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Can hydrogen economy help addressing regional economic inequalities: A regional hydrogen integration framework

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ABSTRACT

Hydrogen is emerging as a cornerstone of global energy transitions, with its potential to drive economic growth and transform energy systems. As hydrogen can be produced by utilizing renewable resources and investing in production technologies, it has the potential to create new energy powers. The spatial nature of hydrogen systems in terms of where and how it is produced, stored, transported and used, means associated investments will have an impact on the economy and inherent regional inequalities within a nation. Using a systematic literature review, we find that there are comparatively fewer macroeconomic models that analyze the regional dimensions of the hydrogen transition than those examining national level impacts. By synthesizing our findings, we make the following contributions: (i) we show that the regional impacts of the hydrogen economy are realized through three mechanisms: the production method chosen, the hydrogen system segment a region hosts, and the geographic pattern of investment, (ii) we argue that whether these impacts alleviate or exacerbate regional inequalities is governed by two overarching forces: the spatial comparative advantage and local value creation capacity, (iii) we highlight that current macroeconomic models lack the spatial, technological and segmental resolution necessary to capture forward and backward linkages that hydrogen systems may instigate, pointing to the need for closer collaboration between regional scientists and engineers to understand how these opportunities and challenges may shape regional economies, and (iv) the conceptual framework we offer can help with supporting hydrogen's role to alleviate regional inequalities by recognizing the interplay between economic, technological, and policy factors through three mechanisms, two overarching forces, and the feedback loops linking policy and distributive outcomes.

1. Introduction

Hydrogen plays a critical role in achieving net-zero emissions targets by enabling the decarbonization of hard-to-abate sectors like manufacturing industry, especially when produced from renewable sources. In 2024, global hydrogen demand reached 100 million tonnes (Mt) which is mainly produced via steam reforming of fossil fuels (IEA, 2025). Of this, less than 1Mt is produced via less carbon-intensive methods. To keep global warming to 1.5C, International Energy Agency predicts global hydrogen demand to reach 530 million tonnes (Mt, equivalent to 33 exajoules) by 2050 (IEA, 2023). This five-fold increase in global hydrogen demand implies almost a 700-fold increase in electrolyzer capacity (from 5.2 gigawatts capacity to 3600 gigawatts), currently main commercially available technology[1] to utilize renewable energy for hydrogen production.[2] Hydrogen can be produced via various technological pathways, each with distinct emissions profiles depending on their feedstock and production technology, as illustrated in Table 1. These pathways range from green hydrogen, produced using renewable electricity sources with minimal greenhouse gas emissions, to fossil-based methods such as gray, blue, brown, and black hydrogen, each associated with higher emission intensities. For a detailed exploration of hydrogen production routes and the constraints associated

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[1] There are a number of alternative electrolyzer technologies. The more mature ones are alkaline based which have limited operational flexibility to ramp up or down depending on the availability of renewable power in the grid. Proton exchange membranes, main types deployed across Europe, offer this operational flexibility. However, they require the use of precious metals the production of which are limited. For a review of these technologies, please see Arsad et al. (2023).

[2] The Global Hydrogen Production Technologies Center focuses on a very new nascent technology, solar photocatalysis which uses sunlight directly to help water break apart into oxygen and hydrogen.

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Table 1
Classification of hydrogen production methods.
Source: Adapted from Cheng and Lee (2022).

	Terminology	Technology	Feedstock / Electricity source	GHG footprint*
PRODUCTION VIA ELECTRICITY	Green Hydrogen	Electrolysis	Wind, Solar, Hydro Geothermal, Tidal	Minimal
	Purple/Pink Hydrogen		Nuclear	
	Yellow Hydrogen		Mixed-origin grid energy	Medium
PRODUCTION VIA FOSSIL FUELS	Blue Hydrogen	Natural gas reforming + CCUS Gasification + CCUS	Natural gas, coal	Low
	Turquoise Hydrogen	Pyrolysis	Natural gas	Solid carbon (by-product)
	Grey Hydrogen	Natural gas reforming		Medium
	Brown Hydrogen	Gasification	Brown coal (lignite)	High
	Black Hydrogen		Black coal	

with their deployment, including high production costs, infrastructure limitations, and efficiency challenges, readers are referred to Yue et al. (2021). Once hydrogen is produced, it needs to be stored and transported for utilization in sectors like marine, road and air transport, power generation, and manufacturing industry, requiring some degree of end-use technology[3] In this paper, the term "hydrogen system" encompasses the full segments of production, storage, transportation, and end use sectors. replacement to deliver carbon savings. As hydrogen can be produced by utilizing renewable resources, it has the potential to create new energy powers, resulting in a mix of developed and developing countries, including Japan, Germany, South Korea, Chile, and Saudi Arabia, to develop hydrogen strategies (IRENA, 2022a). For example, the UK government has positioned hydrogen as a "home-grown" fuel in its Energy Security Strategy (UK, 2022), doubling its production targets to reduce reliance on energy imports and support the transition to net-zero. Similarly, other countries in Europe, including Denmark, Portugal, Spain, France, Belgium, Italy, Germany, Austria, the Netherlands, and Switzerland have established hydrogen targets focusing on electrolyzer capacity and hydrogen production (S&P Global, 2021). Germany, for instance, has committed €7.9 billion of euros, approximately 0.19% of its GDP in 2023, to develop its hydrogen infrastructure and projects, aiming to become a leader in green hydrogen technologies (Nunez and Quitzow, 2024). France has launched a €7 billion plan, about 0.23% of its GDP, to support the clean hydrogen industry as part of its broader energy transition strategy (Bouacida, 2024). The Netherlands is focusing on leveraging its extensive gas pipeline network to transport hydrogen (Stam et al., 2024). Furthermore, the European Commission has approved substantial public funding for Important Projects of Common European Interest on hydrogen (IPCEI), covering technology development (namely Hy2Tech), end-use applications (Hy2Use), infrastructure development (Hy2Infra), and mobility solutions (Hy2Move), totaling over €18.9 billion (Zabanova, 2024). In addition to Europe, Japan has set ambitious targets for hydrogen use and exports, focusing on creating green jobs and reducing carbon emissions (METI, 2023).

Beyond its potential for contributing to decarbonization, energy security and causing geopolitical shifts in energy markets, pursuit of hydrogen economy is paving the way for new industries to emerge across its production, transportation, and storage segments. The UK government designates clean energy industries sector, including hydrogen, as one of eight sectors with the highest potential to increase national productivity, strengthen economic security and resilience, and support environmental goals and the net-zero transition (HM Government, 2025). Academic scholars share this ambition as the expansion of hydrogen infrastructure will likely stimulate industrial growth by establishing new supply chains and fostering technological innovations, particularly in heavy industries (Magazzino et al., 2024). This growth in the hydrogen sector is anticipated to generate substantial employment opportunities (Hepburn et al., 2020), not only through direct job creation but also by driving regional[4] development and strengthening local economies. Such multiplier effects such as generating new supply chains and significantly boosting regional economies are noted for renewable energy projects like wind and solar power (IEA, 2024a).

Given the spatial nature of hydrogen systems in terms of where and how they are produced, stored, transported and used, to what degree and how they may fulfill their potential to stimulate economic growth across related sectors – including impacts on regional inequalities and long-term growth – are unknown. More explicitly, decisions about where, when and through which policy mechanisms, say, Germany allocates 0.2% of its GDP, would impact its national economy and inherent regional inequalities. Yet to date, the potential impacts of the development of hydrogen systems on both national and regional economies have been overlooked. The aim of this paper is to fill this gap by systematically reviewing the macroeconomic literature to understand not just the scale of hydrogen's economic impacts, but the spatial mechanisms that determine how these impacts may be distributed across regions. We aim to address the following research questions: (i) what are the macroeconomic impacts of the development of hydrogen systems and how do they depend on policy mechanisms? (ii) how do macroeconomic models represent different segments of hydrogen systems in terms of production, storage, distribution and end-use? (iii) in what ways might the development of hydrogen systems alleviate or exacerbate regional inequalities? Fig. 1 summarizes our conceptual framing: regional outcomes are driven by the joint interaction of the characteristics of hydrogen system with underlying regional and national economic conditions. As hydrogen systems both influence and react to these national and regional economic structures, they create mechanisms that can either exacerbate or alleviate disparities. Our analysis yields four key findings. First, we show that the regional impacts of the hydrogen economy are realized through three mechanisms: the production method chosen, the hydrogen system segment a region hosts, and the geographic pattern of investment. Second, we argue that whether these impacts alleviate or exacerbate regional inequalities is governed by two overarching forces: the spatial comparative advantage and local value creation capacity. Third, existing macroeconomic models represent only a narrow set of hydrogen production methods and provide even thinner coverage of storage, distribution and end-use segments, so we still know little about how hydrogen systems generate forward and backward linkages across regions. This highlights the need for closer collaboration between regional scientists and engineers to better understand how these opportunities and challenges may shape regional economies. Fourth, we propose an analytical framework designed to mitigate the risk that hydrogen systems exacerbate existing regional inequalities.

The remainder of this article is structured as follows: Section 2 outlines the literature review methodology employed in the analysis.

[4] In this paper, a region is defined as a sub-national unit–a state, province, county or metropolitan area.

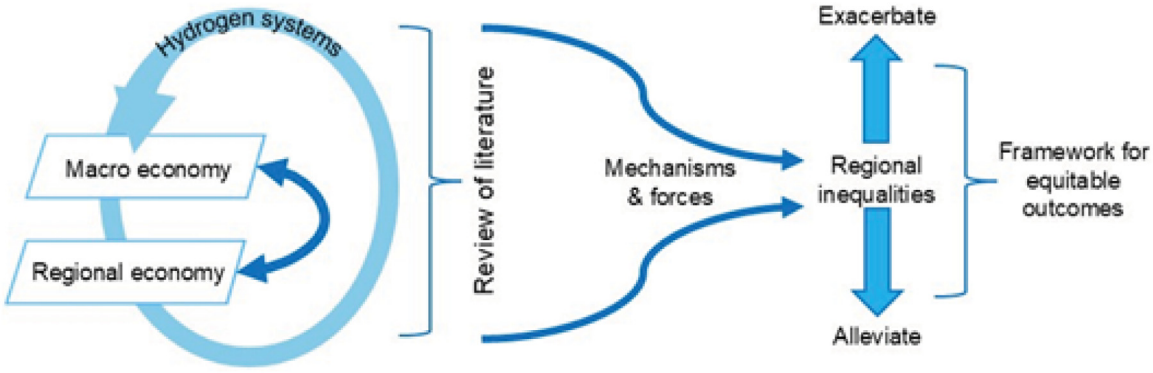

Fig. 1. Overall approach of the study.

Section 3 delves into the findings related to specific research questions. Section 4 synthesizes our findings, interprets inequality-relevant mechanisms, presents our integration framework, and identifies research gaps. Finally, Section 5 concludes.

2. Methodology

This section outlines the systematic literature review process and provides details on the data collection process and results.

2.1. Systematic review

This paper aims to systematically review the literature that examines the macroeconomic implications of hydrogen, focusing on economic growth and employment, while also considering how environmental impacts are integrated into these analyses.

Following Pickering and Byrne (2014), this review is conducted in several key stages. First, the topic is precisely defined, and research questions are formulated to guide the review. Second, relevant keywords are selected to construct search strings for querying databases. Third, detailed inclusion and exclusion criteria are established to filter studies that are directly relevant to the macroeconomic analysis of hydrogen. Finally, a structured database is created to collect and analyze the data from the selected studies. Critically, this review process is structured to capture not only the national-level macroeconomic implications but also to explicitly identify and synthesize findings on how these impacts vary at the regional level.

