings of this study will immensely contribute to the energy justice scholarship through a multi-method research approach.

The primary objective of this study is to understand the social and ethical challenges associated with GH production and transitioning to a GH economy. To achieve this, the study has employed a mixed-method approach, consisting of a systematic literature review, analyses of a causal loop diagram and an online survey. This paper is structured as follows. After the introduction, the methodological approach will be elaborated. This will be followed by the results section, consisting of findings from the systematic review and the global survey. Finally, the results will be discussed in relation to energy justice and sustainable literature followed by the concluding remarks including policy implications and remarks for future research.

Methods

Systematic literature review

A systematic review was conducted to guarantee a thorough and pertinent investigation of ethical and social challenges associated with transitioning to a GH economy [10]. As the first step, three research questions were created:

- (1) What are the key ethical and social challenges associated with transitioning to a GH economy, and how do these challenges impact diverse communities and stakeholders?
- (2) Which variables define the ethical and social dimensions of GH development, and what are the relationships and interactions among these variables?
- (3) What strategies can effectively promote the development and adoption of GH technologies while ensuring alignment with ethical principles, social equity, and environmental sustainability?

These research questions were designed to complement one another, offering a holistic understanding of the socio-economic and ethical aspects of GH development by mapping the existing literature and examining the associated risks and opportunities. Then, keywords were generated based on an initial review of relevant literature, aiming to address Social and Ethical Challenges, Community Impacts, Gender Dimensions, Global and Policy Perspectives, and Resource and Environmental Impacts. Boolean operators AND and OR were employed to ensure a comprehensive keyword selection that effectively targeted contemporary, relevant literature while minimizing irrelevant results, such as articles focused exclusively on policy analysis. Two carefully crafted keyword strings were developed to align closely with the research questions and provide a focused framework for the study (see Table 1).

SCOPUS and Web of Science databases were searched, focusing on titles, abstracts, and keywords. To ensure the inclusion of high-quality, up-to-date studies, strict criteria were applied, limiting the selection to peer-reviewed articles published in English between 2020 and 2025. These searches yielded 400 publications, with 217 articles identified in SCOPUS and 183 in the Web of Science. These search results were imported into Covidence for further processing.

Covidence automatically identified 147 duplicate entries, with one additional duplicate found manually. The first two authors, screened the titles and abstracts using Covidence, applying strict exclusion criteria to decide which papers to retain for full-text review and which to exclude. The disagreements regarding inclusion and exclusion criteria were resolved through discussion, and the third author sometimes joined the discussions where consensus was not reached between the first two authors. Although no formal inter-rater reliability statistics were conducted, consistency of selections was ensured through iterative discussions throughout the screening process.

Table 1 The keyword strings search for the review

No.	Search	SCOPUS	Web of Science
1	("green hydrogen" OR "green hydrogen transition" OR "green hydrogen technologies" OR "green hydrogen infrastructure" OR "green hydrogen production") AND (justice OR equity OR "social impacts" OR "energy poverty" OR "marginalized communities" OR "policy frameworks" OR regulations OR "equitable deployment" OR "ethical challenges" OR "resource allocation" OR "environmental justice" OR "ethics" OR "social dimensions" OR "community impact")	182(13)	161(7)
2	("green hydrogen" OR "green hydrogen production") AND ("International supply chains" OR "Global supply chains" OR "Informal livelihoods" OR "Small-scale farming" OR "Fishing" OR "Displacement" OR "Marginalisation" OR "Technological lock-in" OR "Technology dependence" OR "Cultural identity" OR "Indigenous communities" OR "Cultural disruption" OR "Social cohesion" OR "Cultural heritage" OR "Water privatisation" OR "Carbon leakage" OR "Hidden carbon costs" OR "Renewable energy diversion" OR "Social costs" OR "Gender inequality" OR "Wage gap" OR "Women in rural areas" OR "Domestic burden")	35(2)	22(2)
	Total (24)	15	9

Source: Authors

Articles with a purely technical focus (e.g., designs for innovative hydrogen batteries) or a significantly different emphasis (e.g., cost projections, regulatory impacts on hydrogen competitiveness, or general sustainability topics) were removed. This step excluded 189 irrelevant articles.

The remaining articles were subjected to a full-text review, during which an additional 39 papers were excluded for primarily focusing on the hydrogen economy without addressing the study's core questions. Ultimately, the search yielded 24 relevant papers (see Fig. 1).

The selected 24 studies were then thoroughly reviewed to address the research questions. Additionally, variables for the CLD process were identified, analysed, and interpreted. A thorough grasp of the social and ethical effects of GH development is ensured by this methodical approach, which also adds to the larger conversation on just and sustainable energy transitions. A formal quality appraisal of the included studies was not undertaken intentionally. This was because the review primarily aimed at mapping and synthesising the ethical and social issues of a GH economy, rather than comparing effect sizes or assessing the effectiveness of different interventions across selected regions.

The study contexts, methodology, stakeholder groups affected, key social and ethical issues identified, and proposed governance strategies were captured through a structured data extraction approach. A narrative synthesis approach was adopted, considering the heterogeneity of study regions (Fig. 2).

Causal Loop Diagram (CLD)

In the systems thinking field, CLD is a powerful tool for dealing with complex problems. It could uncover the underlying feedback structures and leverage points in a system [11]. A CLD is a method used to examine the complex relationships between activities and their impacts within a system [12]. It offers a holistic view of the phenomenon under investigation by revealing the entire chain of interactions between system elements [13]. This approach enhances understanding by encouraging iterative refinement of thought processes [14]. Such a technique is essential for effectively identifying where and how various impacts—whether direct, indirect, or cumulative emerge from planned developments [15]. In this systematic review, the CLD was employed with three purposes (1) to present key social and ethical impacts associated with GH production that are comprehensively supported by empirical evidence, (2) to capture feedback structures that shape distribution of risks and benefits of GH production, and (3) to understand leverage points for governance and policy measures to effectively influence system behaviour.

Identification of variables

The results of the narrative synthesis of the selected 24 studies from the systematic literature review served as the basis for identifying variables for developing the CLD. The concepts such as gender equality, employment, community well-being, environmental justice, resource access, etc., that repeatedly appeared across studies were coded and grouped thematically. These themes were subsequently included as variables in CLD. These variables were clearly discussed, conceptually and empirically linked to GH production, and presented in the context of the GH economy in the systematically reviewed literature (see Table 2). This ensured that the CLD consists of and reflects comprehensively reviewed scholarly understandings rather than hypothetical or anecdotal claims.

