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Review

Greenhouse Gas Reduction Potential and Economics of Green Hydrogen via Water Electrolysis: A Systematic Review of Value-Chain-Wide Decarbonization

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Abstract: Green hydrogen generated via water electrolysis has become an essential energy carrier for achieving carbon neutrality globally because of its versatility in renewable energy consumption and decarbonization applications in hard-to-abate sectors; however, there is a lack of systematic analyses of its abatement potential and economics as an alternative to traditional technological decarbonization pathways. Based on bibliometric analysis and systematic evaluation methods, this study characterizes and analyzes the literature on the Web of Science from 1996 to 2023, identifying research hotspots, methodological models, and research trends in green hydrogen for mitigating climate change across total value chain systems. Our review shows that this research theme has entered a rapid development phase since 2016, with developed countries possessing more scientific results and closer partnerships. Difficult-to-abate sectoral applications and cleaner production are the most famous value chain links, and research hotspots focus on three major influencing factors: the environment; techno-economics; and energy. Green hydrogen applications, which include carbon avoidance and embedding to realize carbon recycling, have considerable carbon reduction potential; however, uncertainty limits the influence of carbon reduction cost assessment indicators based on financial analysis methods for policy guidance. The abatement costs in the decarbonization sector vary widely across value chains, electricity sources, baseline scenarios, technology mixes, and time scenarios. This review shows that thematic research trends are focused on improving and optimizing solutions to uncertainties, as well as studying multisectoral synergies and the application of abatement assessment metrics.

Keywords: green hydrogen; full value chain systems; climate change mitigation; carbon reduction potential; carbon abatement costs

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1. Introduction

With carbon neutrality targets, green hydrogen energy has re-emerged with the versatility to drive the transition to carbon neutrality as the cost of renewable energy declines and global pressures to address climate change increase [1]. Green hydrogen plays an important role in decarbonization pathways in energy-intensive sectors that are difficult to electrify while serving as a long-term seasonal storage energy source to balance renewable electricity supply and demand [2]. Projections and analyses under different scenarios have been carried out at the global level [3–6]: by 2050, low-carbon hydrogen demand is in the range of 0.5–6.6 billion tons/year, accounting for 6–16% of total final global energy consumption and contributing to reductions in greenhouse gas (GHG) emissions in the range of 8–22%.

GHG emission reductions and the economic benefits of emission reductions from green and low-carbon technologies replacing conventional technologies can be used as reference indicators for technology selection, promotion investment, and the formulation of market incentive policies [7,8], some of which have already enacted relevant policies for the substitution of fossil energy fuels by low-carbon fuels [9,10]. As attractive alternatives to fossil fuels, green hydrogen and its derived electrofuels are critical for climate neutrality; however, rapidly scaling up the supply is challenging [11]. There are economic issues in the scale-up of green hydrogen, and scientific accounting and quantification of the emission reduction contribution from green hydrogen systems, analysis of the economic benefits of their decarbonization pathways, and support of incentive policies can mitigate or solve the challenges and issues affecting the development of green hydrogen. Studies that systematically summarize and analyze the positive role of hydrogen energy in promoting carbon neutrality and achieving sustainable development (Table 1) show that green hydrogen plays a multifunctional role in promoting the transition to clean energy.

Table 1. The literature review of the role of hydrogen decarbonization.

Target	Research Dimensions	Ref.	Research Topics	Year
Hydrogen	Hydrogen economy and social	[12]	Hydrogen economy	2006
		[13]	Hydrogen economy and sustainable development goals (SDGs)	2021
		[14]	Hydrogen economy	2022
		[15]	Socioeconomic aspects of hydrogen energy	2023
	Industry chain of hydrogen production–storage and transportation and supply chain–application	[16]	Hydrogen production impact on climate change	2022
		[17]	Low-carbon hydrogen projects toward decarbonization	2023
		[18]	Global trends in low-carbon hydrogen production	2023
		[19]	Modeling approaches used in the hydrogen supply chain (HSC)	2017
		[20]	Industrial decarbonization via hydrogen	2021
		[21]	Applications and industry chain technologies of hydrogen	2022
	Low-carbon transition of energy systems	[22]	Role of hydrogen in low-carbon energy futures	2018
		[23]	Role, cost, and value of hydrogen energy systems for deep decarbonization	2019
		[24]	Developing international activity in hydrogen technologies and fuel cells	2020
		[25]	Role of hydrogen in the 21st-century energy transition	2021
Green hydrogen	Hydrogen economy and social	[26]	Green hydrogen economy	2006
		[27]	"Renewable" hydrogen: prospects and challenges	2011
		[28]	Green hydrogen economy for a renewable energy society	2021
		[29]	Green hydrogen research	2022
		[30]	Green hydrogen market	2022
		[31]	Policy design for green hydrogen	2023
	Industry chain of hydrogen production–storage and transportation and supply chain–application	[32]	Hydrogen production from renewable and sustainable energy resources	2016
		[33]	Hydrogen production from renewable energy, change energy, and fuel markets	2019
		[34]	Green hydrogen advances the carbon-free society	2022
		[35]	Solar and wind-based green hydrogen production systems	2023
		[36]	Renewable hydrogen production technologies	2023
		[37]	Renewable hydrogen-based strategies for stationary power applications	2021
	Low-carbon transition of energy systems	[38]	Green and blue hydrogen in the energy transition	2020
		[39]	Blue and green hydrogen energy to meet decarbonization objectives	2022
		[40]	Energy decarbonization via green H_2 or NH_3	2022

These studies focused on the thematic scope of hydrogen energy and green hydrogen, and the research dimensions can be categorized into three levels: the hydrogen economy and society; the industry chain of hydrogen production–storage and transportation and supply chain–application; and the low-carbon transition of energy systems. Currently, carbon emission reduction analyses of the entire value chain system for green hydrogen to replace traditional technologies from a climate change perspective are lacking. With the explosive growth of green hydrogen projects [17], the economic benefits of the green hydrogen decarbonization pathway are significant for the sustainable development of industry and the formulation of market incentive policies, and a basic and comprehensive systematic analysis is necessary. This systematic overview addresses the following questions:

(1) What are the hotspots for research on the potential and economics of emissions reduction from green hydrogen in mitigating climate change in the context of the entire value chain system? What are the primary influencing factors?
(2) Methodological modeling of carbon emission reduction potential and the cost of green hydrogen for climate change mitigation. What are each value chain's assessment indicators, uncertainties, and solutions? What are the implications of value-chain-wide mitigation effects?
(3) What are the trends and directions for research on the potential and economics of green hydrogen emission reduction?

This system provides an overview of the impact of green hydrogen for solar and wind renewable electricity electrolysis water on global climate change and analyzes the research hotspots, methodological models, and research trends of green hydrogen carbon emission reduction from the perspective of climate change mitigation through bibliometric measurements from 1996–2023; it is oriented to the whole value chain system, improves the methodology of green hydrogen emission reduction, facilitates the incorporation of green hydrogen emission reduction into the carbon market, provides a theoretical basis for policies such as the subsidy of green hydrogen carbon emission reduction, and provides suggestions for the formulation of an incentive policy for green hydrogen for countries or regions undergoing energy transition.

2. Methodology

2.1. Research Framework

This study assessed the characteristics of the literature on the potential and economics of GHG emission reductions from green hydrogen from 1996 to 2023 through bibliometric analysis and a systematic evaluation approach. Figure 1 illustrates the research framework of this systematic review.

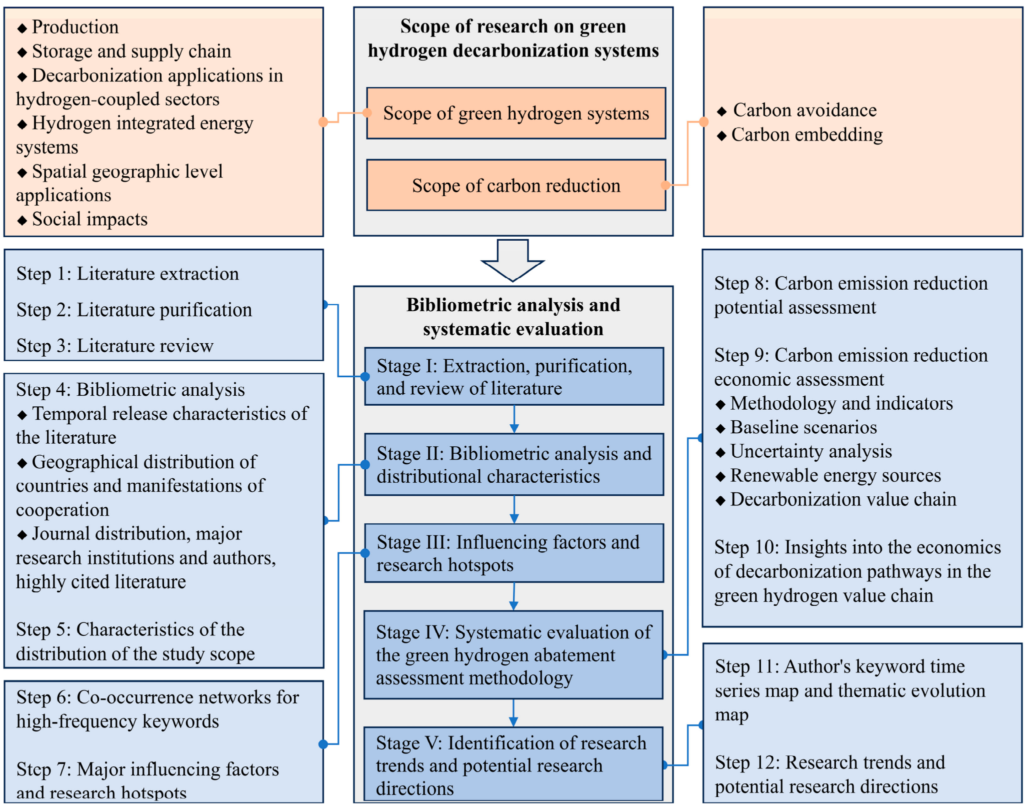

Figure 1. Research framework for a systematic review of the literature.

2.2. Research Scope

Green hydrogen generated from water electrolysis using solar and wind as renewable energy sources (RES) is called "green hydrogen". This review considers green hydrogen production in off-grid and grid-connected modes, where grid electricity is only used as a storage buffer and a backup supply under strict limitations (no more than 10% of the electricity supply [41]). Hydrogen production systems mainly include mature alkaline (ALK) and promising polymer electrolyte membrane (PEM) electrolysis equipment [3]. Combined with a systematic review of the reviewed literature (Table 1), the green hydrogen decarbonization system includes green hydrogen production, hydrogen storage, transportation and supply chain, hydrogen application, hydrogen integrated energy system, and green hydrogen decarbonization research at different geospatial levels (Figure 2); the relevant technology maturity indices related to the production and conversion pathways in the hydrogen value chain refer to the results of the global state-of-the-art analysis in the International Energy Agency (IEA) [42].