2.2. Data search and selection

The methodology was applied to analyzing the macroeconomic impacts of hydrogen by breaking down broad questions into more detailed research inquiries. To answer this, several sub-research questions were formulated related to: (i) the macroeconomic indicators used to measure the impact of hydrogen, (ii) the extent to which these outcomes are disaggregated to capture regional variation, (iii) the modeling frameworks applied in the reviewed papers, and (iv) the ways in which hydrogen systems are characterized.

In alignment with the research questions, a structured search string was developed, composed of different categories of keywords to identify relevant studies. These categories included: (i) hydrogen end use (e.g., "hydrogen","h2", "fuel cell") (ii) hydrogen production methods (e.g., "*hydrogen", "CCS", "electrolysis", "biohydrogen", "steam reforming", "methane", "fossil fuel", "gas"), (iii) macroeconomic modeling approaches (e.g., "CGE", "input–output", "macroeconom*", "general equilibrium", "social accounting"), (iv) economic and environmental outcomes (e.g., "GDP", "output", "production", "employment", "emission", "export"), (v) regional elements (e.g., "regional", "subnational", "state", "province", "city").[5] The keywords within each category were combined using the Boolean "OR", and the categories were linked using the Boolean "AND" to ensure that the selected studies addressed both hydrogen systems and macroeconomic analysis. To reflect the evolving nature of this research area, the review also includes selected working papers.

To refine the search results, two additional specifications were applied: first, articles that did not align with the research questions (such as those focused purely on engineering or technical aspects) were excluded, and second, only studies published in English were considered to ensure accessibility for a broad audience. The search was conducted using the Scopus and Web of Science databases, chosen for their wide interdisciplinary coverage and relevance to energy economics, covering literature published from 2010 to 2025.

The initial search yielded 727 results. The titles and abstracts of these papers were screened to assess their relevance to the research topic (see Fig. 2). If a paper was deemed relevant or if there was any uncertainty, a full-text review was conducted. To be included in the final analysis, studies had to meet specific criteria: they must employ macroeconomic models to assess hydrogen systems, focus on the economic and environmental impacts of hydrogen, and provide quantitative analyses of key macroeconomic outcomes, such as GDP, employment, sectoral outputs and carbon emissions.

2.3. Search analysis

Table A.3 describes the key findings from studies. The analysis of the selected studies is organized to include the year of publication, the journal affiliation, and model characteristics.

All 44 papers included in this review were published between 2010 and 2025. Fig. 3 shows the breakdown of papers by publication year, with a noticeable increase in publications in recent years, reflecting growing academic interest in hydrogen's economic potential. Of the key journals, the International Journal of Hydrogen Energy and Renewable and Sustainable Energy Reviews feature a blend of technical and economic studies, while Energy Policy and Energy Economics are more focused on economic analysis and energy policy.

Fig. 4 presents the modeling methodologies used across the various studies in this review. A significant portion of the studies employed CGE models, which are well-suited to analyzing the macroeconomic effects of hydrogen technologies. Many of these studies built on pre-established models rather than developing entirely new approaches. For example, the widely known Global Trade Analysis Project (GTAP)

[5] Due to the scarcity of studies explicitly modeling hydrogen's macroeconomic impacts at the sub-national level, an alternative search using the regional keyword block via a Boolean 'OR' was conducted.

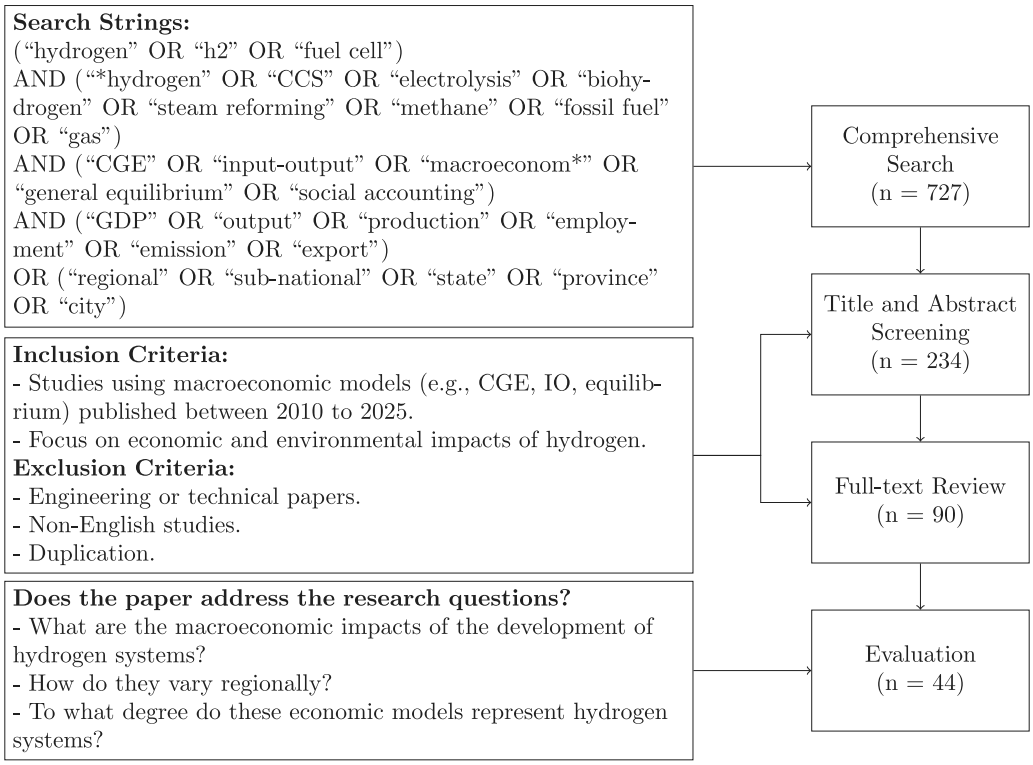

Fig. 2. Literature review paper selection process.

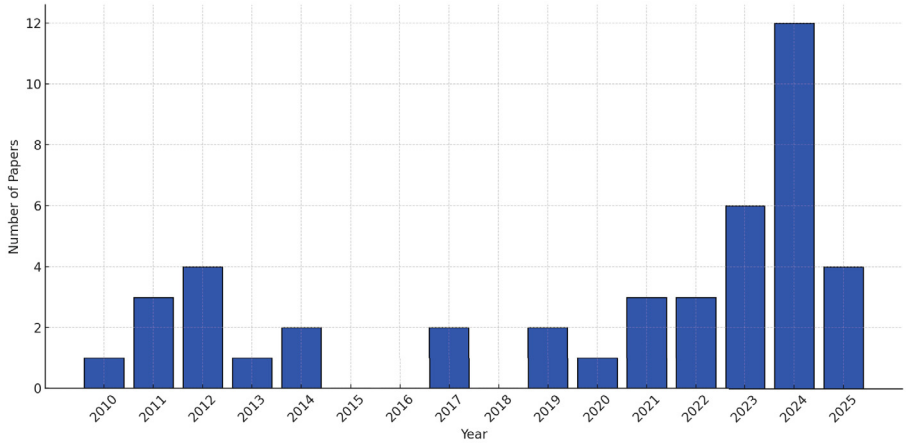

Fig. 3. Number of papers per year.

model was applied in a study (e.g., Lee (2014)). Additionally, models such as the WEGDYN model, which allows for an investigation of the macroeconomic effects of sectoral production changes, and country-specific models like UKENVI (UK), REMES (Norway) and TAIGEM-CE (Taiwan) were also applied in the sample. These models were useful for conducting in-depth regional and country-specific analyses of hydrogen technologies. Lee et al. (2011b) offers the fundamental comparison among different modeling methodologies of biohydrogen development.

Some studies integrated CGE models with other approaches to offer a more holistic perspective on hydrogen adoption. For example, Espegren et al. (2021) utilized a framework that combined a CGE model with an energy system model to analyze the energy transition in the context of hydrogen. Similarly, Lee (2020) linked the data envelopment analysis (DEA) with their CGE study to analyze the impact of hydrogen production efficiency. This combination of methods allowed for a more nuanced analysis of economic and environmental implications of different hydrogen production methods. Overall, approximately 32% of the papers in the sample applied such hybrid modeling approaches, reflecting a growing trend in energy-related economic research. In addition, the review shows that Input-Output (IO) models were frequently employed to assess the socio-economic and environmental impacts of hydrogen. A variety of IO models, including Hybrid IO and Recursive IO, were used to capture the broader economic impacts of hydrogen systems, particularly in sectors such as transportation and heavy industry. It is worth noting that IO models were integrated with life-cycle assessment (LCA) to assess the environmental and economic trade-offs of hydrogen technologies. This approach was especially useful for studies evaluating hydrogen's role in decarbonizing high-emission sectors. The review did not reveal any significant patterns in the choice of modeling methodologies based on publication year.

As shown in Table 2, the geographic focus of the studies reviewed varies significantly. Approximately 18% of the papers conduct a global

Table 2
Countries covered by geographic classification.

Geographic classification	Papers (%)	Countries
Global	18%	Multiple countries
Developing	23%	China, India, Brazil, Saudi Arabia
Developed (European)	23%	Norway, Italy, Switzerland, Germany, Romania, France, and UK
Developed (Other)	36%	Japan, South Korea, Taiwan, US

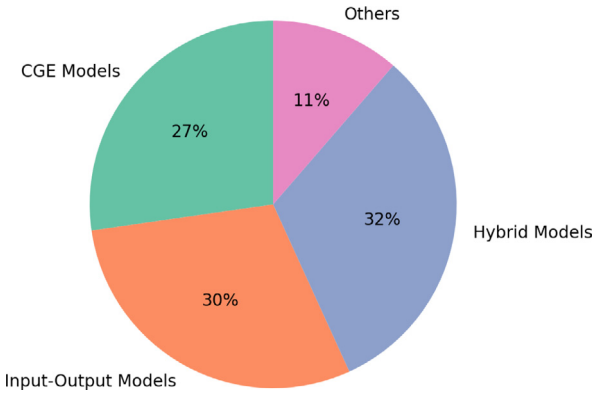

Fig. 4. Model methodologies of the sample.

analysis, integrating both developed and developing countries. Studies focusing solely on developed countries represent around 59%, while those addressing developing nations account for 23% of the sample. On average, papers that take a global perspective encompass a broad range of countries, though the exact number varies. For instance, some studies specify the number of countries, such as one (Zhang et al., 2024) that includes 32 countries. However, many studies adopt a single-country approach, particularly in Asian countries. For example, multiple papers focus on Japan, South Korea, China, and Taiwan. European countries also feature prominently, with studies analyzing the hydrogen economies of Norway, Germany, and the broader European Union.

The time horizons in the studies reviewed reflect a wide range of projections for hydrogen adoption and impact. Many studies focus on 2050 as a key milestone, while others set nearer targets, such as 2025 for fuel cell vehicles and 2030 for broader hydrogen goals. Some papers extend their projections up to 2060. In several cases, the time horizon aligns with life cycle assessments or multi-decade projections, typically spanning 10 to 15 years for specific end use like hydrogen vehicles or fuel cells (e.g., Gupta et al. (2023), McKenzie and Durango-Cohen (2012), Hienuki (2017)). Given this extended time frame in the hydrogen-related CGE literature, dynamic models are widely used, with 13 studies in our sample taking this approach (e.g., Lee et al. (2011a), Lee (2020), Espegren et al. (2021)). These models capture the gradual adoption of hydrogen and its sustained economic impacts, offering insights into evolving market and policy landscapes. Additionally, four studies applied recursive-dynamic models (e.g., Mayer et al. (2019), Liang et al. (2022)), reflecting a growing trend toward using this approach to account for the evolving nature of hydrogen adoption and its long-term impacts on the economy.