Development of causal relationships

The causal relationships between the selected variables were derived through qualitative narrative synthesis of the systematic review. Explicit arguments or empirical evidence from the review that indicated how changes in social or ethical factors influence another has been the basis for establishing causal links - for instance, how export-oriented GH production leads to energy colonisation. A CLD is composed of nodes representing variables and links (or edges) indicating the causal relationships between them. A “+” sign on a link denotes a direct

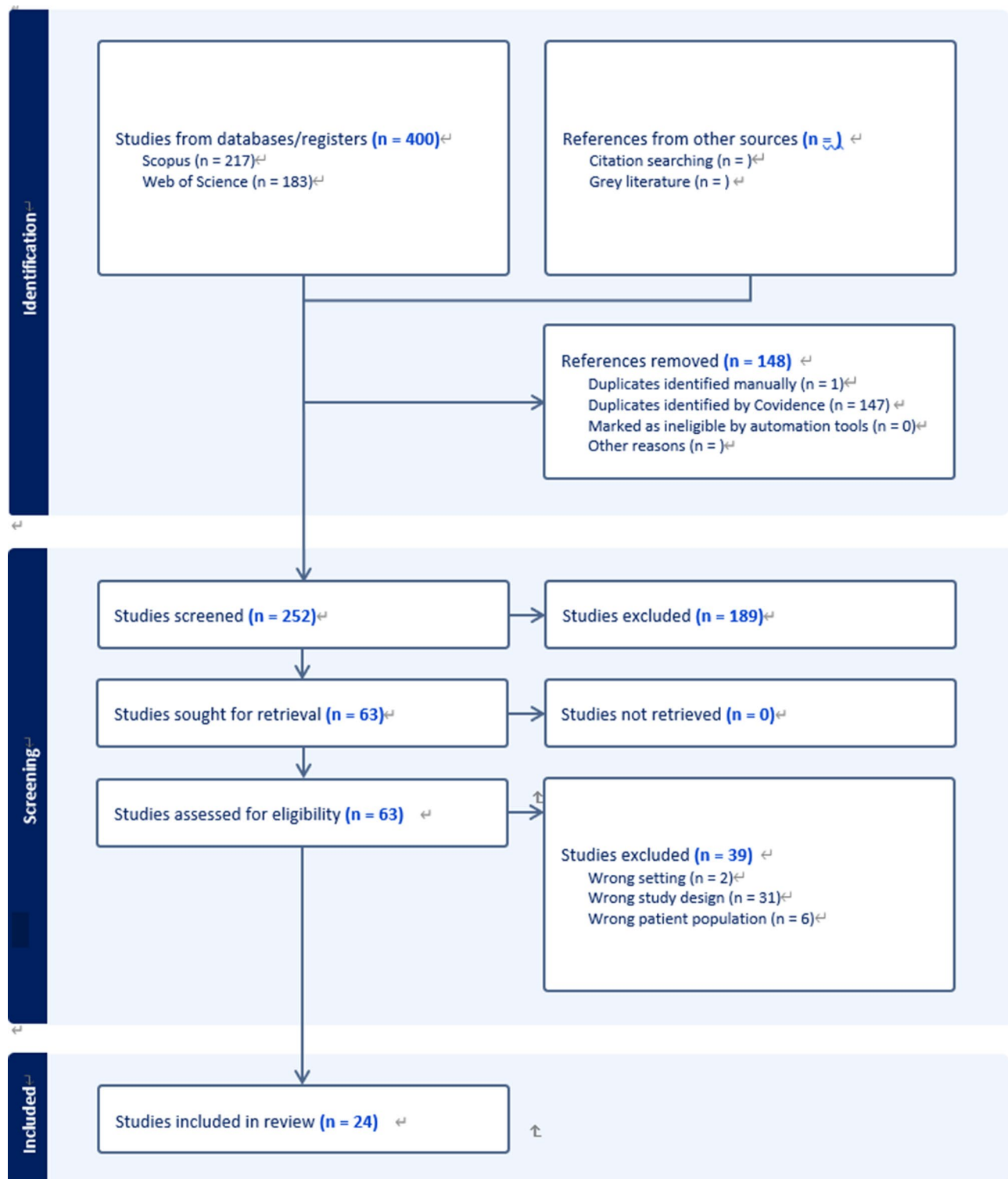


Fig. 1 PRISMA 2020 flow diagram for systematic review for SCOPUS, Web of Science. (Source: Authors)

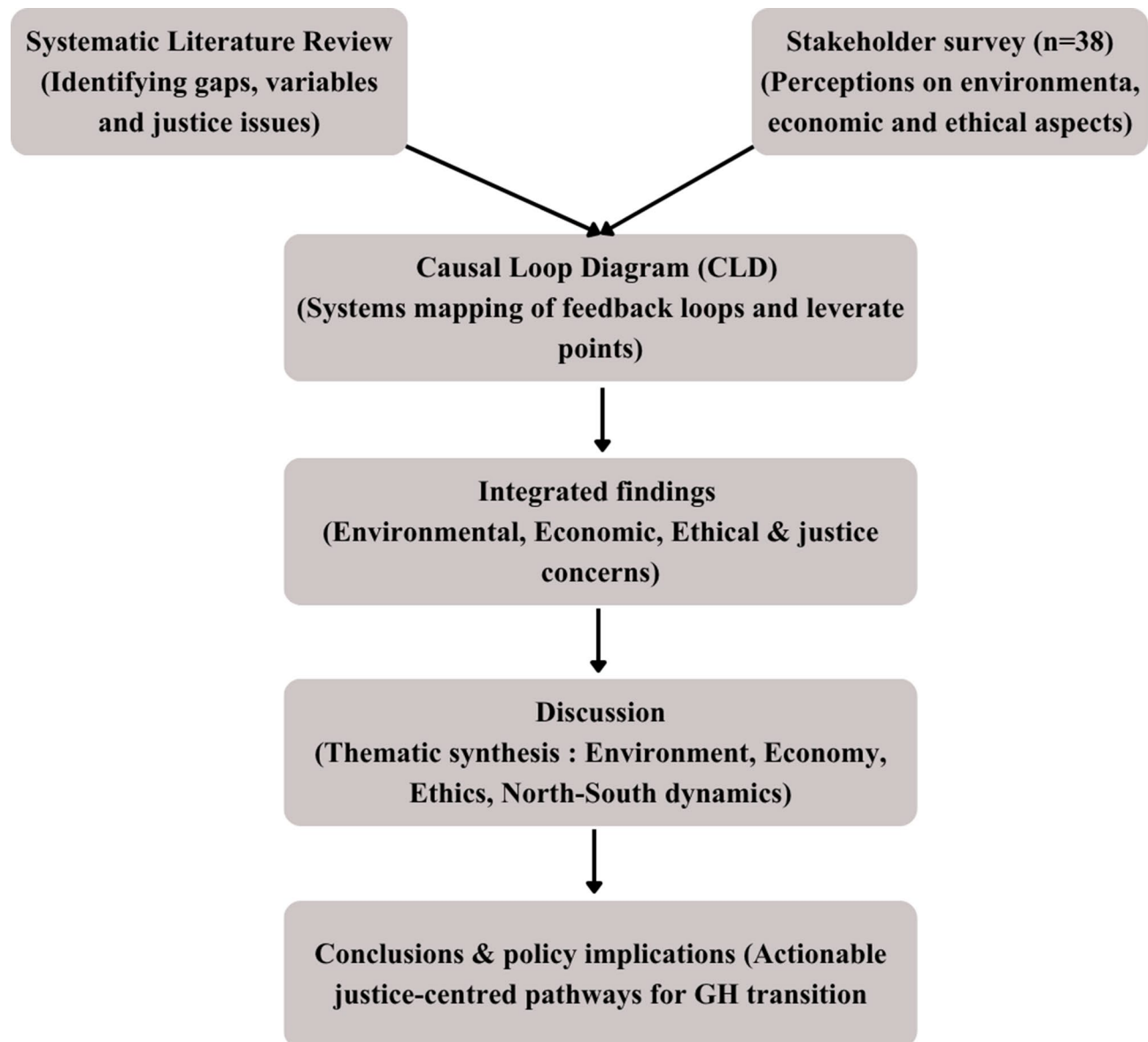


Fig. 2 The framework of the study: Integrating Methods, Findings, and Policy Pathways. (Source: Authors)

relationship, where an increase in the starting node leads to an increase in the end node, and vice versa. A “-” sign represents an inverse relationship, where an increase in the starting node causes a decrease in the end node, or a decrease in the starting node results in an increase in the end node.