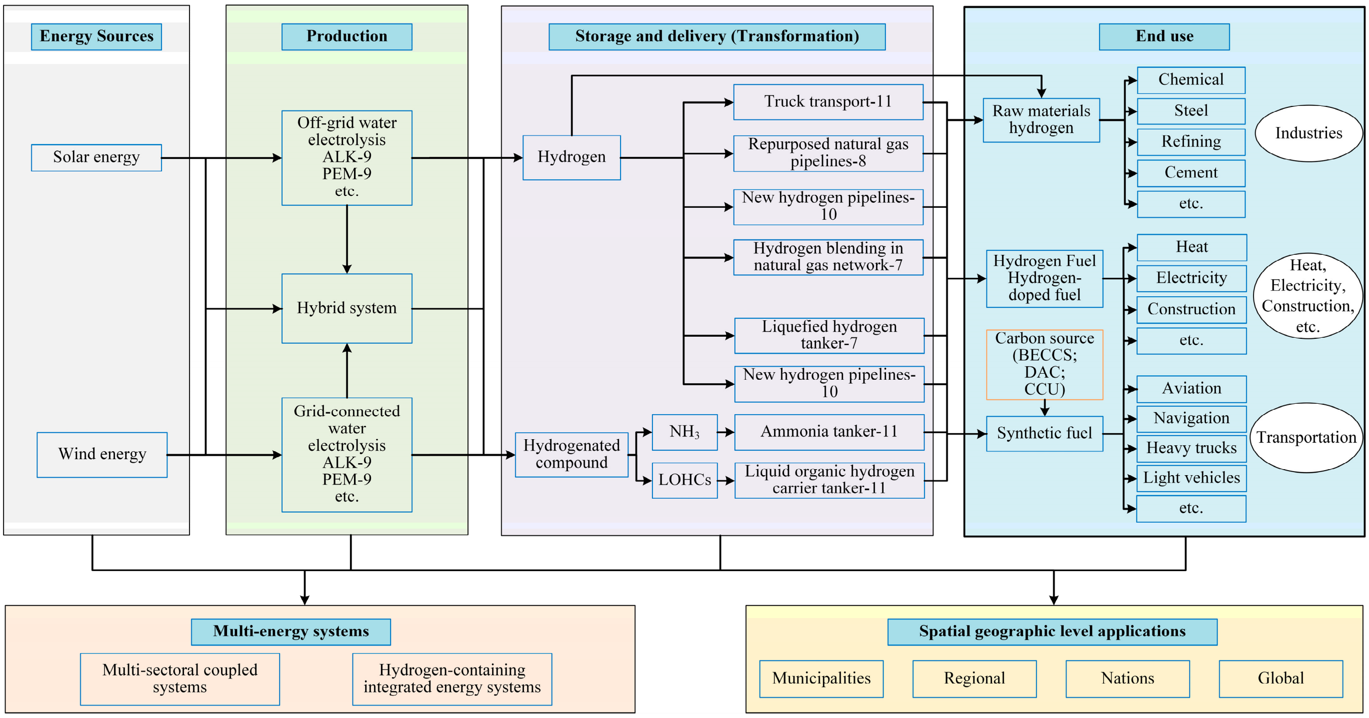

Figure 2. Value-chain-wide systems for green hydrogen via water electrolysis. 11 represents mature; 9–10 represent market uptake; 7–8 represent demonstration.

In this review, carbon emissions refer to GHG emissions in a broad scope concerning the concepts and paradigms of ISO's IWA 42:2022(E) document net-zero guidelines [43]. GHG emission reduction refers to the quantified decrease in GHG emissions related to or arising from an activity between two points in time or relative to a baseline. In comparison, the GHG baseline refers to quantified GHG emissions and the removal of an organization at a specified time against which progress to net zero assessment can be performed between two points in time or relative to a baseline. Furthermore, the scope of carbon reduction across the green hydrogen value chain has expanded based on the concept of three types of climate change mitigation programs proposed by Babacan et al. [44]. Decarbonization of green hydrogen production, application, and other links in the value chain in the baseline scenario is carbon avoidance. The synthesis of green hydrogen and CO_2 into fuels is carbon embedding, where the carbon source is defined as carbon dioxide obtained from direct air capture or biopoint sources [45].

2.3. Method Implementation

The bibliometric analysis and systematic evaluation consisted of the following five stages:

2.3.1. Stage I: Extraction, Purification, and Review of the Literature

The first stage of this analysis involved the literature extraction, purification, and review based on a systematic review. The data used for this study were mainly from the Science Citation Index Expanded (SCIE) and Social Science Citation Index (SSCI) published in the Web of Science (WOS) core repository. Appendix A Table A1 documents the detailed three-step process and basic information about the literature reviewed;

2.3.2. Stage II: Bibliometric Analysis and Distributional Characteristics (Section 3)

The second stage of this analysis is an econometric analysis of the literature on green hydrogen emission reduction. In the first step, the characteristics of the field are analyzed using bibliometric analysis, which, in general, includes the characteristics of the temporal and spatial distribution of the research results, the influence of authors and institutions, collaborative relationships, citations, and keyword analysis [46]. This study uses the journal impact factor (IF) to measure the journal's impact, and this paper uses the h-index to measure the author's influence [47]. The visualization tool at this stage was the VOS viewer [48]. In the second step, a typological approach and manual coding analysis [49] were used to characterize the distribution of the literature across the range of the study system based on the screening scope of the research literature;

2.3.3. Stage III: Influencing Factors and Research Hotspots (Section 4)

In the third stage, the influencing factors and hotspots of the research topic were identified. In the first step, a map of research hotspots for green hydrogen carbon reduction was created using co-occurrence analysis of keywords and network analysis. Bib Excel was used for network analysis to extract information downloaded from the WOS core repository, and the Pajek and VOS viewers were used to visualize the analysis results [50]. In the second step, based on high-frequency words, papers were classified and systematically analyzed for research hotspots through manual coding analysis to discuss the influencing factors closely related to the research topic [51];

2.3.4. Stage IV: Systematic Evaluation of the Green Hydrogen Carbon Emission Reduction Assessment Methodology (Section 5)

The fourth stage of this analysis used the system evaluation method [49] to analyze the method model of green hydrogen carbon emission reduction assessment from the perspective of climate change mitigation and the value chain system emission reduction effect. It is divided into three steps. The first step analyzes the methodological model of green hydrogen carbon abatement potential, and the second step analyzes the methodological model of green hydrogen carbon abatement economic assessment. These two systematic evaluation steps include analytical carbon emission reduction assessment methods, assessment indicators, baseline scenario analysis, uncertainty analysis, and corresponding decarbonization links. In the third step, the emission reduction economic data of different value chain decarbonization links of green hydrogen were extracted, the main factors affecting the economic impact of emission reduction were analyzed, the emission reduction effects of different sectoral decarbonization pathways were evaluated, and insights were provided;

2.3.5. Stage V: Identification of Research Trends and Potential Research Directions (Section 6)

The final stage of this analysis was further exploratory research based on the results of the analyses in Stages II, III, and IV, combining bibliometric analysis and systematic evaluation methods to identify research trends and potential research directions. It is divided into two steps. In the first step, the time series graph and the thematic trend graph of the literature keywords are plotted, in which the thematic trend analysis is performed by the bibliometrix R-tool [15,52]. In the second step, the research trends and potential research directions for green hydrogen carbon emission reduction are systematically evaluated in each section in terms of the shortcomings of existing studies.

3. Characteristics of the Spatial and Temporal Distributions of the Literature

Based on the extraction, purification, and the literature review, 706 studies (Appendix A Table A2) on green hydrogen carbon emission reduction were obtained. The literature spans from 1996 to 2023 and involves 97 journal sources, with an average of 29.51 citations per document, 31,621 total references, 20,836 total citations, 2359 authors, and 1815 authors' keywords. The econometric analysis of this study focuses on the temporal and spatial distribution characteristics of the literature as well as the research hotspots of the hydrogen energy value chain, and the distributions of major journals, research institutions, and authors are shown in the Supplementary Materials.

3.1. Characteristics of Spatial and Temporal Distributions

3.1.1. Total Number of Articles and Citations by Time

The literature on green hydrogen carbon emission reduction research is divided into three stages according to the number of publications and citations in time (Figure 3): stage 1 is 1996–2005, when the relevant research topics began to be published; stage 2 is 2006–2015 when the number of publications was relatively small, and there was not yet a full awareness of green hydrogen emission reduction; and stage 3, 2016–present, when the number of publications began to grow, and the 2015–2022 growth rate averaged 67.6%. In 2015, the Paris Agreement, which symbolizes positive global action against climate change, was officially signed, and 17 United Nations SDGs were established, aiming to thoroughly address the three dimensions of social, economic, and environmental development in an integrated manner from 2015 to 2030. The clean energy nature of green hydrogen began to receive attention from scholars. In 2020, net-zero and carbon-neutral targets received a global response, and research on green hydrogen–carbon reduction exploded.

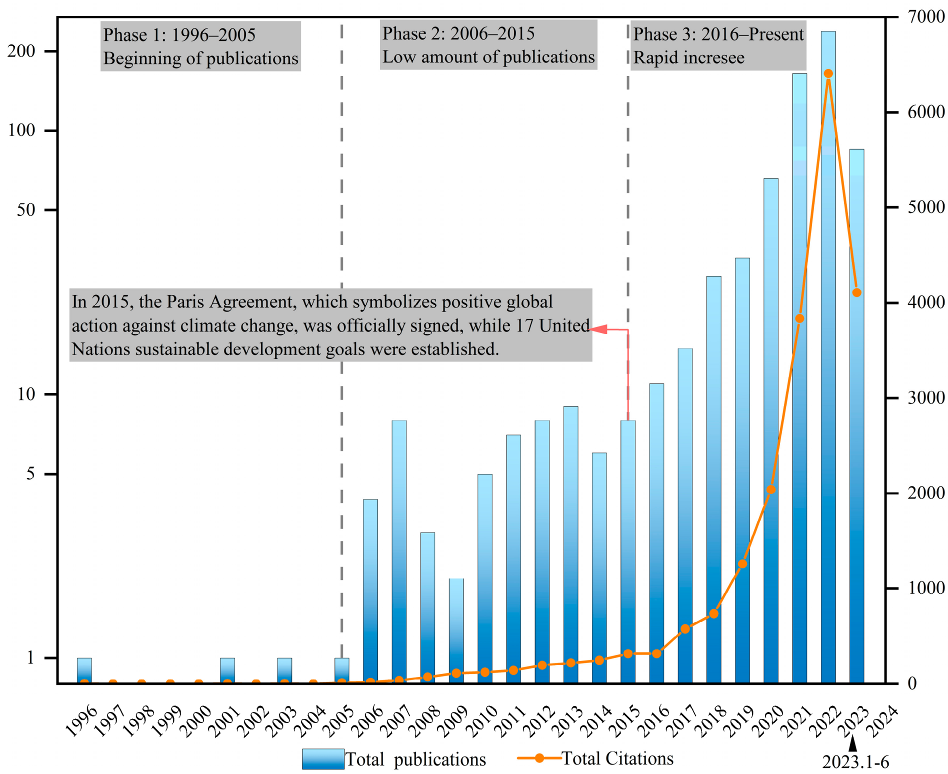

Figure 3. Total publications and citations during 1996–2023. The published literature retrieved has a deadline of 30 June 2023, so the number of documents in 2023 shows a decrease relative to 2022.