3. Thematic findings

3.1. What are the macroeconomic impacts of the development of hydrogen systems?

The diverse research findings across multiple studies underscore hydrogen's important role in catalyzing economic growth and industrial advancement. Investment in hydrogen systems is shown to bring GDP growth and job creation, although these estimates vary depending on whether they account for net job impacts after substitution effects and the specific timeframes under consideration. For instance, in South Korea, the implementation of hydrogen and fuel cell technologies is not only expected to create approximately 7.7 new jobs for every KRW 1 billion invested but also to stimulate substantial GDP growth, to around 2013 billion KRW annually by 2030 due to increased industrial activity (Kim et al., 2024). Moreover, the hydrogen sector is expected to generate 13,484 billion KRW in production by 2040, driven by domestic industrial activity in sectors like industrial gases, machinery manufacturing, and transportation equipment (Chun et al., 2014). Notably, this estimate primarily reflects direct job creation and industrial expansion, with indirect or substitution-related job impacts less clearly delineated. In Brazil, input–output simulations indicate significant job creation during the construction phase, with the establishment of paired electrolytic hydrogen and green ammonia plants expected to mobilize approximately 12000 jobs and expand value-added in machinery, electrical equipment, and wholesale trade sectors. However, during the operational phase, a loss of around 10000 jobs and a GDP decline were observed due to substitution effects from fossil to electrolytic hydrogen (Brito et al., 2025). In Saudi Arabia, construction investments in hydrogen infrastructure capture the majority of domestic economic gains (Müller et al., 2024).

The development of hydrogen systems, including the construction of electrolysis plants and steam methane reforming (SMR) facilities, leads to significant demand for intermediate goods in sectors such as chemical processing and materials manufacturing by requiring specialized inputs to operate these infrastructures. This stimulates the supply chain and creates positive spillover effects. In the United States, the expansion of the hydrogen industry, supported by increased demand for related sectors such as chemical materials, biomass, and electricity, is projected to lead to considerable employment increases and GDP enhancements (Lee and Chiu, 2012). These findings demonstrate hydrogen's capability to act as a major economic stimulant within various economies. In China, the transition toward hydrogen-based technologies, particularly within the steel industry, illustrates hydrogen's ability to catalyze both economic and environmental benefits. The adoption of hydrogen in steel production is anticipated to reduce total emissions by 70%, while simultaneously inducing positive ripple effects across related industries. As hydrogen-based steelmaking integrates with upstream industries, it drives decarbonization in manufacturing, renewable energy, and energy supply chains (Ren et al., 2021). The macroeconomic benefits of hydrogen adoption are further emphasized through its impact on international trade dynamics. For instance, global analyses indicate that hydrogen trade could significantly reduce hydrogen prices, leading to improved trade balances and potentially boosting cross-country GDPs by 1%–6% in areas such as the EU, Japan, and Korea (Zhang et al., 2024). However, realizing these macroeconomic gains hinges on domestically manufacturing and servicing both (i) electrolysers and (ii) downstream green-ammonia PtX plants, as demonstrated by recent input–output studies for Saudi Arabia and Brazil (Müller et al., 2024), (Caiafa et al., 2023).

Country-specific studies provide deeper insights into how hydrogen adoption influences specific sectors. In Japan, hydrogen initiatives in the manufacturing sector have resulted in substantial socio-economic benefits, including temporary employment gains of 44% during the adoption phase. These gains were primarily driven by the construction of hydrogen production facilities, fueling stations, and related infrastructure like hydrogen storage and distribution systems. The key

initiative involved the use of naphtha reforming for hydrogen production to integrate hydrogen into Japan's energy system. Employment increases were particularly significant in industries such as civil engineering, pumps and compressors manufacturing, and chemical machinery (Hienuki, 2017). In the European context, Germany's focus on hydrogen in the aviation sector highlights the broader macroeconomic implications. Gronau et al. (2023) finds that hydrogen aviation could positively impact the macroeconomy by creating new jobs and increasing demand for renewable energy, impacting sectors like machinery, motor vehicles, electricity, gas distribution, and maintenance.

Furthermore, the literature suggests that hydrogen adoption has the potential to stimulate economic growth across various sectors. Specifically, hydrogen deployment in sectors like steel production, transportation, and energy can significantly contribute to GDP growth and job creation. For example, in the UK, the development of a hydrogen transmission sector is projected to increase GDP by 0.20% and create 30,000 full-time jobs by 2050 (Turner et al., 2023). Similarly, in France, the hydrogen sector's construction and operation phases are expected to generate up to €1 billion per year, supporting over 12,000 jobs (Guionie et al., 2023). Notably, the initially negative macro impact of Germany's electrolyzer project becomes positive when regulatory frictions are relaxed (Lagemann and Sacht, 2025).

While these projections point to promising macroeconomic benefits, it is important to consider how underlying modeling approaches treat uncertainty and future technological developments. Across the literature, uncertainty and technological progress are handled almost uniformly through deterministic "what-if" scenarios that yield point estimates rather than probability ranges. Input–output studies typically freeze their coefficients and test only a handful of techno-economic snapshots—Gupta's three demand cases for Switzerland, Lee's stylized 20% annual cost decline for Taiwan, and Conte's three renewable-grid mixes for Italian steelmaking (Gupta et al., 2023), (Lee and Hung, 2012), (Conte et al., 2022). The CGE papers for California and Northern Germany follow the same pattern, contrasting a moderate with an aggressive roll-out path and hard-wiring learning curves and fuel-price trajectories (Wang, 2011), (Lagemann and Sacht, 2025). Only a few works push beyond this: Müller's Saudi PtX analysis runs 160 sensitivity draws that vary local-content shares and cost splits, while Gronau's aviation study scales a range of external employment coefficients, yet even these stop short of Monte-Carlo sampling or endogenous learning (Müller et al., 2024), (Gronau et al., 2023). Across the corpus, improvements in electrolysers, fuel cells or grid decarbonization are imposed exogenously and labor coefficients remain static.

Policy design therefore acts as a critical mediator between hydrogen deployment and macroeconomic performance. Supply-driven policies, such as government subsidies and tax incentives, are acknowledged as fundamental drivers in reducing hydrogen production costs, particularly for green hydrogen. For example, the U.S. Inflation Reduction Act (IRA) includes a tax credit of up to $3 per kilogram for clean hydrogen production and provides investment tax credits for hydrogen-related infrastructure, such as refueling stations and electrolyzer expansion (Suárez-Cuesta and Latorre, 2024), (U.S. Department of Energy, 2024). A Greek study reveals that GDP falls by 1.5% when households fund heavy-duty transport conversion to hydrogen, but rises by 2.6% when external grants cover capital costs (Koutsandreas and Keppo, 2025). Similarly, Bae and Cho (2010) shows that subsidies effectively support hydrogen production, potentially boosting GDP and job creation. Furthermore, integrated policy frameworks, which combine supply-driven and demand-driven elements, are emerging as an essential approach to maximize hydrogen adoption. A dynamic CGE assessment for China shows that combining carbon pricing with infrastructure subsidies lifts GDP by 0.4% by 2040 (Su et al., 2025). At the international level, the importance of coordinated policy efforts to establish international hydrogen trade routes, including standardizing regulations and safety protocols, is underscored by studies like Meng et al. (2024). However, the literature highlights that certain sectors, such as aviation and maritime, are underrepresented in policy frameworks, with primary focus often on transportation and heavy industry (Ikonnikova et al., 2023).

Table A.1 provides details on the impacts on GDP growth, employment, and policy drivers which are drawn from two main modeling approaches, input–output and CGE models. While the studies reviewed in this subsection provide important evidence on national GDP, employment, and sectoral effects, these aggregate results do not, on their own indicate whether hydrogen development alleviates or exacerbates regional inequalities. National gains can mask highly uneven spatial outcomes, with benefits and adjustment costs distributed differently across regions depending on where production occurs and which hydrogen system segments are developed. This motivates the next subsection, which examines how macroeconomic models represent hydrogen system segments.

3.2. To what degree do macroeconomic models represent hydrogen systems?

An essential criterion for evaluating economic models of hydrogen systems is the extent to which they represent the different segments of hydrogen system. In this section, we assess how the literature models four system segments – production, storage, distribution, and end use – and whether this representation is rich enough to capture spatial and interregional interdependencies. Table A.2 presents how the coverage of hydrogen segments varies across different studies.

Among these methods, electrolysis is increasingly central to contemporary studies due to its environmental benefits and potential for significant economic transformation (Wan et al., 2024), (Fattahi et al., 2024). Recent analyses, including studies such as those in Germany (Lagemann and Sacht, 2025), Brazil (Brito et al., 2025), China (Su et al., 2025), Saudi Arabia (Müller et al., 2024), Greece (Koutsandreas and Keppo, 2025), and the Dutch-Brazilian corridor (Caiafa et al., 2023), have predominantly modeled electrolysis as the core hydrogen production approach and link it to new industrial activity, innovation, and employment through electrolyzer supply chains. For instance, Gupta et al. (2023) estimate a significant economic multiplier effect from investments in electrolyzer infrastructure, leading to substantial GDP growth and job creation. The specificity and depth of production details, such as the differentiation among alkaline, Proton Exchange Membrane (PEM), and Solid Oxide Electrolysis Cells (SOEC), remain limited in these macroeconomic assessments.

Of the other production methods, studies adopting SMR generally focus on its traditional role as low-cost source of bulk hydrogen in transport and energy sectors, leveraging existing infrastructure. However, they also highlight its vulnerabilities in the face of increasing carbon taxation and regulatory pressure due to its inherent carbon emissions (Hienuki, 2017). By utilizing existing natural gas infrastructure, blue hydrogen is emphasized as a transitional pathway facilitating a smoother economic transition toward green hydrogen by mitigating emissions without necessitating immediate infrastructure overhaul (Wei, 2024), (Zhang et al., 2024). Biohydrogen production from biomass and organic waste is recognized for its carbon neutrality and its role in circular-economy strategies, but it remains relatively niche in macroeconomic modeling. A small set of input–output and CGE studies for Japan, the U.S. and China introduce dedicated biohydrogen sectors and quantify substantial economic potential: projected production values of 83.1 billion USD and 67 billion USD by 2040 in the U.S. and China, respectively, with multipliers of 9.30 and 8.96 (Lee et al., 2011a). These models capture biohydrogen's upstream linkages to biomass and waste and to energy supply in a national production structure, but they treat biohydrogen at an aggregate level and only implicitly reflect land-use and regional trade-offs, without explicitly modeling waste-management or circular-economy dynamics.

Economic models that consider multiple hydrogen production methods, generally recognize the flexibility they provide in system planning and decarbonization pathways. Studies such as those by Ikonnikova

et al. (2023) and Meng et al. (2024) suggest that combining hydrogen types can optimally cater to different sectoral demands and timelines for decarbonization. They advocate a phased transition approach, where blue hydrogen initially complements green hydrogen, thus offering continuity in infrastructure and industrial processes until green hydrogen achieves cost competitiveness (Espegren et al., 2021).

Other segments of the hydrogen systems, storage, distribution, and end-use, are often inadequately represented in the studies, despite their profound influence on cost structures and macroeconomic impacts.

Hydrogen storage methods, including compressed gas, liquid hydrogen, salt cavern storage, and metal hydrides, are typically underrepresented. Physical storage methods, including tanks and underground hydrogen storage in salt caverns, help maintain a balance between supply and demand (Hassan et al., 2021). Hydrogen storage, particularly in the form of liquid hydrogen and innovative storage materials like metal hydrides, plays a crucial role in addressing the challenges of intermittency in hydrogen production and its subsequent use in transportation and other sectors. For example, Meng et al. (2024) highlight the technical and economic challenges associated with large-scale hydrogen storage, particularly for transportation end uses. Storing hydrogen safely and efficiently remains a critical barrier to the widespread adoption of hydrogen technologies, as the infrastructure for liquid hydrogen storage and compressed hydrogen systems is still under development due to insufficient policy support. Studies such as Huang et al. (2024) and Nakano and Washizu (2017) emphasize the importance of advancing storage technologies to improve safety and scalability.