Both reinforcing and balancing feedback loops that shape social and ethical outcomes in GH production were highlighted in the resulting CLD. “Reinforcing loops” occur when an increase in the starting node leads to a continuous increase in the end node, typically characterised by all “+” signs or an even number of “-” signs in the loop [16]. As shown in Fig. 3, a reinforcing loop is money in a savings account that accumulates interest, thereby increasing the balance and generating more interest. As shown in Fig. 4, a balancing loop is hunger that prompts eating, which satisfies hunger. For instance, export-oriented development reinforces economic dependence on Global North markets, while balancing loops reflect how social or environmental constraints limit the expansion of GH production, given resource limitations. Identifying these causal loop points is critical, as they

Table 2 Variables in social and ethical aspects

Dimension	Aspects	Variables	Articles
Social Aspects (Direct Community and Societal Impacts)	Employment and Job Creation	Employment Opportunities for Women; Local Capacity and Employment; Female Participation in Workforce	Sharma et al. (2023); Mininni & Hiteva (2024); Akhtar et al. (2023)
	Community Well-Being and Development	Community Well-Being; Displacement of Local Community	Hassan et al. (2024); Müller & Lawrence (2023); Cremonesi et al. (2023)
	Public Participation and Policy	Representation in Decision-Making	Müller & Lawrence (2023); Dillman & Heinonen (2022)
	Social Inequality and Marginalization	Marginalization of Women; Household Burdens of Women	Hiteva (2023); Mininni & Hiteva (2024)
	Local Development and Economic Growth	Export-Oriented Projects; Foreign Investment; Cost Competitiveness; Market Share; Profits Flow Back	Kalt & Lunn (2022); Lindner (2022); Hassan et al. (2024); Althar et al. (2023); Crawford (2024)
	Gender Disparities in Employment	Marginalization of Women; Employment Opportunities for Women; Female Participation in Workforce	Dematies et al. (2021); Mininni & Hiteva (2024); Blohm & Dettner (2023); Sharma et al. (2023)
	Ethical Considerations (Moral and Fairness Issues)	Equity and Justice	Müller & Lawrence (2023); Scott & Powells (2020); Hassan et al. (2024); Akhtar et al. (2023)
		Human Rights	Lindner (2022); Mininni & Hiteva (2024)
		Environmental Justice	Kalt et al. (2023); Fladvad (2023); Blohm & Dettner (2023)
		Energy Colonialism	Lindner (2022); Müller (2024); Kalt & Lunn (2022)
		Procedural Justice	Müller & Lawrence (2023); Dillman & Heinonen (2022)
		Indigenous Sovereignty	Fladvad (2023)
		Gender Equality in Leadership and Decision-Making	Dematties et al. (2021); Mininni & Hiteva (2024)
		Sustainability and Environmental Integrity	Cremonese et al. (2023); Blohm & Dettner (2023); Hassan et al. (2024); Müller (2024); Lindner (2022)

enable policymakers to achieve optimal outcomes with minimal resource input, thereby facilitating the creation of efficient and impactful policies [17].

This structured approach helps clarify complex issues such as imported social risks, the fair distribution of benefits, and the ethical considerations associated with hydrogen projects. By analysing these loops, the diagram provides a clear view of how different social and ethical factors influence each other within the system, offering valuable insights into the broader impacts of GH initiatives.

The CLD visually represents the social and ethical challenges associated with GH production. The diagram highlights key variables such as social inequality, community engagement, and environmental integrity, as well as the feedback loops influencing these factors. VenSim software was utilised to create a clear and comprehensive

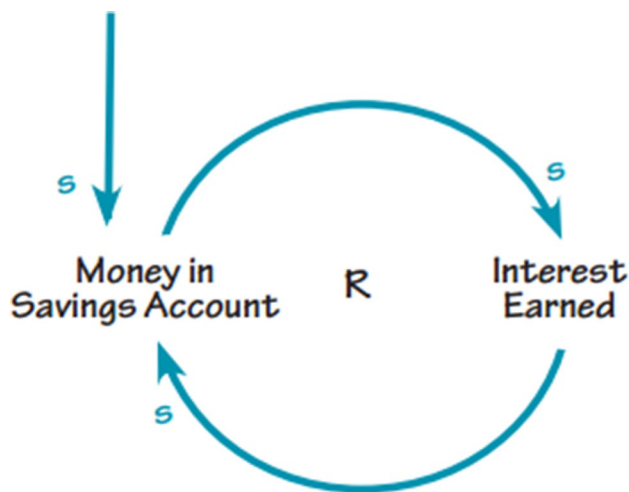


Fig. 3 Example of a reinforcing loop [18]

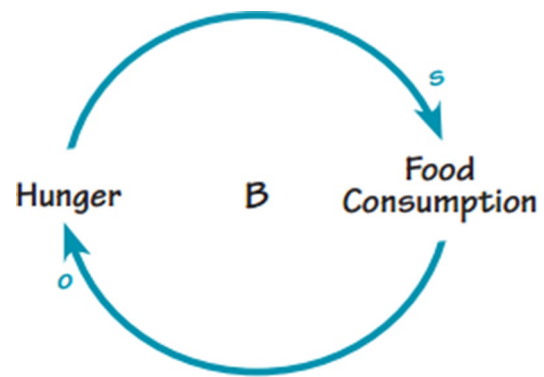


Fig. 4 Example of a balancing loop [18]

visualization, and the CLD is broadly explained in the findings and thematic analysis section of the paper. The variables used for the CLD are shown in Table 2.

Stakeholder survey

A self-administered, semi-qualitative and anonymised online survey was designed and administered using the online survey tool Qualtrics XM platform. The development of the online survey was informed by findings of the systematic literature review that was explained previously. The survey was administered from 15th April to 15th June 2025. The research ethics permission for the survey was obtained from the Research Ethics Committee (File number: KRH/84/2025). The web link to the survey was mainly distributed using the LinkedIn platform as well as directly shared with professional networking websites. To increase the response rate, multiple reminders were sent out. The survey participation was entirely anonymous and voluntary. In the participant information sheet, the participants were informed of their right to withdraw from the survey without any penalty.