3.1.2. Geographical Distribution of Countries and Manifestations of Cooperation

The 706 research papers on green hydrogen carbon emission reduction involve 80 countries and regions, of which the top nine countries account for approximately 80.74% of the total number of articles, and nearly 26.25% of the countries have only one biased article. Table 2 shows the number of publications and citations for the top nine countries.

Table 2. Top nine most productive countries in research. TP is the number of total publications; R (%) is the ratio of the number of one country's publications to the total number of publications; TC is the number of total citations; TC/TP is the number of citations per publication.

NO.	Country	TP	R (%)	TC	TC/TP
1	CHINA	97	13.739	1763	18.18
2	USA	95	13.456	3839	40.41
3	GERMANY	91	12.890	2795	30.71
4	UNITED KINGDOM	67	9.490	3601	53.79
5	ITALY	54	7.649	1542	28.56
6	CANADA	45	6.374	2250	50.00
7	AUSTRALIA	42	5.949	2177	51.83
8	SPAIN	42	5.949	1157	27.55
9	SOUTH KOREA	37	5.241	429	11.59

The U.S. started to study the green hydrogen economy earlier and is in the leading position regarding the number of publications and citations in this field. China started its research later and is now in first place regarding the number of publications but only in sixth place in terms of citations and eighth place in terms of TC/TP indices, reflecting that the overall academic influence is not high. Developed countries such as Germany, the United Kingdom, Italy, Canada, and Australia are generally more advanced, whereas developing countries are lagging. Figure 4 shows the geographical distribution of major countries and cooperation performance (43 countries with more than five articles published). The countries with closer cooperation are characterized by six clusters, with developed countries having closer cooperative relationships.

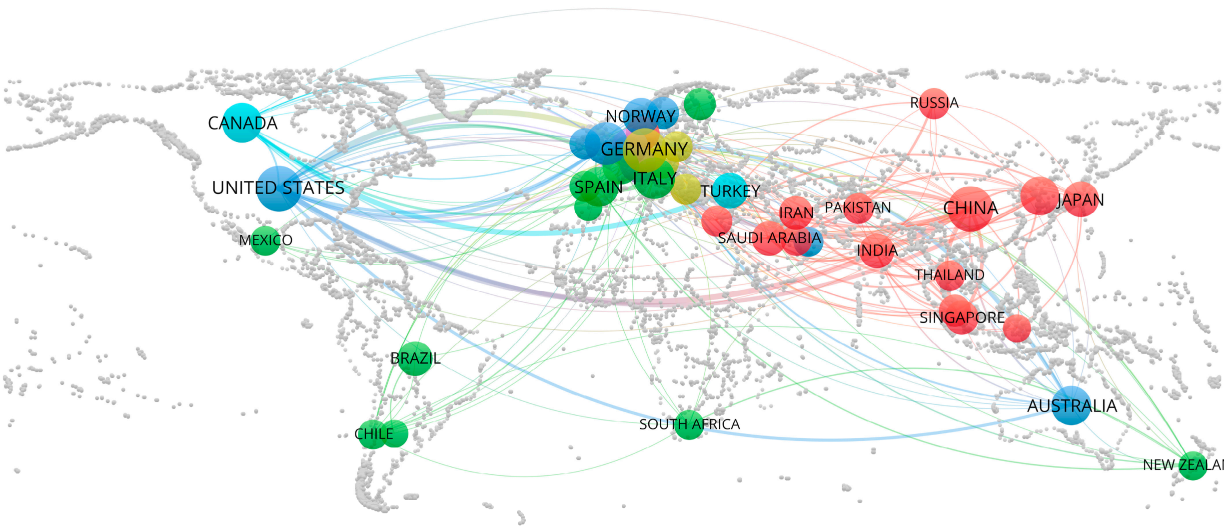

Figure 4. Geographical distribution of countries and manifestations of cooperation. The circle size indicates the number of publications, and the thickness of the connecting lines indicates the closeness of collaboration. Countries of the same color work more closely together, with six colors forming six clusters.

3.2. Characteristics of the Distribution of the Study Scope

Based on the scope of systematic research, the expansion is divided into six green hydrogen value chain segments: (1) hydrogen production; (2) hydrogen storage and supply chain; (3) decarbonization applications in hydrogen-coupled sectors; (4) hydrogen integrated energy systems; (5) impacts of green hydrogen on carbon neutrality targets, such as global and national targets; and (6) social impacts, such as market, policy, and sustainability, of green hydrogen emission reductions. Figure 5 shows the annual research highlights and the heat of decarbonization applications in the hydrogen-coupled sector.

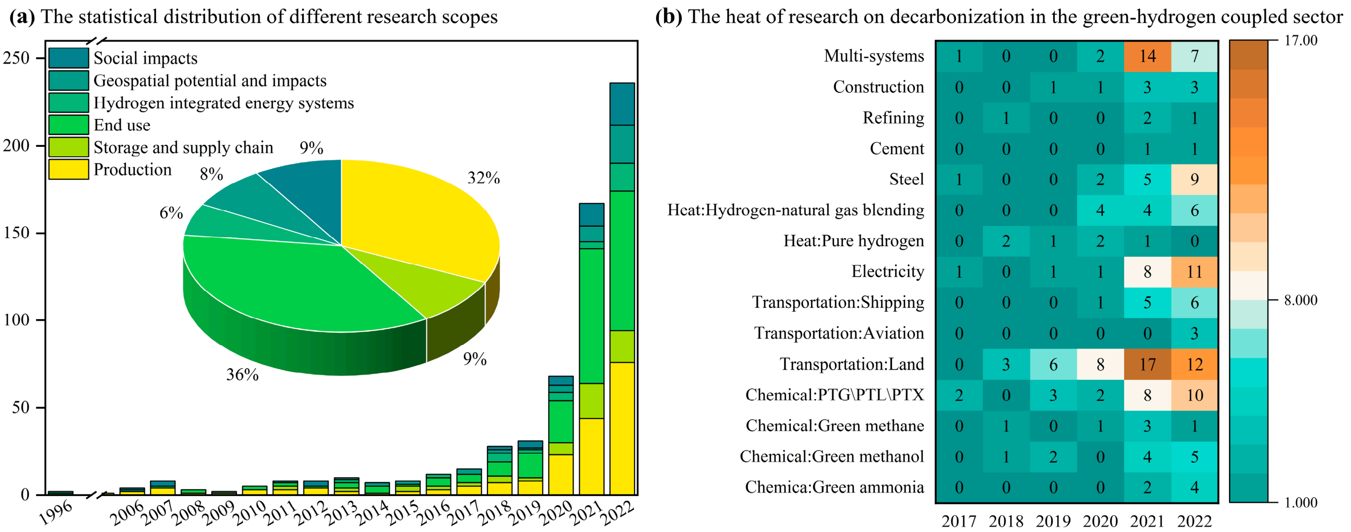

Figure 5. Map of the research scope distribution and heatmap of sectoral decarbonization research.

Overall, green hydrogen coupling for decarbonization in hard-to-abate sectors is the value-chain link of greatest interest (approximately 36%; 253 articles), and green hydrogen is becoming an important decarbonization pathway for hard-to-electrify sectors with increasing research on the economic benefits involved. The most common application of green hydrogen for decarbonization is in the transportation sector, where land transportation dominates, navigation increases annually, and aviation is also beginning to appear in relevant research. Next is the chemical sector, with integrated power-to-gas (PTG)/power-to-liquids (PTL)/power-to-X (PTX) as the main focus and green ammonia and methanol as the research focus. Then, in order, there are multisector coupling, the power sector, the iron and steel sector, and the thermal sector. Among them, the research on the carbon emission reduction benefits of hydrogen blending in natural gas systems belonging to the thermal sector is increasing year by year. The final sectors involved are construction, refining, and cement.

Hydrogen production is another major research hotspot in the value chain segment (approximately 32%, 224 articles), involving defining green hydrogen standards and the carbon emission reduction benefits of green hydrogen production projects. Hydrogen storage is currently the main technical bottleneck restraining market development in the hydrogen energy industry, and HSC optimization is an essential part of carbon emission reduction (approximately 9%, 66 articles). Green hydrogen production can increase renewable energy consumption, which can be connected to heat, electricity, and other integrated energy systems. Its clean energy carrier characteristics promote the low-carbon transformation of energy systems, and the scope of hydrogen energy system research has covered global, national, regional, and other models [22] (approximately 6%, 46 articles). Studying the decarbonization potential and economic development of green hydrogen at the national and regional levels under the carbon neutrality goal (approximately 8%, 54 articles) has become a reference for developing green and low-carbon hydrogen energy policies. More than 30 countries have initiated national hydrogen plans, strategies, and road maps [53]. Green hydrogen development is not economical relative to conventional or fossil energy sources. Market-, policy-, and social-level research promotes the realization of green hydrogen decarbonization (9%; 65 articles).

4. Main influencing Factors and Research Hotspots

A total of 1815 author keywords obtained from 706 studies were sorted and merged by abbreviation, singular or plural type, and gender. Figure 6 shows the co-occurrence network based on high-frequency keywords (more than six). Table 3 presents the classification of high-frequency words using the hand-coding method. Research hotspots focus on environmental, techno-economic, and energy system influencing factors.