Hydrogen distribution networks are another critical but underexplored segment of the hydrogen system. Integrating these distribution aspects into macroeconomic models is essential to simulate the economic impact of large-scale hydrogen adoption. Hydrogen can be transported via various means, such as pipelines, trucks, and ships, to ensure it reaches a wide range of end users. Pipelines are generally the most economical option for long-distance transportation (IRENA, 2022b). Meng et al. (2024) and Fattahi et al. (2024) highlight that distribution networks, such as pipelines and hydrogen shipping in the form of ammonia or liquid hydrogen, are essential to facilitate international hydrogen trade. Moreover, Brauer et al. (2022) point out that the limited availability of hydrogen pipelines may constrain the scale of imports and exports of gaseous hydrogen, particularly for areas like Europe. As a result, models can discuss trade in aggregate, but they struggle to attribute benefits and costs to specific regions.

End-use applications of hydrogen, especially within transportation, heavy industry, and power sectors, are extensively covered, reflecting hydrogen's potential in decarbonizing these hard-to-abate areas. Lee et al. (2011a) and Zhang et al. (2024) explore hydrogen's potential in sectors such as steel production and ammonia manufacturing. In particular, hydrogen fuel cells are viewed as a key technology for decarbonizing the transportation sector, with hydrogen-powered vehicles offering a cleaner alternative to conventional internal combustion engines. However, the suitability of hydrogen-powered vehicles is highly dependent on vehicle type and application. As highlighted by Odenweller et al. (2022) and Ueckerdt et al. (2021), hydrogen use is more feasible for heavy-duty, long-range, or fleet vehicles. Yet, to address the costs associated with fleet replacement and refueling infrastructure development, stronger policy frameworks are needed to make hydrogen-powered vehicles competitive (Fattahi et al., 2024). End-use representation can support spatial analysis only if it is linked to where end-use sectors are located and how costs pass through to regional economies. Many models represent end-use adoption as an aggregate demand shift or sectoral substitution without explicit coupling to storage and distribution constraints. In these cases, models may approximate national decarbonization pathways but cannot evaluate spatially uneven adjustment burdens.

These choices determine how the development of hydrogen systems may both shape and be shaped by existing regional inequalities. Failing to account for this interdependency limits the ability of such models to inform decision making about whether current regional disparities are likely to be mitigated or exacerbated. Section 3.3 therefore presents the inequality-relevant mechanisms identified in the reviewed evidence.

3.3. Through what mechanisms might hydrogen development alleviate or exacerbate regional inequalities?

The macroeconomic impacts of the hydrogen economy are systematically uneven across sub-national regions, as evidenced by recent literature. Table A.3 details the geographic coverage and key findings of relevant studies. Our review shows that these heterogeneous outcomes arise from the interaction of the following mechanisms: (i) the production method chosen (which maps onto different regional resource and infrastructure endowments), (ii) the hydrogen system segment the region hosts (which determines where benefits accrue and costs fall), and (iii) the geographic pattern of investment (e.g., concentrated "hubs" vs. dispersed networks). The findings are synthesized in Table 3, which provides a detailed matrix of regional impacts across production methods and hydrogen system segments, while also indicating the investment patterns.

The choice of production method embeds the consideration of spatial economy by pre-selecting regional beneficiaries according to resource and industrial endowments. Green hydrogen often shifts advantage toward renewable-rich regions. The analysis of green hydrogen deployment in China by Du et al. (2024) finds that northern and western provinces with abundant renewables – Inner Mongolia, Xinjiang, Heilongjiang, and others – are the clear winners, despite their longstanding economic disadvantage relative to China's coastal industrial centers. They can produce hydrogen at a much lower cost and thus reap greater economic and carbon-abatement benefits than other provinces. This is reinforced by Su et al. (2025), who find that solar- and wind-rich western provinces become export hubs. This pathway reveals hydrogen's role to alleviate existing regional inequalities by facilitating a development policy favoring peripheral regions with high-quality wind and solar potential. In contrast, blue hydrogen (CCS-SMR) has entirely different spatial implications, favoring "path dependency". As an essential intermediate solution, its adoption is geographically tied to regions with existing natural gas infrastructure and suitable geology for CO2 storage (Ikonnikova et al., 2023). This reinforces the spatial geography of the fossil-fuel era. The CGE analysis by Espegren et al. (2021) for Norway, for example, shows that a fossil-fuel-rich region can use blue hydrogen to "replace the value lost" from its declining petroleum sector. This leverages the existing energy workforce and infrastructure but runs the risk of creating a sunk-cost effect that delays the full transition to green hydrogen (Ikonnikova et al., 2023). A third pathway, biohydrogen (from biomass) creates a distinct set of regional winners. Its viability is tied to the agricultural sector and land use (Lee and Chiu, 2012). The economic potential identified in input–output studies on the U.S. and China (Lee et al., 2011a) would flow to rural regions with strong agricultural sectors or advanced waste management systems, supporting a circular economy (Lee, 2020). This can be inequality-alleviating when it generates rural multipliers and diversification, but it can also introduce new regional trade-offs, namely "competition with food production" or new strains on regional land and water resources (Lee et al., 2011a).

A second mechanism concerns which segment of the hydrogen system the region participates in. Even with similar national impacts, regional inequality depends on whether activity is concentrated in upstream production, midstream storage and distribution, or downstream end-use. The literature shows that participating in different segments can either alleviate or exacerbate disparities depending on how benefits and costs are distributed across places and time.

First, within the upstream production segment, a temporal–spatial trap can emerge. The input–output analysis for Brazil by Brito et al. (2025) warns that the construction phase of new electrolytic hydrogen

Table 3
Regional impacts across production methods, investment patterns and hydrogen segments.

Production method	Production phase	Storage & distribution phase	End-Use phase
Green Hydrogen	**Impact:** High localized value-added from construction; long-term gains depend on whether operations remain local. **Determinant:** Renewable resource endowment and infrastructure readiness. **Winners:** Regions with high renewable potential. **Investment pattern:** Typically resource-aligned concentration, in some cases export hubs. **Citations:** (Caiafa et al., 2023; Du et al. 2024; Su et al. 2025; Brito et al. 2025; Müller et al. 2024; Huang et al. 2024)	**Impact:** High infrastructure multipliers. **Determinant:** Proximity to ports, stations, transmission routes, and trade links. **Winners:** Connected ports, corridor nodes, and transmission-linked regions. **Investment pattern:** Follows corridor/node logic (ports, stations, transmission routes). **Citations:** (Nakano and Washizu, 2017; Turner et al. 2023; Fattahi et al. 2024)	**Impact:** Decarbonization of incumbent industries (steel, chemicals). **Determinant:** Co-location with hard-to-abate industrial clusters. **Winners/Losers:** Varies (industrial hubs may face short-run competitiveness pressure). **Investment pattern:** Favors industrial-demand clusters connected to supply corridors. **Citations:** (Lagemann and Sacht, 2025; Rinaldi et al. 2024)
Blue Hydrogen	**Impact:** Leverages existing workforce and gas-related capabilities. **Determinant:** Dependent on existing natural gas infrastructure & CCUS potential. **Winners:** Regions with established fossil-fuel industry (e.g., Norway). **Investment pattern:** Reinforces incumbent fossil-energy geographies. **Citations:** (Espegren et al., 2021; Ikonnikova et al. 2023)	**Impact:** Supports incumbent gas-linked infrastructure and transitional supply chains. **Determinant:** Existing gas-network geography and delivery-cost advantages. **Winners:** Regions already embedded in incumbent gas and industrial networks. **Investment pattern:** Path-dependent, often following existing gas network. **Citations:** (Espegren et al., 2021; Ikonnikova et al. 2023)	**Impact:** Transitional supply for industrial users. **Determinant:** Presence of large end-use industrial clusters. **Risk:** Sunk-cost effects and spatial lock-in may delay green H_2 transition. **Investment pattern:** End-use adoption is likely to cluster around existing industrial cores. **Citations:** (Espegren et al., 2021; Ikonnikova et al. 2023)
Biohydrogen	**Impact:** Generates value within circular-economy systems. **Determinant:** Biomass availability (agriculture, waste management). **Winners:** Most likely biomass-rich and agriculture-linked economies. **Trade-off:** Land-use competition (food vs. fuel). **Investment pattern:** Favors decentralized/small-scale development. **Citations:** (Lee et al., 2011a; Lee and Chiu 2012; Lee 2020)	**Impact:** Typically localized; less suited to long-distance transport. **Determinant:** Distributed, local networks. **Winners:** Local economies able to align feedstock, production technology, and nearby demand. **Investment pattern:** Follows distributed/local network logic. **Citations:** (Lee and Chiu, 2012; Lee et al. 2011b)	**Impact:** More likely to support niche or localized applications. **Determinant:** Co-location with biomass production. **Winners:** Evidence is limited, but local waste/agricultural sectors are more plausible. **Investment pattern:** More local-use/decentralized. **Citations:** (Lee et al., 2011a; Lee and Chiu 2012)

and green ammonia plants is projected to be highly positive, mobilizing approximately +12,000 jobs. However, once these plants are operational, the new, less labor-intensive system displaces more labor-intensive incumbent industries. This results in a net loss of 10,000 jobs in the operational phase. This finding reveals a critical dynamic: a region hosting a new plant experiences a temporary surge in construction and machinery sectors, a finding supported by Müller et al. (2024) in Saudi Arabia, which notes that construction investments capture the majority of domestic economic gains. This can alleviate regional disparities when construction booms translate into durable local capabilities; it can exacerbate disparities when the boom is temporary and long-run jobs are displaced. Conversely, a region with a legacy industry (e.g., coal mining, oil refining) that is not chosen for a new project faces a double negative: it sees no construction boom and suffers permanent, long-term job losses.

Second, a clear divide exists between production regions and end-use regions. The regional CGE analysis by Lagemann and Sacht (2025) for Northern Germany provides the clearest example of this stark divergence. In a scenario of switching heavy industry to hydrogen, the established industrial hub of Hamburg, an end-user, suffers a significant GDP decline of nearly 0.9%. In contrast, the less-industrialized, peripheral state of Mecklenburg-Western Pomerania sees a modest GDP increase of 0.5%. The costs of the transition (e.g., upgrading industrial equipment, higher energy prices) are spatially concentrated on incumbent industrial regions, causing them to lose competitiveness. This is reinforced by Rinaldi et al. (2024), whose hybrid I-O model for the EU steel sector finds that hydrogen-based production would increase steel prices by 56%, raising input costs for downstream steel-using sectors and indirectly for final consumers. Taken together, these regional disparities show that the hydrogen transition does not lift all boats uniformly; it can penalize established industrial centers via endogenizing the cost of carbon through hydrogen utilization while creating new growth opportunities in peripheral regions that can host emerging production assets due to renewable resource endowments, thereby reshaping regional economic hierarchies.