The survey combined multiple-choice and open-ended questions, including free-text responses to capture detailed perceptions. The questionnaire included demographic information about survey participants, such as where their work is based. The questions about the key environmental, economic, and ethical aspects/issues associated with transitioning to a GH economy were also included as free-text response options to add other perspectives from the given choices. Here, the method or analysis to a particular sector of the GH economy (especially when questioning the barriers to upscale towards a GH economy) was not confined; rather, the whole supply chain of GH was considered to understand its ethical considerations. The novelty of this research lies in the fact that the responses were drawn from those who are currently engaged in the GH industry in any capacity. Authors reviewed the questionnaire for clarity and content validity and prior to large-scale distribution, a pilot survey was conducted with purposively selected stakeholders. Following the pilot survey, based on the feedback received the questionnaire was reviewed for wording and order of the questions. The full questionnaire is provided as supplementary material (Supplementary Information).

A total of 38 valid responses were exported from Qualtrics to Microsoft Excel. This number indicates the responses after removing, incomplete and duplicate entries from the dataset. The multiple-choice responses were presented in descriptive statistics. The free text responses were reviewed by the authors and coded into pre-defined thematic categories or summarised into unique categories and analysed through reflexive thematic analysis. NVivo software was used for the development of codes and themes. Coding was done by the first author and

reviewed by the co-authors. Iterative discussions and consensus have resolved the discrepancies that emerged during the coding and analysis. The pre-defined themes were based on a systematic review conducted to develop the survey questionnaire. Further, this survey can be considered as an attempt to validate the findings from the systematic review.

Limitations of the study

We acknowledge several limitations of the online survey. Although this is a global survey, the final number of valid responses is as low as 38 and of the stakeholders participated in the survey this number is heavily skewed toward academics. This risks potential selection bias and reduces the ability to generalise the findings. However, since our study was exploratory and not representative, our results have elicited informed and experience-based insights from the stakeholders engage in GH production and associated fields.

Results and discussion

This section consists of the research gaps identified from the systematic literature review that informed the development of the online survey. This is followed by the survey results, together with the thematic analysis of the qualitative questions of the survey, which complements the review findings.

Gaps identified in the systematic literature review

The results of the systematic literature review revealed that globally focused studies (59%) tend toward general insights, often overlooking region-specific socio-economic and environmental challenges. While a global view offers scalable frameworks, it lacks attention to unique regional needs, particularly in the Global South (17%), and specific countries like the UK, Australia, and South Africa. Limited research examines unique challenges in these regions, such as economic dependency, social inequalities, and resource scarcity, crucial for achieving just transitions.

Case studies, empirical assessments, and narrative reviews were dominated in the literature while multimethod approaches that integrate qualitative and quantitative analyses were limited. Integrating quantitative and qualitative methods with policy analysis would provide a more nuanced view of social impacts, bridging theory with actionable policy. Moreover, the scarcity of conceptual and theoretical analyses reveals a gap in foundational frameworks to tackle issues like community displacement, resource exploitation, and gender disparities unique to GH projects.

Most research examines immediate or short-term impacts, often neglecting long-term social and ethical consequences. Aspects such as shifting employment patterns, regional economic dependencies, and cultural impacts may only become apparent over time, underscoring the need for longitudinal studies to assess how GH transitions will affect communities in the coming decades. Additionally, studies often address challenges in the Global North and Global South separately without adequately exploring the interdependencies between these regions through global supply chains, economic ties, and environmental impacts. This separation overlooks how the interconnectedness of these regions affects GH production and its associated challenges.

The identified feedback loops are summarized in Table 3. Figure 5 shows how various social, economic, and ethical variables interact to influence sustainable GH production. These variables are in four key groups: Production and Market (blue), Financial and Economic (yellow), Social and Community Impact (grey) and Resource and Environmental factors (green). Further, this shows a dual dynamic in how GH production drives technological innovation, market growth, and economic dominance in the Global North and how it leads to resource exploitation, social risks, and economic dependence in the Global South.

The reinforcing loops R1, R2, R3 and R4 show how Global North uses GH as a tool for expansion, capturing market share and consolidating technological superiority. Meanwhile, the Global South, rich in natural resources

Table 3 The feedback loops related to GH production based on their sequence, meaning, and impacts, including reinforcing (R) and balancing (B) loops

No.	Loop Name	Feedback Loop	Meaning	Impact on Green Hydrogen Production
1	R1	Green Hydrogen Production → (+) Technological and Resource Requirements → (+) Support and Investments → (+) Economic and Technological Dominance → (+) Cost Competitiveness → (+) Market Share → (+) Green Hydrogen Production	Economic and technological reinforcement	Self-reinforcing cycle promotes continuous technological advancement, investment, and market growth, enhancing economic competitiveness and supporting sustainable green hydrogen production.
2	B1	Green Hydrogen Production → (+) Technological and resource requirement → (+) Foreign investment → (+) Export-oriented Projects → (+) Imported Social Risks → Labor Influx → (-) Resource Access → (-) Displacement of local community → (-) Community wellbeing → (+) Local Capacity and Employment → (+) Green Hydrogen Production Pathways Imported social risks → (+) Resource Exploitation → (+) Water demand → (-) resource access Resource exploitation → (+) Land conflict → (-) Resource Access	Social and environmental balancing	This loop highlights the social and environmental effects of labour influx, imported social risks, and resource exploitation, destabilizing communities and creating resource conflicts that need mitigation for sustainable green hydrogen production.
3	R2	Foreign Investment → (+) Export-oriented Projects → (+) Imported Social Risks → (+) Labor Influx → (-) Resource Access → (-) Economic Dependence on Global North → (+) Foreign Investment Pathways Imported social risks → (+) Resource Exploitation → (+) Water demand → (-) resource access Resource exploitation → (+) Land conflict → (-) Resource Access	Economic and social dependence	This reinforcing loop perpetuates economic dependence on the Global North, with social risks and environmental degradation which may jeopardize the sustainability of green hydrogen projects unless addressed.
4	B2	Green Hydrogen Production → (+) Technological and Resource Requirements → (+) Foreign Investment → (+) Export-oriented Projects → (+) Imported Social Risks → (+) Labor Influx → (+) Gender-based Violence → Marginalization of Women → (+) Employment Opportunities for Women → (+) Female Participation in Workforce → Representation in Decision-Making → (+) Gender Equality → (+) Local capacity and employment → (+) Green Hydrogen Production Pathways Labor Influx → (-) Resource Access → (-) Displacement of Local Community → (+) Marginalization of Women Labor Influx → (-) Resource Access → (-) Household burdens of women → (+) Marginalization of women	Social inequality balancing	This balancing loop focuses on the adverse social impacts of labour influx, especially on women's participation and employment, highlighting the need for gender equity to improve social sustainability in green hydrogen projects.
5	R3	Foreign Investment → (+) Profits Flow Back → (+) Economic Dependence on Global North → (+) Green Hydrogen Production	Financial flow and dependency	This loop creates a reinforcing cycle of financial dependence on foreign investment, limiting local capacity development unless counted by policies for local ownership and control.
6	B3	Green Hydrogen Production → (+) Technological and resource requirements → (+) Foreign Investment → Profit flow back → (-) Community wellbeing → (+) Local Capacity and Employment → (+) Green Hydrogen Production	Community development balancing	Overemphasis on profit flow back to Global North can reduce community well-being, potentially stalling green hydrogen production unless investments improve local capacity and social welfare.
7	R4	Resource requirement (+) → Technological and Resource Requirements → (+) Support and Investments → (+) Economic and Technological dominance → (+) Cost Competitiveness → (+) Market Share → (+) Green Hydrogen Production	Market growth reinforcement	This self-reinforcing loop promotes market growth, cost competitiveness, and economic dominance, expanding green hydrogen production in the Global North but potentially exacerbating global inequalities
8	B4	Green Hydrogen Production → (+) Technological requirements → (+) Foreign investment → (+) Export-oriented Projects → (+) Over-Reliance on Imports → (+) Supply Chain Risks → (-) Cost Competitiveness → (+) Market Share → (+) Green Hydrogen Production	Supply chain balancing	Over-reliance on imports increases supply chain risks and reduces cost competitiveness, threatening the sustainability of green hydrogen production unless more robust local supply chains are developed.