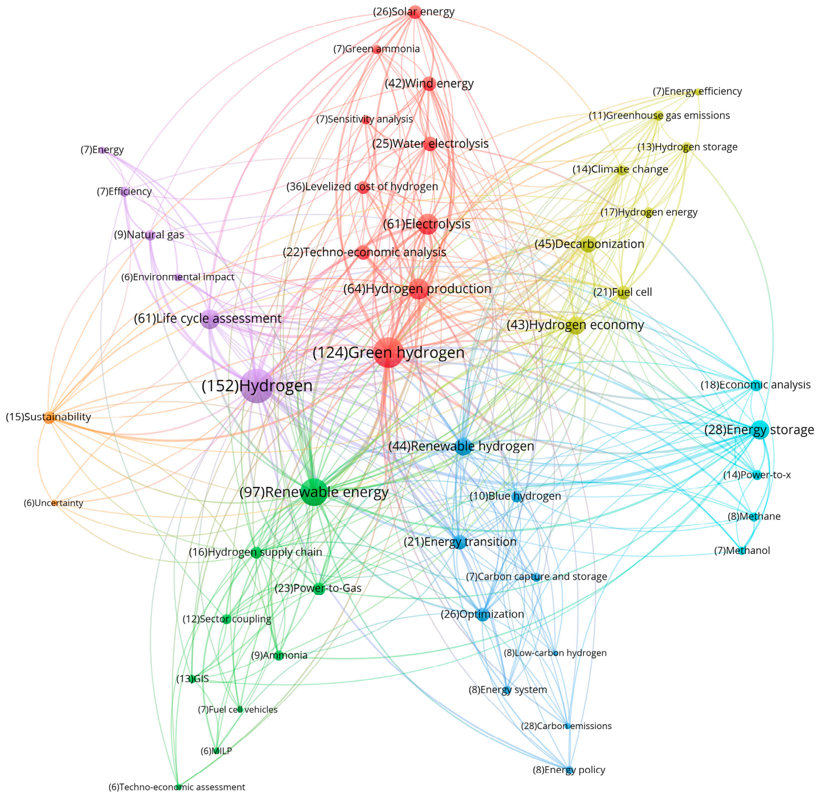

Figure 6. Co-occurrence network of high-frequency keywords. Numbers in parentheses before keywords indicate the number of co-occurrences.

Table 3. High-frequency keyword summary categories. Numbers in parentheses before keywords indicate the number of co-occurrences.

Factor	Research Hotspots	High-Frequency Keywords
Environmental	• Carbon emission accounting for green hydrogen systems • Hydrogen emission Global Warming Potential (GWP) and hydrogen leakage impacts	(61) Life cycle assessment (LCA) (45) Decarbonization (28) Carbon emissions (14) Climate change (11) GHG emissions (6) Environmental impact
Techno-economic	• Cost competitiveness of renewable energy hydrogen production • HSC network and hydrogen application technology and economic optimization • Energy system decarbonization costs	(43) Hydrogen economy (36) Levelized cost of hydrogen (LCOH) (22) Techno-economic analysis (18) Economic analysis (6) Techno-economic assessment

Table 3. *Cont.*

Factor	Research Hotspots	High-Frequency Keywords
Energy systems	• Renewable energy intermittency • Optimization of hydrogen production system capacity allocation • Conversion efficiency of RES for hydrogen production, storage, and synthesis of hydrogen-based products • Expansion of hydrogen production system based on renewable energy utilization	(61) Electrolysis (42) Wind energy (28) Energy storage (26) Solar energy (25) Water electrolysis (23) PTG (21) Energy transition (14) PTX (7) Energy efficiency

4.1. Environmental Factors

Carbon emissions accounting for the green hydrogen value chain system, which is the basis of carbon emission reduction research, suffers from inconsistencies in accounting methods and system boundaries and from uncertainty in accounting data sources. Hydrogen production pathways and leakage rates are key levers for a large-scale transition to a green hydrogen economy to obtain significant climatic benefits [54]. The leakage rate of hydrogen produced by green hydrogen is greater than that of gray and blue hydrogen, and a combination of the leakage rates and long-term global warming trends of hydrogen should be considered in carbon abatement studies based on traditional hydrogen production pathways.

4.1.1. Carbon Emission Accounting Methodology and Data Source Issues

Central to the research on green hydrogen definitions [55] and standards [56] are the carbon emissions of different hydrogen production pathways, with GHG emissions from green hydrogen being lower than those from gray and blue hydrogens [57]. A discussion of the methodology for the GHG life cycle assessment of hydrogen systems revealed that most hydrogen energy systems apply a cradle/door-to-door boundary. The GWP in life cycle impact assessment is mainly based on the characterization factors of the Intergovernmental Panel on Climate Change (IPCC) [58]. Method selection variability significantly affects the results of LCA studies. Valente et al. [59,60] constructed a coordination mechanism for attribution methods, functional units, system boundaries, and multifunctional methods for critical method selection, advancing the development of a protocol form for LCA studies of hydrogen systems. As the scope of LCA systems expands, considering the supply chain for hydrogen transportation and distribution and conducting optimized GHG accounting is becoming widespread [61–64], and the environmental footprint assessment of hydrogen-based chemicals based on green hydrogen is becoming a research direction [65]. A PTX system's power and carbon sources are key drivers of environmental impacts. There is a lack of transparency at both the technical and methodological levels [66].

The main data sources for the background and prospective processes of life cycle inventory analysis are the scientific literature and life cycle databases; however, the current dilemma is that there are no or very few large-scale renewable electrolysis plants operating to collect operational data and plant specifications, and LCA practitioners typically make simplifying assumptions about steady-state operation under average conditions, lacking significant differences arising from the physical and thermodynamic constraints of electrolysis and electrolytic post-treatment in different scenarios [67].

4.1.2. Hydrogen GWP and Hydrogen Leakage Impacts

Hydrogen is an indirect climate gas that induces perturbations in three potent greenhouse gases: methane; ozone; and stratospheric water vapor. However, the role of hydrogen in reducing GHG emissions is uncertain, necessitating a deeper understanding of the GWP of hydrogen. Figure 7a shows the 100-year global warming potential (GWP100) of hydrogen emissions; there is a noticeable trend of increasing scholarly attention to the role of hydrogen in the atmospheric greenhouse effect over the long term and in combination. The latest findings are greater than 5.8 in the IPCC, yet the original data are still used in the Clean Development Mechanism (CDM)'s just-released water electrolysis hydrogen emission reduction methodology [41]. Hydrogen leakage amplifies global warming impacts [68], and hydrogen depletion occurs throughout the value chain [69]. Figure 7b shows the leakage rates of hydrogen value chain links (see Table 4 for detailed data). Green, blue, and gray hydrogen correspond to hydrogen leakage rates ranging from 4.00 to 15.71%, from 1.50 to 13.21%, and from 1.00 to 12.71%, respectively, across the system-wide value chain, which is higher than the IEA's net-zero scenario hydrogen demand under a high-risk scenario, which could result in an economy-wide leakage rate of 5.6% [70]. The future hydrogen transition scenarios considered by Hauglustaine et al. [54] suggested that a green hydrogen economy is beneficial for reducing CO_2 emissions in policy-relevant time horizons and leakage rates.

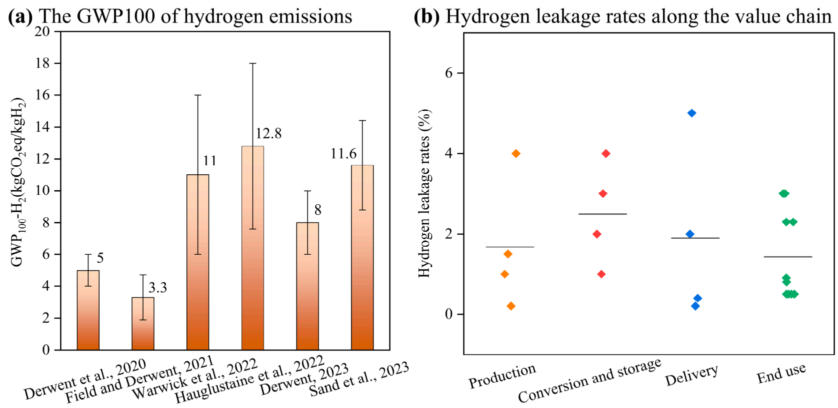

Figure 7. Hydrogen GWP100 and hydrogen leakage rate along the value chain. (**a**) shows the GWP100 of hydrogen emissions [54,71–75], and (**b**) shows the hydrogen leakage rates along the value chain [68,76,77].

Table 4. Hydrogen leakage rate data sheet for full value chain systems.

Category	Leakage Source Process	Hydrogen Leakage Rates	Ref.
Production	Gray hydrogen	1.00%	[78]
	Blue hydrogen	1.50%	[79]
		0.10–1.00%	[68]
	Green hydrogen	4.00%	[80]
		0.10–4.00%	[68]
		0.20%	[81]
Conversion and storage	Conversion–compression	0.14–0.27%	[68]
	Conversion–liquefaction	0.15–2.21%	[68]
	Storage—above-ground liquid	0.05–0.54%	[68]
	On-board storage	0.30–1.00%	[76]
End-use	Natural gas blending	0.90%	[82,83]
	Chemical synthetic fuels	0.50%	[77]
	Iron and steel	0.50%	[77]
	Refineries	0.50%	[77]
	Other industries	0.50%	[77]
	Electricity generation	3.00%	[82]
	Road transport	2.30%	[82]
	Aviation	3.00%	[77]
	Shipping	2.30%	[77]
	FC and on-board system	0.10–1.00%	[76]
	Buildings	0.80%	[84]

Table 4. *Cont.*

Category	Leakage Source Process	Hydrogen Leakage Rates	Ref.
Delivery	Pipeline transport and storage	2.00%	[85,86]
	Transportation–transmission	0.02–0.06%	[68]
	Pipeline local distribution	0.40%	[82,87]
	Transportation–distribution	0.0003–0.16%	[68]
	Truck transport and storage	5.00%	[88]
	Direct use on-site	0.20%	[82,86]
	Transportation by shipping	0.00–0.17%	[68]
	Ship	0.00–2.00%	
	Pipeline	0.10–5.00%	[76]
	Truck (transfuse and boil-off)	2.00–5.50%	

4.2. Technoeconomic Factors

The techno-economic cost of a green hydrogen system directly determines the economic benefits of green hydrogen carbon emission reduction. Considering the environmental benefits of green hydrogen emissions, hydrogen production pathways will have different cost values [89]. The techno-economic optimization of electric hydrogen systems aimed at minimizing economic costs [90], optimization of the HSC design with integrated consideration of the environment and economy [91], and the techno-economic optimization of hydrogen substitution for traditional energy sources after integrating it into the energy system [92,93] have advanced the optimal application of green hydrogen decarbonization pathway options, increasing the economic value of green hydrogen emission reduction.