Finally, the phases of storage and distribution are critical but under-explored components that add additional layers to hydrogen's spatial geography. While green hydrogen production is primarily shaped by renewable resource endowments, the storage phase is largely dictated by geology. Large-scale, low-cost seasonal storage is essential to buffer the intermittency of green hydrogen, and the most promising option is underground storage in salt caverns. Regions with these specific geological formations can become the strategic energy reserves for an entire continent. This advantage translates into a new, high-value industry (energy storage) and associated investments and jobs. The distribution phase, meanwhile, is governed less by natural resource endowments and more by the configuration of pipeline and port infrastructure. These factors determine which regions are connected and which are bypassed, and the economic impact of this infrastructure is substantial. The input–output analysis by Nakano and Washizu (2017) for Japan, for instance, found exceptionally high economic multiplier effects—ranging from 2.6 to 3.27, from investments in distribution infrastructure like hydrogen stations and tankers. Furthermore, the method of distribution creates a critical path dependency. As the CGE analysis by Turner et al. (2023) for the UK shows, a key strategy is repurposing the existing natural gas pipeline network. This is an efficient choice, but it is also a profound spatial one. It inherently reinforces the economic centrality of regions that are already hubs in the fossil-fuel economy. This path-dependent development benefits existing industrial corridors, ensuring their continued relevance but potentially failing to level up peripheral regions that are not currently connected to the gas grid. At the international scale, Fattahi et al. (2024) show that hydrogen and ammonia trade is shaped by corridor logic, with pipelines and shipping routes linking exporters and importers across regions.

The third mechanism is geographic pattern of investment – whether concentrated in hubs or dispersed across a network – which can

strongly influence whether regional inequalities are widened or narrowed.

The hub model, for example, can be a powerful and intentional tool for regional development. The analysis of a proposed "green hydrogen export hub" in Ceará, Brazil (Caiafa et al., 2023) projects substantial local value-added gains on the order of +$2.5 billion in GDP. In this case, spatial concentration is a deliberate policy to channel massive investment into a specific, targeted region, with the goal of creating a new industrial center. However, the structure of the hydrogen system shows that this success is not guaranteed and depends critically on the local integration of its segments. The same study (Caiafa et al., 2023) provides a warning: if the project is import-heavy relying on foreign technology, external contractors, and imported components (like electrolysers and turbines), the local economic multipliers collapse to a fraction of their potential. The value-added then flows out of the host region to the established, high-tech manufacturing centers that produce this equipment. The analysis by Huang et al. (2024) in China is the clearest evidence of this mechanism. It finds that wealthier coastal cities are able to mobilize private R&D labor markets significantly faster than policy-driven inland cities. These coastal hubs have the pre-existing R&D ecosystems, skilled labor pools, and access to capital that a new industry needs. This mechanism exacerbates disparities in innovation capacities and average incomes. In this sense, the hydrogen economy does not create new centers of growth; it simply follows established patterns of agglomeration, thereby deepening regional inequalities. Another pattern of concentration is resource-driven, which creates a geographic lottery. Here, investment is not concentrated by policy or by existing wealth, but by the availability of prime natural resources. The provincial analyses of China by Du et al. (2024) and Su et al. (2025) both identify this pattern. Conversely, a more dispersed network model – decentralized, smaller-scale production integrated with local renewable grids – may support more geographically broad-based benefits. Emerging evidence suggests that distributed hydrogen systems can reduce reliance on large centralized pipeline build-out and enable local employment opportunities in remote communities that hub-led systems may bypass (Handique et al., 2024). However, the distributional advantage depends on cost, scalability, and local capability to create value, rather than assuming dispersion automatically reduces inequality.

4. Discussion of results

4.1. Macroeconomic implications and role of policy mechanisms

The findings underscore hydrogen's multifaceted macroeconomic impact, including driving industrial expansion through the emergence of new industries for hydrogen production and utilization, while also delivering broader economic benefits such as job creation and economic growth. Investments in hydrogen systems, say the development of electrolysis plants, not only generate direct employment and GDP but also stimulate industrial activity within and beyond the hydrogen sector. South Korea's and Brazil's projections of employment growth and industrial expansion exemplify hydrogen's capacity to reinforce a national industrial ecosystem surrounding hydrogen production and end use. Moreover, hydrogen's role in reshaping industrial production networks is crucial. As hydrogen-based technologies like steel production gain traction, they create new demands across different segments of hydrogen systems. This interconnected growth is particularly evident in China's hydrogen steelmaking sector, which supports decarbonization in manufacturing and generates demand for renewable resources. In addition to domestic impacts, hydrogen also has the potential to influence international trade and global economic dynamics. By establishing new markets and reducing reliance on fossil fuel imports, hydrogen trade is expected to strengthen trade balances and potentially boost national GDP, partly through the reduction of national carbon prices by 1%–6% (Zhang et al., 2024). Beyond economic and trade advantages, hydrogen adoption may drive innovation by increasing demand for advanced infrastructure, which could, in turn, lead to technological advancements in manufacturing, chemicals, and materials processing. However, literature does not fully cover the extent to which these technological advancements could bolster productivity within hydrogen-linked industries. Further research could deepen the understanding of the long-term impacts of hydrogen-driven innovation on competitiveness and adoption in evolving markets. However, lack of incorporation of social cost of carbon in today's fossil fuel-based energy systems result in seemingly high production cost of hydrogen fuel as well as lack of demand policies. These challenges are recognized in studies like Liang et al. (2022), Su et al. (2025), and Lee (2014), which highlight that large-scale hydrogen deployment and its associated macroeconomic gains only materialize in scenarios with strong policy support. At the same time, these macroeconomic projections need to be interpreted with caution. The regional dimension of the hydrogen economy is tightly coupled to technological performance and infrastructure configuration, yet most macroeconomic studies still represent the hydrogen system in a highly stylized way. In particular, energy losses across production, storage, transport and end-use, as well as the limited conversion efficiencies of electrolysers and fuel cells, are only coarsely captured (Rinaldi et al., 2024; Nakano and Washizu, 2017). As a result, regional-level estimates of GDP and employment should be understood as exploratory scenarios rather than precise forecasts of real-world outcomes.

In response, countries have implemented a range of mechanisms to support the adoption and scaling of hydrogen technologies (IEA, 2024b). Germany has introduced Carbon Contracts for Difference (CCfDs), offering financial support to industries by covering the gap between carbon market prices and the actual cost of emissions reduction through hydrogen use. Japan has established a Hydrogen Society Promotion Act, including auction mechanisms for hydrogen and ammonia-based electricity generation. In South Korea, a combination of carbon pricing and direct subsidies supports hydrogen projects, particularly focusing on fuel cells and infrastructure development. The European Union employs mandates like the ReFuelEU Aviation initiative and promotes hydrogen hubs to reduce infrastructure costs. It also introduces market-based instruments such as the Carbon Border Adjustment Mechanism (CBAM) to prevent carbon leakage and incentivize cleaner hydrogen production both within the EU and among trading partners. On the demand side, policies like carbon pricing and purchase incentives aim to create markets for hydrogen end uses, including fuel cell vehicles. For instance, the European Union's Emissions Trading System creates a financial incentive for clean fuels. Moreover, international trade agreements, such as those between Germany and Australia, are increasingly facilitating cross-border hydrogen trade by establishing market linkages (Antweiler and Schlund, 2024). Canada's Hydrogen Strategy, for instance, incorporates production support (e.g., funding for green hydrogen projects) and consumption incentives (e.g., industrial adoption of hydrogen technologies) (Natural Resources Canada, 2020). In addition, the socio-economic benefits of hydrogen are not evenly distributed across all sectors and countries, primarily due to differences in energy resources, industrial capabilities, and policy environments. Countries like Germany and France invest heavily in hydrogen infrastructure, while others, particularly in Eastern Europe, lag due to limited resources and infrastructure (Magazzino et al., 2024). In terms of sectoral disparities, hydrogen can generate substantial decarbonization benefits for sectors such as transportation, steel, and energy production, which have shown advanced readiness levels and targeted policy support. At the same time, industries such as chemicals and heavy manufacturing, although facing higher barriers to adopting hydrogen technologies, could experience similar benefits as infrastructure expands and costs decrease (UK, 2024).

While policy interventions for hydrogen technologies are advancing, there are gaps in the literature regarding the comprehensive evaluation of these mechanisms, particularly in terms of comparative effectiveness

across different policy types and countries. Current studies emphasize financial incentives and international cooperation as critical elements but often lack in-depth comparative assessments of different policy tools, such as subsidies versus carbon pricing, in fostering hydrogen adoption. For example, while subsidies effectively lower production costs, it is less clear if they work more effectively compared with carbon pricing or other mechanisms that drive demand for low-carbon alternatives. This gap points to the need for cross-country studies, as national contexts – such as market maturity, resource availability, and regulatory environments – can significantly influence the success of different policy approaches. Comparative cross-country analyses can provide insights into which policies yield the most substantial economic and environmental benefits. Recent efforts, such as the evaluation of carbon border adjustment mechanisms by Dechezleprêtre et al. (2025), illustrate the value of such analysis in understanding how the EU's CBAM affect both economic competitiveness and decarbonization.

A further implication is that national hydrogen policy instruments are not spatially neutral. Measures such as subsidies, carbon pricing, tax incentives, and infrastructure support are typically designed at the national level, yet their economic effects are mediated by regional differences in industrial structure, resource endowments, existing infrastructure, and local capabilities. Consequently, the same national policy can generate asymmetric regional outcomes, accelerating investment and employment in some regions while concentrating transition costs and adjustment pressures in others.

Additionally, the literature often isolates supply-driven and demand-driven policies, rather than examining the compounded effects of integrated frameworks that support the hydrogen system. This approach limits a holistic understanding of how comprehensive policy frameworks could optimize hydrogen's economic viability across diverse sectors and countries. The national variability in policy impacts also requires further analysis to address disparities in resource availability and infrastructure development.

Moreover, a broader sectoral application of hydrogen policies could strengthen the decarbonization potential across industries beyond the frequently discussed sectors like transportation and heavy industry. Studies point to the need for a more inclusive approach that encompasses underrepresented sectors such as aviation and maritime transport, which are integral to achieving full-scale decarbonization. In conclusion, future research should aim to incorporate cross-sectoral and national comparisons within macroeconomic models, assessing not only individual policy impacts but also how coordinated, cross-sectoral policy frameworks might drive hydrogen's competitiveness and scalability more effectively.

Relatedly, one may argue that production method representation is sufficient to estimate national-scale investment and sectoral reallocation effects. However, such models cannot evaluate the regional distribution of impacts unless they also consider differences in regional endowments (e.g. renewable resources, gas/CCS infrastructure, industrial base) and a mechanism that ties production siting to those endowments. Without consideration of siting constraints or regional resource heterogeneity explicitly, production method remains a technological assumption rather than a driver of regional allocation. Likewise, storage is treated as an enabling assumption rather than an endogenous segment with its own investment decisions, operational constraints, and geographic characteristics in most models. This matters because storage can constitute a place-specific advantage that shapes where hydrogen hubs can scale and which regions emerge as strategic nodes. If storage is not modeled with capacity, investment dynamics, and geographic characteristics, models cannot assess whether regions with favorable storage endowments are likely to acquire disproportionate infrastructure rents or emerge as strategic nodes within hydrogen networks.

4.2. Economic implications on regional inequalities

The spatial heterogeneity of hydrogen's macroeconomic impacts extends beyond simple differences in regional growth trajectories. Section 3.3 identifies three mechanisms through which these impacts materialize: the production method, the hosting of specific hydrogen-system segments, and the geographic pattern of investment. Through these mechanisms, the hydrogen transition can play a dual structural role, either alleviating or exacerbating existing regional inequalities. Which outcome prevails depends on how hydrogen-system development interacts with underlying features of regional economy — endowments, incumbent industrial structures, and the configuration of infrastructure networks, that is, spatial comparative advantage. It also hinges on whether regions are able to generate sustained value added beyond short-lived construction activity or create local economic multipliers during the operational phase. While the three mechanisms describe how regional impacts are realized, two overarching forces determine their direction: spatial comparative advantage and local value creation. Depending on the mechanism, these forces may exert direct or mediated effects (summarized in Table 4), shaped by institutional capacity, including planning regimes, procurement practices, and the capabilities of public institutions (Klagge et al., 2025).