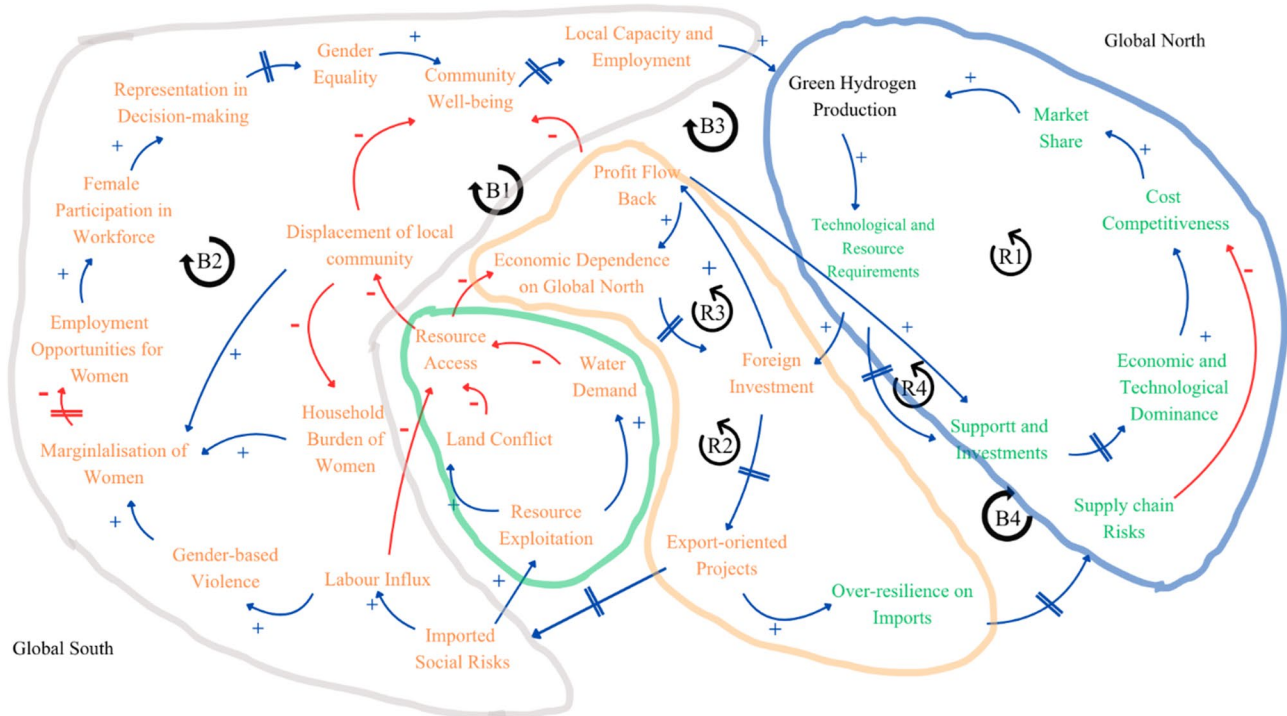


Fig. 5 The CLD of the social, economic and ethical variables interact to influence sustainable GH production. (Source: Authors)

but often lacking technological and economic power, is at risk of becoming a site of resource extraction for the benefit of the Global North, echoing patterns of energy colonialism. The balancing loops B1, B2, B3, and B4 expose the Global South's inherent trade-offs and social costs, such as displacement, gender inequality, resource depletion, and the risk of long-term unsustainability. The CLD further highlights justice outcomes are contingent to the combined interactions of economic incentives, governance capacity and social wellbeing.

Results of the online survey

A total of 38 participants took part in the survey, and the majority (89%) represented the Academic/research sector, followed by industry (11%), civil society organisations (NGOs) (4%) and the remaining 7%. It is important to acknowledge that the total sample size of 38 participants limits the generalisability of the findings, but the exploratory nature of the findings generates preliminary insights and informs future, more intensive research.

Of the total participants, the majority's work was based in Europe (48%), and Australia/Oceania (26%) was the second highest region. Moreover, 15% of the participants identified themselves as experts in the field of green hydrogen, while 41% were moderately familiar. Key environmental concerns related to GH, as identified by the participants, are shown in Fig. 6. Accordingly, high energy consumption in the GH production is the most concerning aspect in terms of environmental aspects. The 'other' option was specified by concerns such as efficiency in terms of energy usage, misusing the GH title for greenwashing, and storage/containment.

The economic challenges to upscaling GH production were multifaceted. Of them, the highest responded challenge was the high initial investment costs (77%) (Fig. 7). Lack of government financial support to underpin GH production compared to fossil fuel subsidies in Australia was among the other responses.

Respondents viewed displacement of fossil fuel workers (52%) and land/resource conflicts (48%) as the most pressing ethical issues (Fig. 8). The 'other' option included the petrol lobby, conflict with fishermen, etc.

Fig. 6 The percentages of key environmental concerns related to GH production as identified by the respondents