4.2.1. Cost Competitiveness of Hydrogen Production

The cost of renewable energy has fallen dramatically, and renewable hydrogen produced from RES through the PTG process has become cost-competitive in market applications [94]; the cost of green hydrogen synthesized chemical products such as green ammonia [95], green methanol [96], and related hydrogen-based fuels [97] is mainly affected by the price of electricity, the capital cost of electrolysis tanks, and the capacity factor of the power plant. Considering conditions such as gains in carbon emission reduction, environmental benefits, and technological advances, green hydrogen is being scaled up. The LCOH based on levelized cost of energy (LCOE) has become the most dominant evaluation metric for comparing hydrogen production pathways and the economics of hydrogen-based synthetic fuels [98–100]. The levelized cost of carbon mitigation (LCCM), applicable to the hydrogen production pathway, has also become a new metric for discussion [101].

4.2.2. Optimization of the HSC and Hydrogen Application Pathways

The economic feasibility of the hydrogen supply was discussed concerning the application of decision-making tools for hydrogen transportation routes and distribution methods [102]. Sustainable large-scale hydrogen transportation projects based on existing natural gas pipelines are feasible [103,104]. In addition, cross-border green hydrogen can meet the basic requirements of trading countries [105]. Applying green hydrogen in emission-intensive sectors, such as steelmaking [106] and transportation [107], is generally not economical compared to traditional technologies. However, research on optimization models based on mixed integer linear programming (MILP) provides the most cost-effective decarbonization pathways for hydrogen [108,109].

4.2.3. The Decarbonization Cost of Green Hydrogen in the Energy System Is Controversial

Hydrogen plays a conflicting role in the global energy scenario [110], and there is currently controversy regarding the decarbonization cost of green hydrogen. Based on life cycle economic evaluation, green hydrogen positively impacts the investment payback period and overall life cycle net profit from renewable energy generation [111]. However, due to infrastructure investment, the energy supply system transformation costs increase when green hydrogen schemes replace traditional hydrogen production methods [92]. In an integrated energy system model analysis, coupling hydrogen production from various RES with various industries led to a 13–56% increase in renewable energy generation and a 7–16% decrease in the overall system cost under deep decarbonization scenarios [112].

4.3. Energy System Factors

Green hydrogen production, storage, and conversion to hydrogen-based products are manifestations of the multifunctionality of hydrogen as an energy carrier. The efficiency of the energy utilization and energy conversion process is an influential factor that cannot be ignored, and energy utilization and optimization based on the expansion of the hydrogen production system play an important role in economic and environmental aspects. The expansion and optimization of energy utilization systems increase the difficulty of environmental–economic analysis, and the carbon emission reduction economics of solar off-grid water electrolysis hydrogen production systems considering energy storage have been discussed in the literature on the carbon emission reduction economics of green hydrogen [113].

4.3.1. Renewable Energy Intermittent Solutions

Renewable energy intermittency and power volatility directly affect green hydrogen production [114]. Electrolyzers can provide additional flexibility to the grid [115], and green hydrogen can significantly reduce renewable energy curtailment [116], thus expanding the emission reduction potential and the role of electrohydrogen systems in the energy transition. The electrolyzer to renewable energy power ratio and capacity allocation ratio are key system parameters for the efficiency of green hydrogen production [117], with ratios ranging from 1:2 to 1:5 in the current findings [98,118].

4.3.2. Energy Utilization and Conversion Efficiency Constrain Overall Effectiveness

Energy utilization losses and the decreasing efficiency of multiple conversions attenuate emission reduction benefits. The amount of electricity needed for water electrolysis at a low calorific efficiency of 60% is approximately 55 kWh/kgH_2 [119]. In an environmental LCA study of hydrogen production technologies, PEM was identified as a long-term option for hydrogen production, requiring 54.6 kWh of electricity and 9.1 kg of water to produce 1 kg of H_2 [120]. In a feasibility study evaluating CO_2 reduction options regarding energy use, the average energy consumption for hydrogen production by water electrolysis was 201.93 MJ [44]. According to a comparative assessment of renewable energy-based hydrogen production methods, the overall energy efficiency of solar photovoltaic (PV)-based hydrogen production systems was 16.95% [121]. Hydrogen storage systems, although feasible in current technology, lose 60% to 85% of their electricity owing to losses during conversion and storage, with electricity-to-hydrogen-to-electricity efficiencies ranging from 15% to 40% [122]. The green hydrogen conversion of hydrogen-based products versus direct electrification has a final efficiency gap of 2–14 times for different end-use applications [45].

4.3.3. Multiobjective Optimization of the Energy–Environment–Economy for Hybrid Hydrogen Production Systems

Energy sources determine the entire life cycle of GHG emissions and cumulative energy demand, and expanding hydrogen production systems based on energy sources often focus on energy–environment–economy multiobjective optimization problems. Multiple hydrogen production methods are dominated by renewable electricity [123,124], and hydrogen production systems have primarily expanded into hybrid systems based on renewable electricity sources and grid-connected systems based on connections to the grid [67,124–126]. Hybrid systems include the mixing of wind and PV power sources of electrical energy [127,128], as well as the mixing of renewable energy systems with energy storage systems, where the mixing of renewable sources of electrical energy serves to increase emission reductions, improve the efficiency of the system, and reduce the cost of production [129,130]. Hydrogen is combined with short-term energy storage technologies such as batteries and ultracapacitors to balance efficiency and cost through control systems and energy management strategies [122]. By setting the optimal size of the energy storage system capacity to minimize the cost per unit of hydrogen production, carbon footprint analysis was performed to quantify the carbon dioxide emissions of the proposed system, and the environment–economy optimization enhanced the benefits of emission reduction [131].

5. Methodological Study of the GHG Reduction Potential and Economics of Green Hydrogen

5.1. GHG Reduction Potential of Green Hydrogen

5.1.1. Green Hydrogen Plays an Important Role in Coupling with Carbon Capture and Storage (CCS) Technology

Carbon sources are important for measuring the potential for emission reduction. Carbon embedding is part of carbon emission reduction, and green hydrogen emission reduction is mainly reflected in the synthesis of hydrocarbons from renewable hydrogen and CO_2, in which the carbon source is mainly CCS technology. In the study of hydrogen-based e-fuel climate change mitigation, carbon capture, and carbon cycling are emphasized to achieve climate neutrality, and the amount of CO_2 from direct air capture utilization or biomass utilization can be considered part of emission reduction [45]. Taking green methanol as a study, optimal cross-sectoral cooperation is required for the chemical sector to achieve a sustainable economic transition, which may eventually become an essential chemical that may be produced exclusively from carbon dioxide obtained from decarbonized electric power mixes, direct air capture, or from biopoint sources to close the carbon cycle at this point, taking into account global ecological constraints, as well as economic and social criteria, the electric power mix, the available sources of carbon dioxide, and the temporal evolution of natural gas and hydrogen prices to determine the best plan [132].

5.1.2. Methodology for Assessing the Green Hydrogen Emission Reduction Potential and Uncertainties

The analysis modes of the green hydrogen emission reduction potential can be divided into two main modes: the bottom–up analysis mode, which is mainly reflected in the analysis of carbon emission reduction, with common indicators such as unit emission reduction and total system emission reduction; and the top–down analysis mode, with the amount of hydrogen demanded or the amount of hydrogen consumed under the carbon emission target, as well as the amount of hydrogen allocated or the amount of product substitution under different application scenarios. Decision-makers must carefully analyze the carbon emission reduction effects generated by different hydrogen application pathways and explore metrics that can be used to assess the energy savings and emission reduction effects of specific hydrogen application pathways [133]. Table 5 summarizes methodological studies of the key literature on the emission reduction potential of green hydrogen.

The climate impact assessment of various hydrogen production routes in the literature varies widely, which relates to the perception of low-emission hydrogen pathways by policymakers, investors, and consumers [134], as well as to the fact that the International Hydrogen Trade Emissions Certification System faces many policy challenges in defining the boundaries of accounting for hydrogen production emissions [135]. Some studies do not consider indirect emissions from renewable electricity or default zero-carbon emissions from renewable power generation [130]. In contrast, studies on green hydrogen emission reductions relative to different baselines, such as gray and blue hydrogens, discuss the variability of methodological choices for versatility. When electricity is sourced from additional RES, the GHG footprint varies depending on the source of the electricity and distribution choices [134]. The deep decarbonization benefits of renewable hydrogen are influenced by the intensity and variability of solar or wind resources, the operational performance of renewable electrolysis equipment, and the energy and GHG emissions embodied in the global supply chain [67].

Based on the characteristics of the HSC, the emission reduction analysis model of hydrogen in the sectoral decarbonization pathway is based on the bottom–up engineering model, with the baselines mainly based on traditional fossil energy technology. The indicators of the emission reduction potential are mainly the GHG emission reductions per unit of product, and the emission reduction potentials are reflected by the emission reductions at the sectoral level and the substitution of the low-carbon products in some studies [136,137]. The analysis model at the regional and global levels is carried out in a top–down manner, generally analyzing the emission reduction potential under various scenarios or assumed carbon emission targets and adopting a bottom–up engineering model considering the technical characteristics of the HSC. The emission reduction potential indicators are regional or global emission reductions and involve quantitative assessments of green hydrogen production, demand, and energy consumption. Notably, emission reduction technologies, such as CCS, are used as the baseline for comparison, reflecting the competition and synergy between low-carbon and carbon-negative technologies [138]. Uncertainty influences on carbon reduction potential analysis include uncertainty in scenario analysis assumptions such as carbon neutral time, environmental targets, energy targets, and economic targets; uncertainty in hydrogen leakage rates and hydrogen GWP; uncertainty in markets such as energy prices and hydrogen prices; uncertainty in policy support such as carbon taxes and carbon budgets; uncertainty in market demand; and uncertainty in resources such as land use, mineral extraction, and use.

Table 5. Methodological study of green hydrogen emission reduction potential.