The first force concerns whether hydrogen investment and transition-related adjustment pressures reallocate economic opportunity toward new places or entrench the dominance of established industrial hubs. This captures the allocation rule through which assets, connectivity rents, and adjustment burdens are distributed across regions. As Bridge et al. (2013) argue, energy transitions are fundamentally spatial reconfigurations driven by changing resource maps. Therefore, this force is primarily shaped by pathway-dependent siting through natural and infrastructural endowments and the geographic pattern of investment, as these directly dictate where hydrogen assets and network advantages locate.

In inequality terms, hydrogen can support convergence when it enables credible growth trajectories in lagging regions through new activity that is connected to broader innovation dynamics such as skill formation, supplier development, and durable infrastructure connectivity (e.g., pipelines, ports, storage, and grid access). Conversely, hydrogen can deepen divergence when it reinforces established gateways and industrial corridors through path dependence: the places that already control strategic infrastructure and industrial capabilities are best positioned to attract and retain the high-value segments of an emerging hydrogen economy.

This spatial comparative advantage force also operates through distribution of transition costs. Even when hydrogen supply investment occurs outside established cores, the costs of end-use conversion and competitiveness adjustment can concentrate in incumbent industrial regions. At the same time, infrastructure and network build-out can reproduce corridor effects, where ports, transmission routes, and established hubs capture the rents of connectivity while bypassed regions see limited spillovers. The combined implication is that inequality outcomes depend not only on where projects sit, but also on how network rents and adjustment burdens are allocated. Crucially, national and sub-national strategies should explicitly manage adjustment burdens in vulnerable industrial regions, while distributing network rents in ways that avoid automatically privileging established gateways.

The second force concerns the extent to which host regions can create durable value added rather than experiencing leakage of high-value activities. This force is grounded in Global Production Network theory (Coe and Yeung, 2015), which emphasizes that territorial development outcomes depend on a region's strategic coupling within global value chains. Accordingly, this force is shaped primarily by which segment of the hydrogen value chain a region hosts. As demonstrated in adjacent clean-tech sectors like offshore wind (Dawley et al., 2015), resource endowments and spatial hubs influence this force only secondarily while multi-level governance and policy activism play a more important role.

Table 4
Overarching forces underlying the mechanisms.

Mechanism from Section 3.3	Direct influence	Mediated influence
M1. Production method	**Spatial Comparative Advantage:** Natural resources and infrastructure decide where hydrogen plants are built. This directly determines which regions get the new economic activity and which face the environmental burdens.	**Local Value Creation:** The chosen hydrogen technology creates different forward and backward linkages. However, keeping that wealth local depends on the region's existing skills and policies, not just where the plant is located.
M2. Segment hosted	**Local Value Creation:** A region's economic benefit depends heavily on which part of the hydrogen system it hosts. Securing long-term operations and advanced services creates lasting wealth, whereas just hosting the initial construction phase leads to temporary booms.	**Spatial Comparative Advantage:** The specific segment hosted influences who bears transition costs (like retrofitting local industries), but it does not dictate the overall national map of hydrogen investments as strongly as natural resources do.
M3. Investment geography	**Spatial Comparative Advantage:** Whether investments are concentrated in massive industrial hubs or spread across distributed networks directly decides which regions get connected to the new hydrogen economy and which get left behind.	**Local Value Creation:** Building a hub does not guarantee local wealth. Whether a hub builds local supply chains or imports everything from outside depends on government rules, local ownership, and workforce readiness.

Hydrogen projects, especially export-oriented, can generate impressive headline investment figures without producing proportional local upgrading if key segments remain concentrated in external metropolitan centers or foreign firms. Recent work highlights precisely this risk: hydrogen can become a future-making agenda that mobilizes investment narratives faster than it delivers long-term local development, particularly where local institutions have limited leverage over project design, procurement, and capability building (Klagge et al., 2025). Research on spatial planning for export-oriented hydrogen megaprojects similarly emphasizes that planning regimes and governance instruments shape whether projects develop as locally embedded regional development strategies or as enclave-style investments with limited local linkages (Walker et al., 2025).

This value creation force interacts with fiscal capacity and financing conditions. Where sub-national governments face borrowing constraints and uneven credit ratings, poorer regions may confront higher capital costs for shared infrastructure and may be pressured into regressive fiscal arrangements (Dougherty et al., 2025). When hydrogen strategies rely on local co-financing in fiscally constrained regions, a paradox can emerge: ambitious green-industrial investments coexist with underfunded public services and heightened fiscal stress, potentially worsening multidimensional disadvantage even if GDP rises. The risk is amplified when project structures are import-heavy and contractor-led, limiting local multipliers and reinforcing unequal distributions of rents (Caiafa et al., 2023). Labor-market structures and innovation capacity further condition capture: regions with thin pools of specialized skills and weaker innovation ecosystems are more likely to retain lower-wage work, while established innovation centers mobilize high-value R&D and managerial roles more quickly (Huang et al., 2024). In short, inequality outcomes depend on whether governance and policy arrangements convert hydrogen investment into capability formation – skills, supplier depth, innovation, and locally retained rents – rather than short-lived construction gains and externalized high-value segments.

Together, these points highlight the classical dilemma in regional science: trade-off between efficiency and equity. Concentrating hydrogen infrastructure in economically optimal locations can reduce costs through economies of scale and established infrastructure networks. However, such concentration risks deepening regional inequalities. Conversely, spatially diversified hydrogen investments, although potentially less cost-efficient initially, may promise broader socio-economic benefits. To what degree and how policymakers can reconcile this tension through targeted interventions, including subsidies, strategic public investments, and incentives to encourage the development of hydrogen projects in less-developed regions? How are these visions aligned with the desires, wishes and perceptions of local communities given a range of factors determining their social acceptability (Gordon et al., 2022)? In what ways are the existing hydrogen projects giving rise to forward and backward linkages to support regional integration? Achieving equitable outcomes necessitates a tailored, regionally differentiated policy mix encompassing adjusted network tariffs that distribute network revenues more fairly across regions, localized workforce development programs, fiscal equalization mechanisms recycling hydrogen revenues into disadvantaged regions, and integrated spatial planning aligning hydrogen clusters with broader regional development goals. Such coordinated policy frameworks may offer a pragmatic pathway toward harnessing hydrogen transitions as a medium for reducing rather than exacerbating regional economic disparities which we discuss next.

4.3. A conceptual framework of hydrogen ecosystem to address regional inequalities

Building upon the insights from previous sections, we offer a conceptual framework that provides a structured approach to understanding how hydrogen can drive economic outcomes across regional contexts. Because large-scale hydrogen deployment is still nascent and the macroeconomic evidence on sub-national distributive impacts remains limited, we present this framework as a critical, exploratory synthesis. To ensure hydrogen alleviates rather than exacerbates regional disparities, policy cannot be treated separately from spatial and institutional realities. As illustrated in Fig. 5, our framework maps a vertical pathway comprising four core layers–from initial policy design to final distributive outcomes–which are dynamically mediated by the depth of regional integration and linked via a continuous feedback loop.

The framework begins with deliberate policy interventions. Supply-side and demand-side instruments – such as subsidies, carbon pricing, and local regulations – serve as catalysts for the adoption and integration of hydrogen technologies. These policy interventions are essential in addressing market and infrastructure limitations that currently impede hydrogen's scalability and competitiveness.

Policy then steers the hydrogen system mechanisms through which these impacts materialize: the production method adopted, which hydrogen system segments a region hosts, and the geographic pattern of investment. As the physical hydrogen system is deployed geographically, it activates the two central overarching forces defined in Section 4.2. First, the spatial comparative advantage determines whether the new infrastructure reallocates economic opportunity to peripheral regions or entrenches the dominance of established hubs. Second, the local value creation determines whether the host region possesses the institutional capacity to retain high-value supply chain activities, or if that wealth leaks back to external metropolitan centers. Critically,

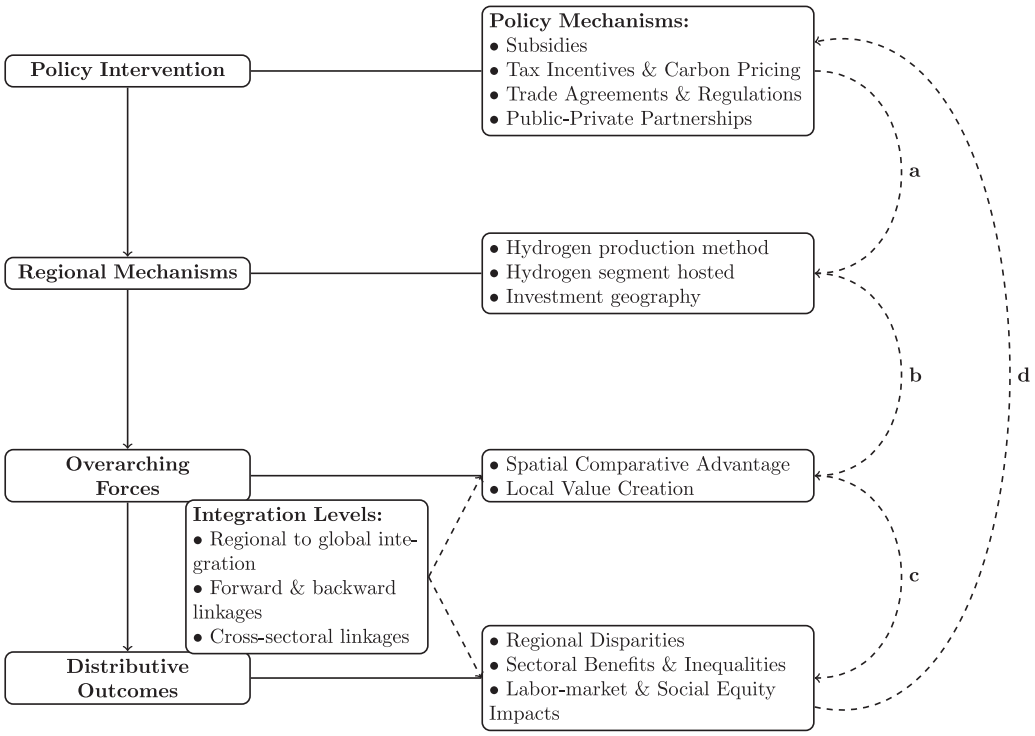

Fig. 5. Conceptual framework of regional hydrogen integration for equitable economic outcomes.

the operation of these overarching forces is heavily conditioned by the system's regional integration level. Territorial integration, strength of forward and backward linkages, and cross-sectoral integration do not have a uniformly positive distributive effect. The distributive significance of integration therefore depends on who is connected, on what terms, and with what capacity to create value.

The distributive impact is the ultimate outcome layer of the framework. These social and economic impacts extend beyond immediate job creation and GDP growth to include distributive aspects, such as regional disparities and sectoral inequalities. For instance, driven by the spatial comparative advantage, regions with pre-existing infrastructure may experience accelerated growth and economic benefits, while areas lacking resources and infrastructure might lag, potentially widening economic disparities. A feedback loop (d) between distributive impacts and policy mechanisms ensures that policy adapts in response to observed socioeconomic outcomes. As hydrogen adoption progresses, regional economies, employment, and industry growth provide insights that inform the refinement of existing policies. This feedback loop supports an adaptive, responsive policymaking process that maintains alignment with broader socioeconomic objectives, such as regional equity and sustainable growth.