Key environmental concerns related to GH production

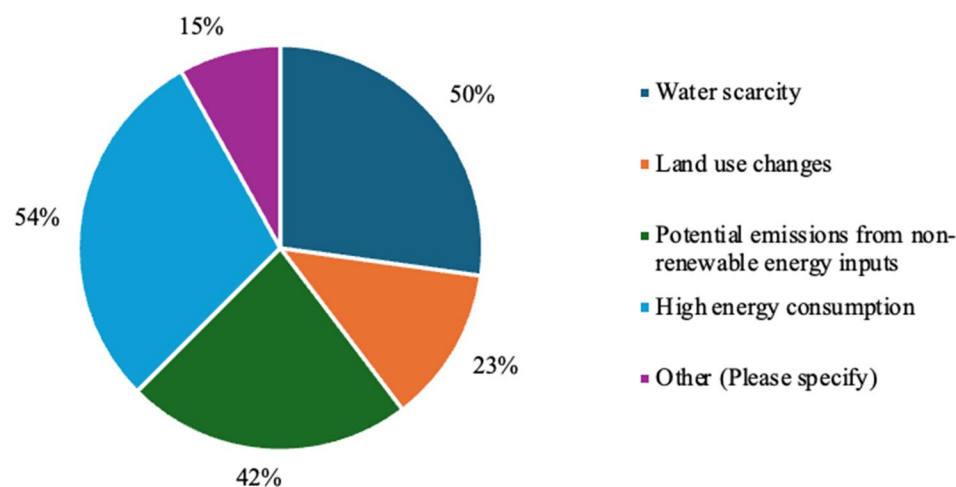
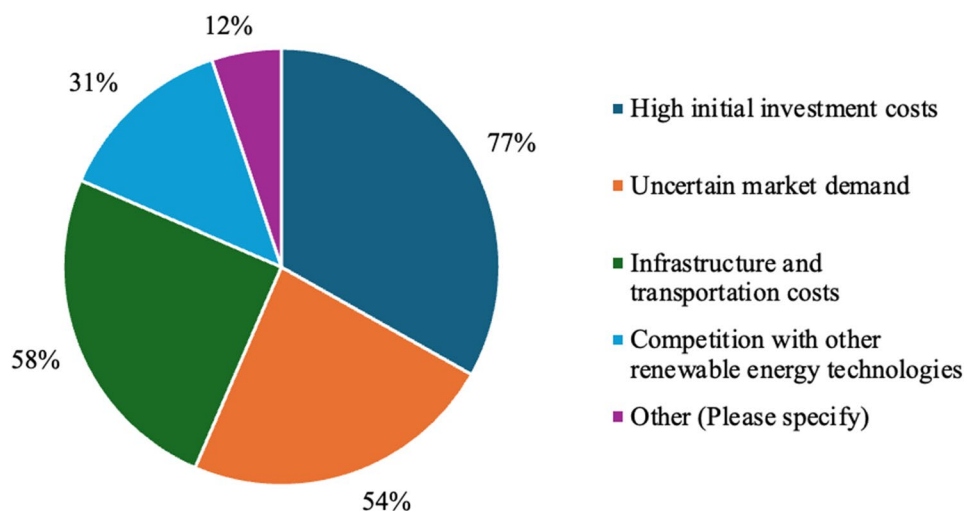


Fig. 7 The percentages of key economic concerns of upscaling GH production

Economic concerns of upscaling GH production



To ensure an equitable transition to GH production, the respondents have selected a mixture of measures. Among which, government policies that support workforce transition was the most mentioned with a 73% response rate, (Fig. 9).

The responses about the effective policy measures to promote GH adoption have also included mixed responses, as the respondents were asked to select multiple responses from the given options. Accordingly, strengthening international cooperation and regulations was selected by the majority of the respondents (67%), while subsidies and financial incentives accounted for the fewest responses with 43%, (Fig. 10) below. Moreover, 48% of the participants considered public engagement as very important in shaping GH policies and projects.

The respondents were asked to share their ideas about the biggest challenges to a just and ethical transition towards a sustainable GH economy as an open-ended question. These responses were analysed using NVivo software to develop them into three themes as shown in Fig. 11.

The open-ended responses from the online survey resulted in three main themes of challenges: structural and technical challenges, societal awareness and perception, and power, politics and social justice.

Fig. 8 The percentages of key ethical issues to transition to the GH economy

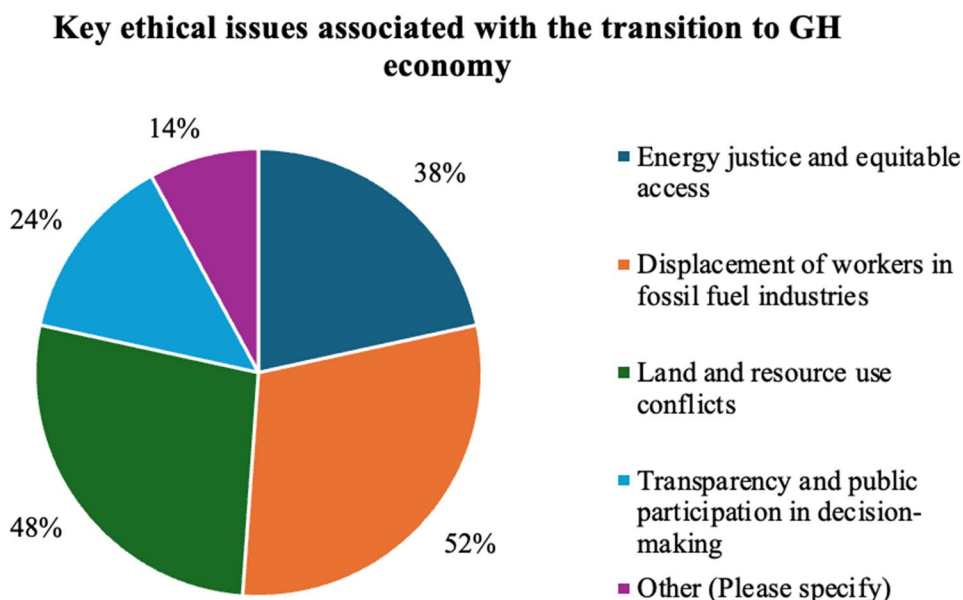
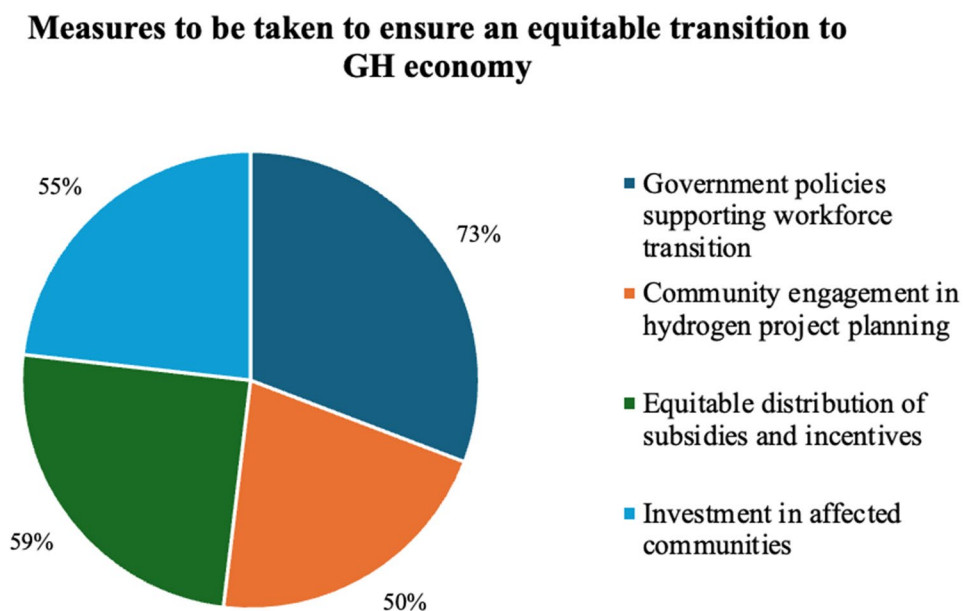


Fig. 9 The percentages of measures chosen to ensure an equitable transition to the GH economy



Combined insights from the literature review, CLD analysis, and an online stakeholder survey reveal consistent results, ultimately increasing confidence in our findings. First, the justice concerns of all three studies were similar, including how land, water and energy resources were used and power dynamics between the Global South and Global North. Hence, the challenges and other key concerns associated with GH production can be identified as not isolated but perpetuating across time and space. Second, the complementary nature of the methods used in each study strengthened the interpretation of the results. Third, the use of mix method supported in identifying different perspectives on widely appreciated policy views. For instance, although financial subsidies have been highly appreciated in literature the survey respondents have shown cautious valuation of those kind of incentives while highlighting the importance of other aspects such as regulation and coordination in GH transition. Overall, the results show that GH transitions are shaped through multifaceted aspects and not largely on technological constraints; these include governance, political and social aspects.