Ref.	Baseline	Main Influencing Factors	Decarbonization Chain
[119]	Steam methane reformation (SMR)	Electricity portfolio	Production
[134]	① Blue hydrogen ② Gray hydrogen	① Electricity source ② Multi-functionality ③ Baseline	Production
[139]	Coal-fired power	Technological changes	Electricity
[140]	Conventional natural gas	① Functional unit ② Multifunctional methods	Chemical
[137]	Conventional oil refining	Greenhouse gas emission intensity of electricity (GHGE)	Refining
[141]	Conventional steelmaking	GHGE	Cement
[142]	Conventional steelmaking	① Multifunctional methods ② System boundary	Cement
[136]	Diesel forklift	Social cost of carbon (SCC)	Transportation
[143]	Truck fuel (gasoline/diesel)	Hydrogen supply	Transportation
[138]	① Fossil fuels ② CCS	① Carbon source ② Carbon price ③ Quantity demanded ④ Renewable energy capacity	Transportation
[144]	Fossil fuel	① Construction and operation of power plants, hydrogen plants ② GHGE ③ Energy conversion efficiency ④ Hydrogen compression pressure ⑤ Upstream fossil fuel extraction and transportation	Transportation
[145]	Fuel-efficient vehicle	① Hydrogen vehicle substitution rate ② The minimum environmental objective ③ Energy objective ④ Economic objective	Regional (transportation)

Table 5. *Cont.*

Ref.	Baseline	Main Influencing Factors	Decarbonization Chain
[146]	-	① Hydrogen prices ② Hydrogen demand	Regional (transportation)
[147]	-	① Time to peak emissions ② Cumulative carbon budget	Country—China
[148]	-	① Future costs and efficiencies of existing technologies ② Disruptive new technologies or energy carriers ③ Aggregate demand for energy and commodities ④ Other assumptions (policy, trade, market functioning and integration, social issues, etc.)	Region—Europe
[54]	① Blue hydrogen ② Blue hydrogen and green hydrogen ③ Gray hydrogen, blue hydrogen, and green hydrogen ④ Blue hydrogen and green hydrogen	① Hydrogen leakage rate ② Single or different combinations of hydrogen source baselines	Global (production)
[149]	-	① Power sourcing and integration ② Energy conversion and efficiency ③ Siting, land use, mineral extraction and use, water and electrolytes, electrode materials for electrolysis, etc.	Global (production)
[150]	-	Representative concentration pathway (RCP)	Global

5.2. GHG Reduction Economics of Green Hydrogen

Green hydrogen abatement costs must reflect value chain characteristics because in different decarbonization segments, such as hydrogen production, hydrogen storage and transportation, hydrogen application, and integrated hydrogen energy systems, the baseline and targets for abatement are different, and the adaptability of the abatement cost methodology is relatively different. Decision-makers rely on marginal abatement costs (MAC) to assess feasible strategies and associated costs for achieving emission reduction targets [151]. Babacan et al. [44] addressed the concept of carbon abatement and proposed a carbon abatement cost of energy metric to compare the CO_2 abatement performance of different technologies. The reduction in total cost after introducing green hydrogen into the energy system also indicates the economic benefits of emission reduction [112].

5.2.1. Evolution of Financial Analysis Methods Influenced by Uncertainties

Bottom–up modeling is the dominant approach in studies assessing abatement costs [50]. Finance accounting analysis (expert-based) is predominant in the green hydrogen production and application value chain segments. Table 6 summarizes the literature on using financial analyses to assess the cost of green hydrogen abatement. Granovskii et al. [152] first analyzed the economic factors of green hydrogen to reduce GHG emissions, and the financial analysis method was used to assess the abatement economics for hydrogen production from underground coal gasification [153]. The LCOH has become an effective indicator of the economics and competitiveness of different hydrogen production processes [99]. Based on the LCOE [154], the LCCM has been proposed as an indicator of improved cost assessment methods for achieving a net-zero emission world [155]. The LCCM, which applies to the hydrogen production pathway, has emerged as a new metric for discussion [101] and has been used in hydrogen-based fuel abatement applications [156,157].

The green hydrogen value chain system involves multiple paths and is complex, and financial analysis methods suffer from uncertainties, such as the time-lapse of discounted costs, changes in the cost of technological advances, behavioral explanations, and market transactions [158–160]. The main methods used in the literature to address the impact of uncertainty are scenario analysis and sensitivity analysis. Monte Carlo simulations also address uncertainty in studying the economics of hydrogen energy abatement [161]. Dynamic abatement costs based on the hydrogen energy value chain and studies considering the benefits of policy implementation have also been explored [162]. In addition to improvements in uncertainty resolution, a research trend in financial analysis methods is an attempt to integrate abatement costs with the impact of climate policies to clarify the role of derisking policies, including carbon pricing and subsidies, which affect the cost of capital when incentivizing green-hydrogen low-carbon technologies [162].

Table 6. Economics of green-hydrogen emission reduction using financial analysis methods.

Ref.	Energy Sources	Baseline	Assessment Indicators	Time	Main Influencing Factors/Uncertainties	Decarbonization Chain
[113]	Solar energy	① SMR ② SMR with CCS	Carbon avoidance cost (CAC-1)	2030	① Natural gas–SMR levelized cost ② Natural gas–SMR process emissions ③ Location ④ PV capacity factor	Production
[149]	Renewable energy	SMR	Marginal cost of CO_2 removal	Now	① Renewable electricity potential ② LCOE	Production (Global)
[163]	Offshore wind	SMR	Carbon abatement cost (CAC-2)	Now	-	Production
[101]	① Wind energy ② Solar energy	SMR	LCCM	Now	① LCOE ② Electrolyzer technology ③ Capital cost ④ GHGE ⑤ Overall system efficiency ⑥ Weighted average cost of capital (discount rate) ⑦ Generation technology capacity factor	Production
[136]	Solar energy	SMR	GHG abatement cost (GAC-1)	Now	① Solar plant lifetime ② Solar irradiance ③ Solar to electricity efficiency ④ Electrolyzer efficiency	Production
[164]	Unspecified	Natural gas or gasoline fuel	CAC-1	Now	① GHG of different supply chains ② Grid CO_2 emissions factor ③ Transmission distance ④ HSC energy penalty ⑤ Landed cost of hydrogen	End-use: Multisectoral (transport, power, industry)
[165]	① Wind energy ② Solar energy	Fossil MeOH	CAC-1	2020–2035	① Large-scale PEM cost ② CO_2 certificate prices ③ LCOE	End-use: Synthetic methanol
[45]	① Wind energy ② Solar PV	①Natural gas ②Fossil fuels	MAC_{GHG} (fuel-switching CO_2 prices)	① 2020–2025 ② 2050	① Energy efficiencies ② Life cycle GHG emissions ③ Levelized cost and fuel-switching CO_2 prices of e-fuels	End-use: Multisectoral

Table 6. *Cont.*

Ref.	Energy Sources	Baseline	Assessment Indicators	Time	Main Influencing Factors/Uncertainties	Decarbonization Chain
[161]	Unspecified	Fossil fuels	CAC-2	Now	Capital expenditures ① Operational ② Exhaust aftertreatment ③ Financing ④ Additional Operational expenditures ① Fuel ② Maintenance ③ Carbon ④ Additional	End-use: Transportation (maritime)
[166]	① Wind energy ② Solar energy	① Pipeline imported natural gas ② Imported liquefied natural gas	GHG avoidance cost (GAC-2)	2020–2050	① GHG ② Cost	End-use: Synthetic low-carbon natural gas
[167]	Wind energy	Conventional oil refining	CAC-2	Now	① LCOE ② Penetration of renewable energies ③ Capital costs of wind farm	End-use: Oil refineries
[157]	① Wind energy ② Solar energy	Oil, gas, fossil fuels	LCCM	Now	① Capacity factor ② Capital cost ③ CO_2 resources price ④ Jet fuel price ⑤ Electricity price ⑥ Biomass price ⑦ Natural gas price ⑧ Input feedstock intensity ⑨ GWP of hydrogen	End-use: Synthetic fuel
[152]	① Wind energy ② Solar energy	Gasoline fuel	C_{GHG}	Now	① Renewable sources of electricity ② Hydrogen compression ③ Ratios in costs of electricity produced ④ Renewable natural gas costs	End-use: Transportation
[168]	Solar PV	Conventional natural gas fuel	CAC-1	Now	① PV size ② LCOH ③ Energy over-price ④ H_2 content	End-use: Natural gas system
[169]	Renewable energy	Conventional natural gas system	CAC-1	Now	① Natural gas price ② Electrolyzer operating time at full capacity ③ LCOE from RES ④ Injection configurations	End-use: Natural gas system

5.2.2. Bottom–Up Engineering Modeling Approach and Its Optimization Recommendations

Regarding decarbonization pathways for hydrogen applications in energy systems, using system modeling approaches based on engineering-based analytical data is common in the bottom–up models. A review based on global, multiregional, and national integrated energy system modeling showed that hydrogen generates higher MAC owing to the higher cost of hydrogen technologies [22]. Table 7 summarizes the typical literature on engineering modeling approaches for assessing the cost of green hydrogen abatement.

Janzen et al. [170] evaluated the GHG emission levels and MAC of renewable or low-carbon energy supply options as alternatives to conventional fossil energy technologies in oil sands using a long-range energy alternative planning system (LEAP). Wang et al. [156] used the levelized cost of carbon abatement as an indicator of the economic benefits of an urban hydrogen energy system with a multisectoral application using an engineering model to conduct system cost discussion and optimization. Davis et al. [171] investigated the GHG abatement potential and cost-effectiveness of blending hydrogen and natural gas for economy-wide end-use energy consumption based on the LEAP model in conjunction with an HSC model, considering a range of hydrogen production technologies, natural gas–hydrogen blending rates, infrastructure strategies, and carbon policies. Yang et al. [172] conducted a comprehensive dynamic least-cost modeling analysis of the role of clean hydrogen in hard-to-abate sectors, such as heavy industry and heavy transportation, using the multimodal prompt learning model, which encompasses the decarbonization potential and abatement cost of green hydrogen, demonstrating that clean hydrogen can be used as both a primary energy carrier and feedstock to significantly reduce carbon emissions from heavy industries. Zhang et al. [173] addressed hydrogen decarbonization pathways in multiple sectors of electricity, transportation, and heating, and abatement economics were discussed in multiple aspects with indicators such as total system cost, the absolute cost of abatement, and the marginal cost of abatement, and the impacts of technological learning, energy efficiency, natural gas prices, and renewable energy subsidies on abatement economics were analyzed in detail.

MAC curves can be optimized using the modeling tool EnergyPLAN [174,175]. The EPLANopt MAC, a methodology used to determine the least-cost decarbonization pathway for sectorally coupled energy systems, has been expanded and applied [176] and was used in the study of hydrocarbon economics of transitioning from natural gas-fired generation to 100% renewable energy generation [177]. Compared with financial analysis methods, engineering modeling methods are more accurate, have a smaller margin of error, and are more influential when used to guide policy [178]. Furthermore, green hydrogen carbon abatement cost modeling and optimization studies can be conducted based on the EPLANopt MAC methodology in conjunction with minimum MAC curves for carbon abatement strategies [179].

5.2.3. Economic Valuation of Emission Reductions Based on the SCC

One of the most important concepts in the economics of climate change is the SCC, which refers to the economic cost of each additional ton of carbon dioxide or its equivalent emissions. Estimates of the SCC are a measure of climate-policy objectives; however, there is uncertainty about the value of the SCC. Over the past 10 years, the estimated SCC has increased from USD 9 per ton of CO_2 to USD 40 per ton of CO_2 at a high discount rate and from USD 122 per ton of CO_2 to USD 525 per ton of CO_2 at a low discount rate [180].