Overall, the framework follows a structured pathway–from policy interventions through mechanisms (a) and forces (b) to eventual impacts on regions and sectors (c). This conceptual framework reveals critical interdependencies. For instance, specific policy choices, such as international export agreements versus local content requirements, play a decisive role in shaping the system and determining the region's ultimate integration level. While purely export-driven policies might push a peripheral region toward becoming an isolated energy enclave, targeted capability-building can elevate integration toward an embedded regional cluster. This shift in integration level alters the macroeconomic mechanisms, ensuring value creation favors the host community rather than leaking to external centers. However, studies that comprehensively assess these patterns – particularly how specific governance configurations influence regional integration levels and subsequent spatial equity – remain sparse. Current macroeconomic literature often focuses on the isolated effects of individual policies or examines limited segments of the hydrogen system (such as production and end-use applications), treating geographic space as a neutral backdrop rather than an active institutional variable. It is therefore important to be transparent about the limitation of this framework. The reviewed literature provides relatively stronger evidence on national-level technological pathways, aggregate investment and energy-system requirements, and broad spatial factors shaping production siting. However, it offers limited ex-post empirical evidence on sub-national distributive outcomes and the long-run implications for regional inequality. Accordingly, the spatial comparative advantage and local value-creation forces in the framework should not be read as deterministic rules; rather, they are evidence-informed, theoretically grounded hypotheses that organize what the literature suggests and highlight priorities for future work. By explicitly considering regional heterogeneity in resource endowments, industrial structures, infrastructure systems, and policy contexts, this framework can serve as an analytical tool to assess the distributional implications of hydrogen investments and alternative policy interventions. Operationalising this framework will require empirical detail on technology choices, infrastructure configurations that macroeconomic models cannot generate on their own. This, in turn, calls for closer collaboration between regional scientists and engineers to co-produce the micro-level evidence needed to parameterize and validate regional hydrogen models.

5. Conclusion

Understanding the macroeconomic implications of hydrogen is essential for assessing its potential to drive economic growth and contribute to long-term sustainability goals. This paper has provided a

systematic review of the 44 papers on hydrogen's role in economic growth, with a particular focus on the coverage of different hydrogen segments and their regional implications. Through this analysis, a conceptual framework was developed to elucidate how policy interventions, the hydrogen ecosystem, and distributive impacts may be harnessed to address regional inequalities.

The hydrogen economy has the potential to drive significant industrial growth, especially in sectors such as steel manufacturing, transport, and chemicals, where it can replace carbon-intensive fuels. The construction and operation of hydrogen production facilities, storage infrastructure, and distribution networks are expected to stimulate demand and generate substantial employment. As observed in renewable energy projects like wind and solar, the hydrogen investments may have significant multiplier effects, promoting not only direct job creation but also growth in sectors like engineering, construction, professional and financial services. Consequently, investments in hydrogen infrastructure are likely to contribute significantly to GDP growth and economic stability.

However, the economic impacts of hydrogen are likely to differ markedly across regions. Our analysis reveals that hydrogen plays a dual role: it can either structurally alleviate or exacerbate existing regional inequalities. These regional impacts are realized through three mechanisms: the production method chosen, the hydrogen system segment a region hosts, and the geographic pattern of investment. Whether these impacts ultimately reduce or deepen regional disparities is governed by two overarching forces: spatial comparative advantage and local value creation capacity. Policy therefore has a strong role to play in shaping these outcomes. Policy mechanisms are crucial to the growth and competitiveness of hydrogen technologies across national economies. Both supply-driven approaches, such as government subsidies and tax incentives, and demand-driven mechanisms like carbon pricing and purchase incentives, have been employed to foster hydrogen production and infrastructure development. Balancing supply- and demand-driven strategies while addressing regional inequalities will be crucial to maximizing hydrogen's contribution to economic growth, a role that regional scientists can play. While centralized production may lower transportation costs and enhance reliability of supply, it may risk exacerbating existing regional inequalities by limiting investment opportunities in less-developed areas. Regional scientists are vital in ensuring that investments in the development of hydrogen systems do address regional inequalities, like the effect of large-scale government investment in defense and military-related infrastructure during and after World War II.

Yet, only a few studies consider production methods and fewer of them consider other segments of hydrogen economy. There is a need for further research to evaluate the role of hydrogen in sectors like aviation and maritime transport, alongside its regional and sectoral disparities. A significant gap also exists in understanding what forward and backward linkages hydrogen systems may give rise to and how their formation depends on the access to resources, including skilled labor, financial capital, natural resources and precious metals. How do benefits of economies of scale compare against alleviation of regional inequalities in decentralized versus centralized hydrogen systems? When nascent technology is in initial deployment phase, maybe it is not surprising that existing macroeconomic models do not capture types of technologies across hydrogen segments and their spatial distribution in sufficient detail. Yet, given the risks for exacerbating regional disparities, regional scientists can play a more active role to engage with the growing number of hydrogen projects (IEA, 2025) early on and collect micro data (e.g. forward and backward linkages) to inform these macro models. This requires regional scientists to broaden their disciplinary boundaries to work with engineers and scientists to understand what the emerging risks and opportunities may mean for regional economies.

Developing models, tools, and frameworks that can inform decision making on associated regional disparities is essential for both policymakers and the households. The latter is particularly important because perceptions of how the benefits and burdens of the net zero transition are distributed are key determinants of households' adoption of hydrogen technologies (Gordon et al., 2023); (Gordon et al., 2024), as highlighted in the science and technology studies literature. By generating outputs and insights at a regional scale – one that residents can relate to more directly – regional analysis can inform household level energy technology choices and shape their socio-political acceptance (Gordon et al., 2022). Consequently, by providing insights on these regional trade-offs, regional science can extend its influence beyond industrial and energy policy and help accelerate the pace of the net zero transition in the domestic sector.

To support regional science fulfilling this potential, we propose a four-layer integration framework that maps the interdependencies across policy design, hydrogen system, inequality mechanisms, and ultimate distributive outcomes. This framework can form the basis of more detailed and robust modeling tools to capture the interplay between economic, technological, and policy factors across international, national, regional and sectoral impacts. Future studies should aim to conduct detailed comparative analyses of policy mechanisms across supply and demand markets – such as subsidies and carbon taxes – and assess their impacts across different national and international contexts. Through such robust and detailed models, regional science discipline can play an important role in ensuring energy transition. Specifically, the development of hydrogen economy is just one that delivers sustainable development goals on clean energy, sustainable industry, and resilient communities.

CRediT authorship contribution statement

Weizhao Huang: Writing – original draft, Visualization, Data curation. **Nazmiye Balta-Ozkan:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

See Tables A.1–A.3.

Data availability

No new data were created or analyzed during this study. Data sharing is not applicable to this article.

Table A.1
Overview of hydrogen's impacts on macroeconomy.

Sources	Country	Year	Model	Hydrogen role	Scenario	GDP	Hydrogen demand	Employment	P[7]
Bae and Cho (2010)	South Korea	2040	Dynamic CGE	Direct imperfect substitute with fossil fuels	Low subsidy (10%)	+0.02% rb[1]/year	hydrogen demand, 27.6 (vs 19.4) MTOE[2]	n/a	S
					Medium subsidy (20%)	+0.04% rb/year	45.6 MTOE	n/a	
					High subsidy (30%)	+0.07% rb/year	113 MTOE	n/a	
Liang et al. (2022)	China	2060	Endoge-nous CGE	Indirect imperfect substitute with fossil fuels	Carbon pricing policy	−145 (−0.3%) trillion CNY rb/year	n/a	n/a	D
					Technological progress	+10 trillion CNY/year	n/a[3]	n/a	
Lee (2014)	Japan	2060	Global CGE model (GTAP)-LCA	Indirect imperfect substitute with fossil fuels	Baseline Forecasting	Real GDP with negative growth	n/a	n/a	D
					Technology Advancement[4]	+production value	n/a	n/a	
					Nuclear Shutdown	Real GDP with Negative growth -1%/year	n/a	n/a	
					Emission Mitigation Target	−0.45%/year in 2020	n/a	n/a	
Mayer et al. (2019)	Europe	2050	WEGDYN CGE model	Indirect imperfect substitute with fossil fuels	Low cost tech-early implement	+0.6% rb for Western Europe/year	n/a	n/a	D
					Low cost-late	0.10%/year	n/a	n/a	
					High cost-early	−1.80%/year	n/a	n/a	
					High cost-late	−1.50%/year	n/a	n/a	
Espegren et al. (2021)	Norway	2050	REMES	Direct imperfect substitute with fossil fuels	Baseline	358 billion Euros/year	n/a	n/a	D[8]
					Low-carbon	307 billion Euros/year	27 TWh	n/a	
Turner et al. (2023)	UK	2050	UKENVI	UK electricity industry as proxy	New hydrogen transmission sector	0.20%/year	n/a	27100 net FTE[5]/year	S
Guionie et al. (2023)	France	3-5 years of con-struction	Input–output demand-driven model	New H2 sector	H2 investment phase	1 billion Euros/period	350 kt	12k gross jobs/period	S
					H2 operation phase	0.7 billion Euros/year	n/a	n/a	
Gupta et al. (2023)	Switzer-land	2035	Input–output model	New H2 sector	Construction	372 million USD/period	23.3kt	2337 gross FTE/period	S
					Operation	148 million USD/year	n/a	923 gross FTE/year	
Lee and Hung (2012)	Taiwan	2040	CGE (TAIGEM-CE)	Indirect imperfect substitute with fossil fuels	Develop clean energy	1.45%/year	n/a	0.59 million net jobs/year	S

(*continued on next page*)

Table A.1 (*continued*).

Wang (2011)	California	2030	CGE	Indirect imperfect substitute with fossil fuels	Moderate/With hydrogen vehicles	3395 (−5) billion USD/year	182kt	18940(−60)k/year	D
					Aggressive	3397 (−3) billion USD/year	584kt	19020(+20)k/year	
Yamada et al. (2019)	Japan	n/a	Input–output model	Direct imperfect substitute with fossil fuels	Substitute gasoline with hydrogen	500 million Yen/year	49kt	−229 net jobs/year	D
Kim et al. (2024)	South Korea	2030	Input–output model	New H2 sector	Investment in fuel cell sector	2013 billion KRW[6]/year	300mw for fuel cell capacity	13168 gross jobs/year	D
Hienuki (2017)	Japan	n/a	Input–output model	New H2 sector	Hydrogen energy system	n/a	n/a	0.09 gross jobs/t-H2/year	S
Gronau et al. (2023)	Germany	2030	Input–output model	New H2 sector	Robust hydrogen demand	n/a	1.25mt	82800 gross jobs/year	S
Conte et al. (2022)	Italy	n/a	Input–output model	Indirect imperfect substitute with fossil fuels	Baseline	n/a	55% penetration of renewables	12k net jobs/year	S
Lagemann and Sacht (2025)	Germany	2045	Regional CGE	New H2 sector	Full hydrogen core network	–0.92%/year (Hamburg) to +0.48%/year (Meck-Pom)	n/a	–0.23% net/year - +0.26% net/year	S
Brito et al. (2025)	Brazil	2030	Input–output model	Direct imperfect substitute with fossil fuels	Operation (85% load)	–55 million BRL/year	n/a	–10 000 gross jobs/year	S
					Construction	+801 million BRL/period	38.6 kt H2	+12 199 gross jobs/period	
Su et al. (2025)	China	2040	Dynamic CGE	Green H2 scale-up	Spatial-optimized pathway	+3.1% of real GDP/year	24 Mt H2 yr^{-1}	+1.8% net/year	S
Koutsandreas and Keppo (2025)	Greece	2050	CGE	H2 for heavy-duty transport	Policy packages	–1.5% to –0.66% (baseline); +2.25% to +2.6%/year with EU grants	4.9 Mt	n/a	S
Müller et al. (2024)	Saudi Arabia	2030	Input–output model	Export-oriented PtX hub	Hybrid NH3 build-out	0.50 USD value-added/USD invested/year	n/a	7.94–9.50 gross jobs/MUSD/year	S
Caiafa et al. (2023)	Brazil (Ceará)	2030	Input–output model	Green H2 export corridor	Construction, Local Technology	+2500 million USD value-added/period	2 GW electrolysis	93957(+6.4%) gross FTE/period	D
					Operation, Local Technology	+124 million USD value-added/year	2 GW electrolyzer	3295(+0.2%) gross FTE/year	

Notes:
1. "rb" stands for "relative to baseline."
2. MTOE refers to "million tons of oil equivalent."
3. Hydrogen is indirectly supported by renewable energy sources, projected to account for 95% of the energy mix by 2060.
4. 20% annual cost reduction in costs for hydrogen technologies, including hydrogen fuel cell vehicles, hydrogen fuel cells, and hydrogen fueling stations.
5. FTE stands for "full-time equivalent."
6. KRW stands for "Korean won."
7. "P" denotes policy drivers. Those primarily aimed at stimulating demand are labeled "D", while those focused on boosting supply are labeled "S".
8. This study examines both subsidy and tax policy mechanisms.