Fig. 10 The percentages of responses about effective policy mechanisms to promote GH adoption

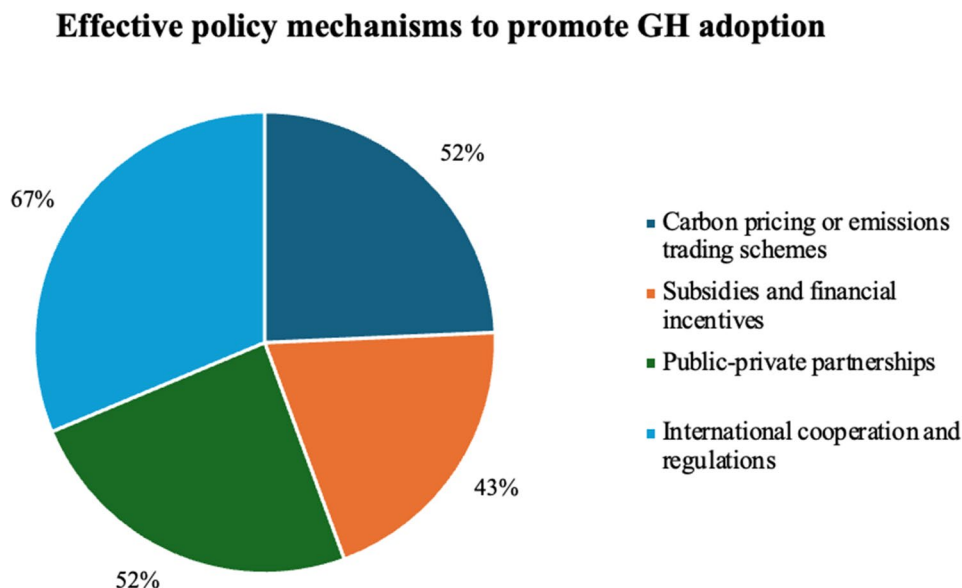
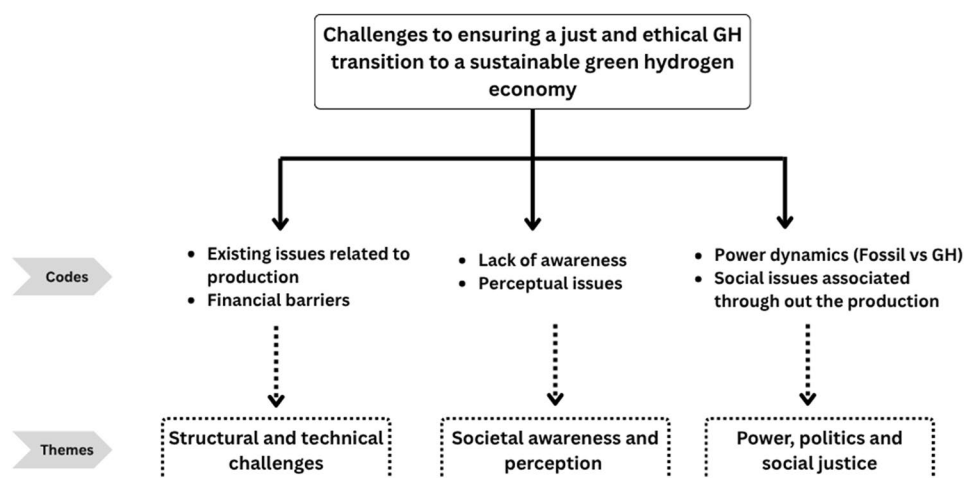


Fig. 11 Challenges to a just and ethical GH transition to a sustainable GH economy



Discussion

The results revealed that understanding GH transition requires a complex socio-economic-technical process, in which social and environmental uncertainties and justice concerns are also considered alongside technological framings. These findings are broadly consistent and also reinforce the emerging breadth of literature on GH transition. Synthesis of results from the systematic review, CLD analysis, and the online stakeholder survey demonstrates that justice outcomes of GH production and transition are embedded in the way they are governed and organised financially and spatially.

Environmental concerns in GH transitions

The environmental risks in GH production were identified throughout this study, across all the methods. For instance, the online survey revealed environmental challenges associated with high energy consumption, which is consistent with life cycle assessment (LCA) studies that show the high-energy incentive nature of electrolytic hydrogen even through renewable sources [19, 20]. Environmental challenges were also associated with intensive

material demand, which leads to ecological risks. This is congruent with Deetman et al. [21] and Carrara et al. [22], who elaborate how increased material demand, including metal, cement, and land use, will increase the risk of biodiversity loss, water scarcity, and ecosystem degradation. The competition for natural resources - for instance, water - will further exacerbate these environmental risks, especially in the regions of the Middle East and North Africa [8]. The CLD analysis also explicitly demonstrated how environmental pressure influences other aspects in GH transition.

Economic challenges and market uncertainties

Our results highlighted economic challenges to GH transition such as the high initial investment costs and limited government support. This is aligning with the policy assessments that identified market demand uncertainties and competition with other renewables as major constraints on GH transitions [23, 24]. However, these constraints can be overcome through finding opportunities to collaborate across scale. For instance, multi-sectoral collaboration across storage, transport and infrastructure sectors [25].

Ethical and social justice dimensions

The ethical and social justice concerns identified from our study not only contribute to but also supported by the emerging scholarships for energy justice. The displacement of fossil fuel worked, and land/resource conflicts were some of the justice challenges identified in the study. This is consistent with the recent findings by Tunn et al. [26], in which they highlight overlooking social and ethical challenges on existing livelihoods impacted by GH production, risk reproducing patterns of energy colonialism. According to Muller et al. [27] these overlooked livelihood categories included small-scale fishers and other vulnerable groups. As Sovacool and Dworkin [9] emphasised, our results also elaborated that GH transitions in the absence of procedural and distributive justice, risk marginalising already vulnerable communities which may also provoke social resistance against GH transitions. Moreover, scholars increasingly call for the integration of social science and systems thinking approaches to better address anticipate unintended consequences in GH transitions [28].