Emission reductions from renewable energy substituting for fossil energy and residual renewable electricity electrolyzing hydrogen to replace fossil fuels were evaluated as alternatives by establishing an economic linkage through the profit gained from short- and long-term SCC concepts to assess the economics of emission reductions [181]. Specifically, for fuel cell commercial vehicles (FCCVs) in the transportation sector, the economic value model of life cycle carbon emission reduction was proposed by evaluating their life cycle carbon emission reduction benefits; the carbon emission reduction effect of the life cycle of FCCVs ranged from 14.53% to 70.19%, with an economic value of 0.02 to 1.19 RMB/kg H_2, which provides a scientific reference for the inclusion of hydrogen energy in China's carbon trading system, and policy provides a scientific reference [182].

Table 7. Economics of green hydrogen emission reduction using bottom–up engineering modeling approach.

Ref.	Energy Sources	Baseline	Assessment Indicators	Time	Main Influencing Factors/Uncertainties	Decarbonization Chain (End-Use)
[170]	① Wind energy ② Solar energy ③ Other low-carbon energy	Traditional technologies based on fossil energy	MAC_{GHG}	2019–2050	① Cost variance parameter ② Capital cost ③ Natural gas price ④ Industry growth ⑤ Carbon credit values	Refining (oil sands)
[138]	① Wind energy ② Solar energy	Fossil fuels	GAC-1	2050	-	Transportation
[156]	Solar energy	Conventional fossil energy	LCCM	Now	① Capital costs ② PV penetration level	Multisectoral (transportation, industry)
[173]	Unspecified	Fossil energy combustion	① Total system costs ② Absolute abatement costs ③ MAC	Now	① Technology learning ② Energy efficiency ③ Natural gas prices ④ Renewable energy subsidies ⑤ Carbon abatement	Multisectoral (electricity, transportation, heating, industry)
[172]	① Wind energy ② Solar energy	Traditional technologies based on fossil energy	CAC-2	2020–2060	① Green hydrogen production scale ② Green hydrogen blending ratio ③ Traditional technology scale	Multisectoral (cement, steel)
[171]	Unspecified	Baseline scenarios with different carbon prices	MAC_{GHG}	2021–2050	① Electrolysis learning rate ② Plant lifetime ③ Natural gas supply emission intensity	Natural gas blending systems
[183]	① Wind energy ② Solar energy	Baseline scenario for district heating	CAC-2	2040	① Share of hydrogen ② Overall efficiency of hydrogen boilers	Building heating

5.3. Insights into the Economics of Decarbonization Pathways in the Green Hydrogen Value Chain

The green hydrogen abatement costs for each decarbonization step in Tables 6 and 7 were extracted (Figure 8), and the different currency units were harmonized. In addition, the conditions for the energy sources, different baselines, and times were labeled accordingly.

The relatively higher abatement cost of green hydrogen from solar energy sources compared to wind power sources is partly due to the consideration of higher emission factors for solar power; the relative abatement is not as large as that for wind power, which is consistent with the results in the hydrogen production segment as well as in the continuation to the decarbonization application sector. In the time-scenario analysis, the abatement cost of the green hydrogen decarbonization pathway decreased substantially, considering the cost reductions due to technological advances. A comparison of the baseline scenarios shows that the natural gas fuel baseline has a higher abatement cost than the fossil fuel baseline, which is related to both the cleanliness and cost of natural gas, reflecting the role of natural gas in driving energy transition and economic issues.

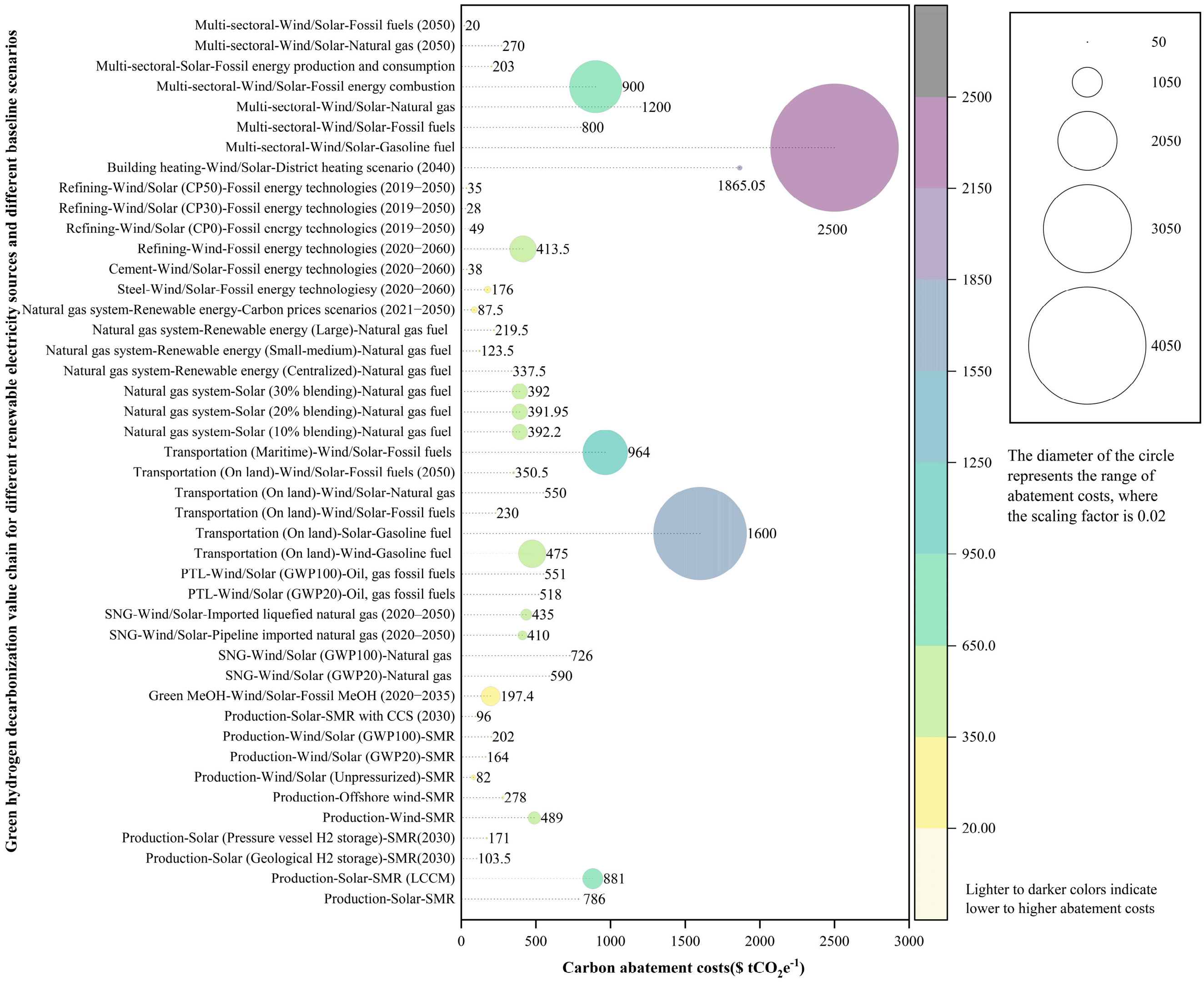

Figure 8. Analysis of abatement costs for different value chain systems. The circle's center represents the average carbon abatement cost, and the diameter represents the range of abatement cost changes.

Among decarbonization applications in hard-to-abate sectors, negative abatement costs occur for green methanol synthesis (USD −131.6 tCO_2e^{-1}) (2020–2035), natural gas systems (USD −16 tCO_2e^{-1}) (2021–2050), and refining (USD −41 tCO_2e^{-1}) (2020–2060). This study shows that abatement cost in the above sectors will reach zero by approximately 2030, indicating that it is competitive with the baseline scenario.

Moreover, the average abatement cost of the chemical sector for the green methane industry is less than USD 726 tCO_2e^{-1}; the average abatement cost of the iron and steel industry is USD 176 tCO_2e^{-1}, and the average abatement cost of the cement industry is USD 38 tCO_2e^{-1}; thus, prioritizing the green hydrogen decarbonization pathway is feasible for these three industries.

In addition, the abatement cost range for the transportation sector is large, with a range of USD 0–3200 tCO_2e^{-1} for land transportation, an average of USD 964 tCO_2e^{-1} for shipping, a maximum of USD 1733 tCO_2e^{-1} for shipping, and a range of USD 1776.8–1953.3 tCO_2e^{-1} for heating in buildings. The relative abatement costs of the transportation and building sectors are large, and the two sectors need to consider the timing of green hydrogen decarbonization applications and improvements in green hydrogen technologies as appropriate. Sectors must consider the timing of green hydrogen decarbonization applications and improvements in green hydrogen technology, where appropriate.

Notably, the green hydrogen-coupled multisector decarbonization application considers integrated system effects, and the research methodology modeling involves multipath combinations and different scenario settings, resulting in the widest range of abatement costs. The current abatement cost is USD 0–4700 tCO_2e^{-1}, with an average range of USD 203–2500 tCO_2e^{-1}. With technological advancements and integrated system optimization, the average abatement cost of the integrated multisectoral system decreases to USD 20–270 tCO_2e^{-1} under different baseline scenarios in the time-scenario analysis for 2050.

6. Trends in Green Hydrogen Emission Reduction Research

Based on the results of the analysis of phases II, III, and IV, we further explore and analyze the uncertainty of the assessment of carbon emission reduction and determine the trend and potential research direction of green hydrogen emission reduction research by combining the econometric analysis of the literature and the systematic evaluation method. Figure 9 is the authors' keyword co-occurrence network time series diagram with the evolution of the theme diagram after network analysis in BibExcel. Co-occurrence network graph Using Pajek and VOSviewer to visualize the analysis results, we created a co-occurrence network time series graph (Figure 9a) using the R language tool bibliometrix to analyze the literature, term deletion, and synonym list processing. The cut point of the time slice was based on the spatiotemporal characteristics of the literature, with 2015 and 2020 as two entry points, to derive the topic evolution data and construct a topic evolution map (Figure 9b).

6.1. Spatiotemporal Scenario Analysis to Address the Effects of Uncertainty

Carbon abatement costs have been applied as a reference indicator for the analysis and formulation of support policies for green and low-carbon technologies [50]; however, due to uncertainties, abatement costs have a limited impact on policy guidance. Table 8 is based on the collation of uncertainties in Tables 6 and 7. Considering technological changes and regional differences, technical recommendations and low-carbon development pathways have substantial biases in different countries [57]. The environmental and economic impact assessment of the green hydrogen value chain system, with full consideration of temporal technological progress or spatial and geographic differences as well as optimization studies, is a research trend that addresses the uncertainty of the benefits of green hydrogen carbon emission reduction.