Table A.2
Hydrogen system coverage in studies.

Sources	Elect	SMR	w/CCS	Gasif	Bio	Stor	Dist	Transp	Indust	Power	Heat
Hienuki et al. (2021)		✓						✓			
Rinaldi et al. (2024)									✓		
McKenzie and Durango-Cohen (2012)	✓	✓						✓			
Lee et al. (2011a)					✓				✓	✓	
Lee et al. (2011b)					✓				✓	✓	
Liu et al. (2024)									✓		
Iordache et al. (2013)								✓		✓	
Wang (2011)		✓						✓	✓		
Lee (2012)	✓								✓	✓	
Lee and Hung (2012)	✓								✓	✓	
Wan et al. (2024)	✓					✓	✓		✓	✓	
Fattahi et al. (2024)	✓					✓	✓		✓	✓	
Meng et al. (2024)	✓		✓			✓	✓	✓			
Brauer et al. (2022)	✓		✓			✓	✓	✓	✓		
Ikonnikova et al. (2023)	✓	✓	✓			✓	✓		✓	✓	
Huang et al. (2024)	✓	✓				✓	✓	✓	✓		
Kim et al. (2024)										✓	
Chun et al. (2014)									✓		
Bae and Cho (2010)								✓		✓	
Ren et al. (2021)		✓	✓	✓					✓		
Liang et al. (2022)									✓	✓	
Du et al. (2024)	✓								✓	✓	
Lee (2020)					✓				✓	✓	
Lee and Chiu (2012)					✓		✓	✓	✓		
Hienuki (2017)		✓					✓	✓	✓		
Yamada et al. (2019)		✓						✓			
Lee (2014)	✓	✓			✓			✓		✓	
Mayer et al. (2019)	✓								✓		
Zhang et al. (2024)	✓	✓	✓				✓	✓	✓		
Wei (2024)	✓	✓	✓	✓					✓	✓	
Antweiler and Schlund (2024)	✓		✓				✓		✓		
Gronau et al. (2023)	✓					✓	✓	✓			
Guionie et al. (2023)	✓								✓	✓	
Gupta et al. (2023)	✓							✓			
Espegren et al. (2021)	✓		✓					✓	✓		
Turner et al. (2023)							✓		✓	✓	
Conte et al. (2022)	✓								✓		
Nakano and Washizu (2017)						✓	✓	✓		✓	✓
Lagemann and Sacht (2025)	✓								✓		
Brito et al. (2025)	✓								✓		
Su et al. (2025)	✓							✓	✓		
Koutsandreas and Keppo (2025)	✓							✓			
Müller et al. (2024)	✓								✓		
Caiafa et al. (2023)	✓										

Notes: Elect = Electrolysis; SMR = Steam Methane Reforming; w/CCS = with Carbon Capture and Storage; Gasif = Gasification; Bio = Biomass; Stor = Storage; Dist = Distribution; Transp = Transportation; Indust = Industrial Use; Power = Power Generation; Heat = Heating.

Table A.3
Summary of macroeconomic and regional focus of hydrogen-related studies.

Sources	Main result	Developed	Developing	Global/Supra	National	Sub-national
(Hienuki et al., 2021)*	Hydrogen fuel cell vehicles have lower greenhouse gas emissions and energy consumption compared to gasoline vehicles, especially for larger vehicles.	✓			✓	
Rinaldi et al. (2024)	Shifting the EU steel sector from Blast Furnace–Basic Oxygen Furnace to hydrogen-based Direct Reduced Iron/Electric Arc Furnace can cut sector-wide carbon emissions by 60% in 2050, but raises average steel prices by 56%.	✓		✓		
(McKenzie and Durango-Cohen, 2012)*	Alternative fuel buses, powered by hydrogen fuel-cell technologies, reduce operating costs and greenhouse gas emissions compared to diesel buses, but increase life-cycle costs.	✓				✓
Lee et al. (2011a)	Investments in biohydrogen are projected to significantly boost production values by 2040, generating large economic multipliers in both the U.S. and China.	✓	✓	✓		
Lee et al. (2011b)	Various econometric models are evaluated for forecasting biohydrogen development, with input–output models deemed most suitable for economic assessments.	✓	✓	✓		
Liu et al. (2024)	Combining CO_2 and air-pollutant reduction strategies in China's steel industry shows significant potential for emission reductions, especially with hydrogen-based technologies.		✓		✓	
(Iordache et al., 2013)*	Romania must integrate more renewable energy sources to transition toward hydrogen effectively.		✓		✓	
Wang (2011)	Hydrogen cars will have a minor presence in California's vehicle fleet by 2030 but could still reduce transportation energy consumption and emissions.	✓			✓	
Lee (2012)	A comparison of wind/solar vs nuclear pathways for green hydrogen production; finds that wind-driven hydrogen cuts GDP, whereas nuclear-based hydrogen raises GDP thanks to lower electricity costs.	✓			✓	
Lee and Hung (2012)	Biohydrogen and hydrogen fuel cells are key players in future energy scenarios, particularly when external support is absent.	✓			✓	
Wan et al. (2024)	China's subregions could play pivotal roles in global hydrogen, ammonia, and methanol trade.		✓			✓
Fattahi et al. (2024)	Hydrogen and ammonia trade between Europe and the MENA area could lead to cost savings of 6% by 2050.	✓	✓	✓		
Meng et al. (2024)	China is poised to play a significant role in international hydrogen trade, with a focus on green hydrogen.		✓		✓	
Brauer et al. (2022)	Multi-criteria screening ranks EU hydrogen import partners; early deals with non-pipeline countries minimize supply-cost risk but shift value-added abroad.	✓		✓		
Ikonnikova et al. (2023)	Highlights the shift toward green hydrogen trade and emphasizes the role of geographic energy systems and carbon policies.	✓	✓	✓		
Huang et al. (2024)	Hydrogen's development in China is uneven across regions, driven by differences in demand, supply, and policy.		✓			✓
Kim et al. (2024)	Investment in hydrogen creates jobs and triggers production and value-added output in South Korea's power sector.	✓			✓	
Chun et al. (2014)	Hydrogen investment in South Korea could generate 13,484 billion KRW in production by 2040.	✓			✓	
Bae and Cho (2010)	Price subsidies on hydrogen production may increase GDP due to higher investments and exports.	✓			✓	
Liang et al. (2022)	Carbon tax and trading can reduce emissions but cause economic strain, while technological innovation such as hydrogen can stimulate economic development in the long term.		✓		✓	
Ren et al. (2021)	Decarbonizing China's steel sector through hydrogen and carbon capture could significantly reduce CO_2 emissions.		✓		✓	
Du et al. (2024)	Green hydrogen production via water electrolysis can reduce carbon emissions in Chinese provinces.		✓			✓
Lee (2020)	Continuous biohydrogen could add output and jobs by 2040, doubling the multipliers of batch systems.	✓	✓	✓		
Lee and Chiu (2012)	Biohydrogen provides more benefits than hydrogen infrastructure investment, with China leading in total output.	✓	✓	✓		
Hienuki (2017)	A hydrogen energy system based on naphtha reforming impacts production and employment in Japan.	✓			✓	
Yamada et al. (2019)	Fuel cell vehicles reduce CO_2 emissions, with methane decomposition offering further reductions.	✓			✓	
Lee (2014)	Hydrogen-related industries in Japan could boost economic growth and reduce CO_2 emissions.	✓			✓	
Mayer et al. (2019)	Hydrogen-based steel production reduces emissions but increases short-term production costs in Europe.	✓		✓		
Zhang et al. (2024)	By 2050, hydrogen trade could cover 25% of global demand, with green hydrogen dominating.	✓	✓	✓		
Wei (2024)	Hydrogen development has a significant multiplier effect on emission reductions.	✓	✓	✓		
Antweiler and Schlund (2024)	Hydrogen trade, particularly blue and turquoise hydrogen, is expected to dominate early market phases due to lower costs compared to green hydrogen.	✓	✓	✓		
Gronau et al. (2023)	Hydrogen aviation could boost the macroeconomy by creating jobs, but large infrastructure investment is needed.	✓			✓	
Guionie et al. (2023)	Replacing grey hydrogen with low-carbon hydrogen in France could boost the economy and create jobs.	✓			✓	
Gupta et al. (2023)	Green hydrogen in Switzerland generates higher GDP and employment than diesel alternatives.	✓			✓	
Espegren et al. (2021)	Hydrogen can replace value lost from Norway's declining petroleum sector, supporting emissions-reduction goals.	✓			✓	
Turner et al. (2023)	A £17.4 billion investment in hydrogen infrastructure could increase UK GDP by 0.23% annually by 2060.	✓			✓	
Conte et al. (2022)	Hydrogen-based DRI coupled with EAF in Italy could reduce CO_2 emissions and increase employment.	✓			✓	
Nakano and Washizu (2017)	Investments in hydrogen infrastructure in Japan yield economic benefits and CO_2 reductions.	✓		✓		
Lagemann and Sacht (2025)	A complete shift to hydrogen in heavy industry without deregulation would reduce regional GDP and jobs, but coupling the hydrogen core network with market deregulation reverses the effect.	✓				✓
Brito et al. (2025)	Replacing grey hydrogen in refining and ammonia cuts emissions yet trims GDP and 10,000 jobs, whereas building domestic electrolytic-ammonia plants boosts short-term growth but internalizes previously imported emissions.		✓		✓	
Su et al. (2025)	High-adoption green hydrogen plus carbon pricing curbs industrial CO_2 by up to 38% and nudges national GDP by +0.4% by 2040; solar- and wind-rich western provinces become export hubs.		✓		✓	
Koutsandreas and Keppo (2025)	Financing hydrogen trucks and buses domestically drags GDP about −1.5% in 2050, but if foreign grants cover capital costs the macro impact flips positive (+2.5%).	✓			✓	
Müller et al. (2024)	Hybrid solar–wind plants yield stronger domestic value-added, while exporting ammonia lifts employment most.		✓		✓	
Caiafa et al. (2023)	When megawatt-scale green-hydrogen projects rely mainly on imported equipment and foreign contractors, local value-added, income and job creation in Ceará collapse to a fraction of their potential and can even widen gender and wage gaps.		✓			✓

Note: Although McKenzie and Durango-Cohen (2012), Hienuki et al. (2021), and Iordache et al. (2013) do not estimate macroeconomic effects directly, they are included because they supply the bottom-up evidence that input–output and computable general equilibrium models depend on. "Developed" and "Developing" classifications follow standard high-income vs. emerging-economy groupings based on the primary countries or regions studied.

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