Regional and Global North-South dynamics

Our study findings on Global North-South asymmetries are in-line with existing literature on political economy and energy transition research. The CLD analysis revealed a duality in GH production expansion where it can reinforce technology dominance and market capture in the Global North but and the same time externalising environmental and social costs on the Global South. Some scholars [26] urge cautions on the risks of increasing extractives and neo-colonial inequalities associated with GH transitions while others [29] argue that the transitions may not lead to perpetuate inequalities provided that mechanisms on inclusive governance are in place.

Theoretical contributions

This study extends the application of energy justice frameworks to GH by integrating distributive, procedural, and recognition justice into a systems-based analysis. Results show that distributive concerns are evident in debates over land, water, and employment trade-offs; procedural challenges emerge in the limited stakeholder participation in GH planning; and recognition justice remains underdeveloped, particularly with respect to Indigenous communities and marginalised groups. By linking these dimensions to the causal loop diagramming, it is demonstrated how reinforcing and balancing feedback loops can exacerbate or mitigate justice outcomes.

In addition, the findings resonate with sustainability transitions theory. The multi-level perspective (MLP) highlights how GH development is shaped by interactions between niche innovations, established regimes, and global landscape pressures. Socio-technical imaginaries, such as visions of “hydrogen superpowers” in Australia

or import dependence in the EU, influence how justice concerns are prioritised. Finally, socio-ecological risks, including extractivist patterns and energy colonialism, are illuminated through the systems mapping. The novelty of this work lies in combining justice scholarship with systems thinking to provide an integrated lens on GH transitions, contributing both to theoretical advancement and to applied energy policy debates.

Regional insights: Australia and the European union

Although this study adopts a global perspective, the findings have particular salience for Australia and the European Union (EU), both of which are rapidly advancing green hydrogen strategies. In Australia, GH hubs in regions such as Gladstone, Western Australia, and South Australia illustrate the promise of large-scale projects, yet also raise questions about workforce transitions in coal and gas-dependent communities. This aligns with Australia's National Hydrogen Strategy [30], which emphasises regional hydrogen hubs and workforce transition. Survey concerns about fossil fuel job displacement align with the national debate on just transition mechanisms, retraining programs, and regional development funds. These dynamics show how distributive and procedural justice issues are embedded in the rollout of hydrogen policies.

In the EU, hydrogen is positioned as central to decarbonisation but import strategies from North Africa and other regions raise concerns of energy colonialism and dependence. This reflects the EU's Hydrogen Strategy [31] and REPowerEU Plan [32], which promote hydrogen imports to secure energy diversification but raise concerns over energy colonialism. The CLD results on North–South dynamics directly speak to these risks, highlighting the importance of transparent benefit-sharing, inclusive governance, and environmental safeguards in cross-border hydrogen supply chains. By situating the findings within these regional contexts, it is shown how global justice concerns manifest in specific policy arenas, offering actionable insights for both domestic and international energy governance [33].

Limitations

While this study provides valuable insights into the ethical and social dimensions of green hydrogen transitions, several limitations should be acknowledged. The survey sample was relatively small and skewed toward academic participants, which constrains the representativeness of the findings. Therefore, survey findings should be viewed as *exploratory perceptions* rather than generalizable evidence. Nevertheless, by triangulating these insights with the systematic literature review and causal loop diagramming, a robust, multi-method perspective was generated that highlights key justice issues and leverage points. Future research with larger and more diverse stakeholder samples, including industry, government, and community actors, will be critical to build on these exploratory findings.

Conclusions

This study highlights that the transition to a GH economy is not only a technological and economic challenge but also a profound socio-ethical transformation. By combining a systematic literature review, exploratory stakeholder survey, and systems-based causal loop diagramming, new insights into how GH transitions interact with justice, governance, and community well-being were provided.

Three key insights have emerged from this study. First, justice centred governance is essential. To achieve this, policies must embed distributive justice (fair sharing of benefits and burdens), procedural justice (inclusive decision-making), and recognition justice (acknowledging diverse groups and vulnerabilities) to avoid deepening inequities. Second, participatory and transparent mechanisms are necessary which can be achieved through systematically integrating Community engagement, labour organisations, and civil society inputs into hydrogen strategies to ensure legitimacy and public trust. Third, CLD analysis demonstrated how systems thinking can

guide better policy *by identifying* feedback loops and leverage points that help policymakers to understand unintended consequences, such as extractivist patterns and resource conflicts, and design interventions that strengthen resilience.

At the policy level, just transition funds, workforce retraining programs, environmental safeguards in international trade, and multi-level governance arrangements are crucial to ensure GH contributes positively to society. For researchers, integrating systems thinking with energy justice frameworks offers a robust pathway for analysing socio-technical transitions.

In sum, green hydrogen holds promise as a decarbonisation tool, but its sustainability depends on how well ethical and social dimensions are embedded into decision-making. Ensuring justice, inclusivity, and governance integrity will determine whether GH becomes a driver of sustainable futures or another iteration of energy colonialism.

Building on the findings, several policy implications emerge:

- Manage resource and energy intensity: Anticipate the high renewable capacity, land, and water demands of GH production. Policies must balance scaling-up with biodiversity conservation and community rights.
- Support just workforce transitions: Establish just transition funds, retraining programs, and employment guarantees to prevent fossil fuel job losses from reinforcing regional inequalities.
- Safeguard against energy colonialism: Embed benefit-sharing, local value creation, and robust social/environmental safeguards in international hydrogen trade agreements to protect resource-rich but infrastructure-poor regions.
- Institutionalize participation and transparency: Mandate community consultation, civil society engagement, and inclusive governance models in GH planning processes to strengthen social acceptance and legitimacy.
- Adopt a policy mix: Combine instruments such as carbon pricing, targeted subsidies, renewable portfolio standards, and international financing mechanisms, rather than relying on a single tool, to accelerate GH adoption while ensuring justice and equity.

In conclusion, GH has significant potential to contribute positively to the global decarbonisation strategies; however, the socio-economic-environmental challenges associated with GH production have not received adequate attention in the sustainable energy literature. To achieve the full potential of the benefits of GH transitioning, it is not only about technological advancements but also contingent on political choices, governance mechanisms, and institutional strategies. Hence, achieving just energy transition through a GH economy requires holistic approaches that address social, economic, environmental, and technical challenges simultaneously.

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Author contributions A.H. conceptualised and designed the research, supervised the overall study, contributed to the systems thinking framework and interpretation of results, and critically revised and edited the manuscript for intellectual content. F.Y. conducted the systematic literature review, collected and analysed the data, prepared the causal loop diagrams, and drafted the original manuscript. G.K. contributed to the interpretation of the ethical and governance dimensions of the study and substantially revised and edited the manuscript, particularly in relation to the socio-ethical and policy discussions. All authors read, reviewed, and approved the final manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate A self-administered, semi-qualitative and anonymised online survey was designed and administered using the online survey tool Qualtrics XM platform. The survey was administered from 15th April to 15th June 2025. The research ethics permission for the survey was obtained from the Research Ethics Committee of Corvinus University of Budapest (File number: KRH/84/2025). The weblink to the survey was mainly distributed using the LinkedIn platform as well as directly shared via professional networking websites. The survey participation was entirely anonymous and voluntary. In the participant information sheet, the participants were informed of their right to withdraw from the survey without any penalty.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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