6.1.1. Impact of Technological Advances over Time

The mitigation strategy with the lowest abatement cost of the currently available options is not necessarily the correct answer. Dynamic costs can better justify policy development for costly abatement technologies as learning-by-doing and technology improvement [184]. Green hydrogen abatement benefits are influenced by the rate of technology learning for renewable power generation and hydrogen production electrolyzers; a reasonable rate of technology learning significantly reduces the total cost and land area required to achieve deep abatement, largely owing to projected decreases in wind, solar PV, and electrolysis costs [173]. The combination of learning curve modeling and Monte Carlo methods effectively describes current changes in hydrogen production technology and uncertainties in technological progress [185].

In industrial chain applications, green hydrogen policy designs can be based on the cost trajectories of relevant future technologies [31]. For the application of fuel cell electric vehicles, the impact of learning-by-doing on abatement costs, the evolution of dynamic costs, the suboptimal trajectory of the "deployment" perspective, and the start-up date are discussed in terms of the impact of learning-by-doing on abatement costs, the evolution of dynamic costs, the suboptimal trajectory of the "deployment" perspective, and the start-up date to discuss the pathway of the green technology that is learning-by-doing to gradually replace the old technology [186]. The internalization of learning by doing has been emphasized in energy systems research. Exploring the potential of low-carbon and renewable hydrogen to decarbonize the European energy system allows for reducing endogenous costs based on deploying technologies in a dynamic programming formula for investment strategies [148]. Without dynamic "learning-by-doing" modeling of electrolysis costs, the scale-up of electrolysis is significantly delayed, the total system costs are overestimated by up to 13%, and the LCOH is overestimated by 67% [187].

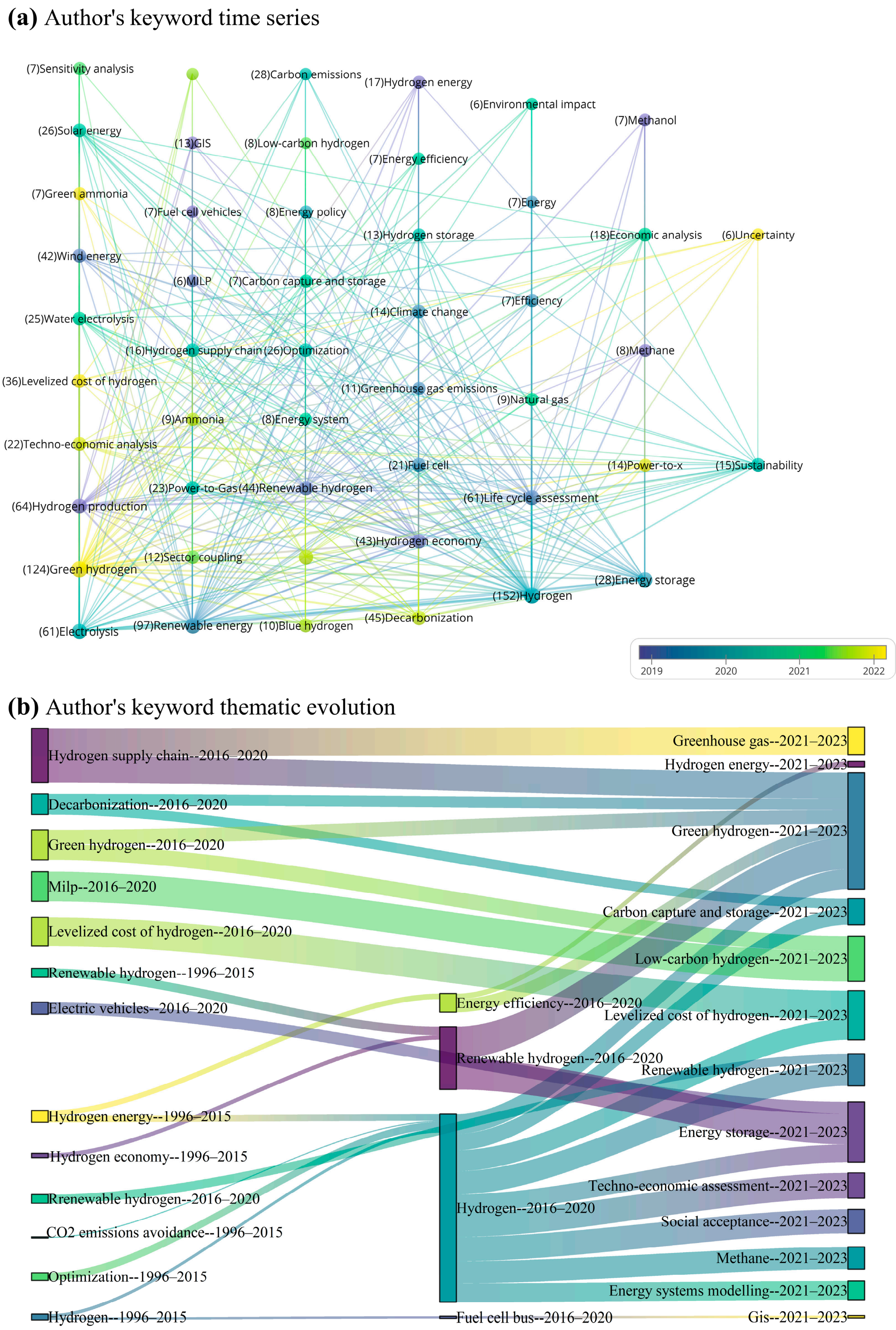

Figure 9. Author's keyword time series map and thematic evolution map. The numbers in parentheses before keywords in Figure 9a indicate the number of co-occurrences.

Table 8. Key uncertainties and solutions in green hydrogen carbon emission reduction assessment.

Categorization	Uncertainties	Solutions
Environmental analysis	• LCA methodology • Carbon accounting for green hydrogen systems • Emissions intensity of the power supply • Green hydrogen system value chain leakage rate • GHG of hydrogen	• Scenario analysis • Sensitivity analysis • Monte Carlo simulation
Technical and cost	• Technology learning (Electrolysis learning rate) • LCOE (LCOE from RES) • Capital and operational expenditures • Wind and solar energy generation technology capacity factor • Plant lifetime • Hydrogen compression • Transmission distance	
Energy resources, energy use, and conversion efficiency	• Resource conditions (land, minerals, water, etc.) • Production potentials of renewable electricity • Electricity and electrolyzer efficiency • HSC energy penalty • Penetration of renewable energies	
Energy markets and market demand	• Energy price (natural gas prices etc.) • Hydrogen prices • Market demand and response • Weighted average cost of capital (discount rate, etc.)	
Policy support	• Carbon price • Renewable energy subsidies • SCC	
Baseline, data sources, and scenario setting	• Baseline scenario • Data assurance • Scenario setting (temporal scenarios etc.)	
Tools for evaluating the cost of carbon emission reductions	• Methodological tools	

6.1.2. Impact of Spatial Geographic Variability

In comparing various options for decarbonizing industrial activities through metrics related to the levelized energy cost, it is argued that geographic and asset-specific factors play a role in selecting options [155]. The levelized abatement cost of green hydrogen based on the LCOE is also affected by geospatial factors because renewable energy generation capacity factors heavily depend on the location's climatic conditions and renewable energy resource distribution, and there is also spatial geographic variability in the demand and consumption of green hydrogen. Hydrogen infrastructure planning should consider multiple spatial constraints, and a high spatial resolution is required for system capacity expansion decisions to identify sites with high-quality renewable resources connected to demand centers [188,189].

Geographic information system (GIS) tools are the most commonly used tools in research on supply chain spatial optimization strategies [190]. It is mostly combined with MILP with the lowest cost as the optimization objective. It is used to help design and plan HSC networks under different CO_2 reduction policies [191]. Furthermore, based on the GIS approach and considering different scenarios of the supply chain and supply and demand sides, calculating the cost of the green hydrogen value chain system for a region is more realistic. This reduces the impact of uncertainty [192,193]. In addition, a study on integrating open-source tools for designing and evaluating green hydrogen production opportunities proposed a comprehensive four-tier framework that fully considers spatial geography and system integration optimization to compare green hydrogen production potentials and costs [194]. Similarly, complex energy system models increasingly require a high spatial resolution [195].

6.2. Multisectoral Synergies and Application of Abatement Assessment Metrics

6.2.1. Sectoral Coupling and Synergies

Sectoral coupling and synergistic effects are reflected in the supply of the electricity sector for renewable energy penetration at the source end of green hydrogen, the decarbonization of the green hydrogen end-use sector, and the synergistic decarbonization effects of multisectoral coupling at the supply and demand ends. Electricity–hydrogen sector coupling can accelerate technological learning, reduce the capital cost of solar PV by up to 4%, increase renewable energy penetration in primary power generation by nearly 5%, and reduce electricity curtailment by less than 5% by 2060 [196]. In assessing the role of green hydrogen in future energy transition scenarios, there is a trend for energy modelers and system planners to consider in more detail the unique flexibility characteristics of the HSC. For a higher share of RES or hydrogen, a more flexible but less energy-efficient large-scale HSC could benefit the power sector by reducing renewable energy power abandonment [197].

Wind–lithium–electron battery–alkaline electrolyzer–grid interactive coupled green hydrogen systems applied to steelmaking [106] and hybrid wind–PV–battery–hydrogen storage systems for residential power supplies [198] have achieved significant emission reduction benefits after economic and technical optimization and standardized sequencing. Considering the effectiveness of coupling the application-side demand with the power sector, renewable energy generation increases by 13–56%, and the total system cost decreases by 7–16% in deep decarbonization scenarios [112]. Moreover, in terms of the synergistic aspects of green hydrogen emission reduction, the synergistic effects of the byproduct oxygen used to reduce the cost of CCS in the decarbonization process of cement clinker production [199], the synergistic clean energy diffusion of green hydrogen, and the promotion of sustainable industrial development have also been verified [200].

6.2.2. Policy Application of Assessment Indicators

Green hydrogen abatement potential and abatement cost can be used as important reference indicators for the competitiveness of investment in green hydrogen production projects, the application of green hydrogen to decarbonize hard-to-abate sectors, and the promotion of green hydrogen to build a new type of zero-carbon energy system, which has a guiding role in the development of incentive policies, such as subsidies for green hydrogen projects, the inclusion of green hydrogen abatement in the carbon market, and the pricing mechanism of carbon-neutral hydrogen [20].

Green hydrogen abatement market mechanisms are similar to those of carbon markets and can be categorized into hydrogen price and quota mechanisms. Impact studies on the renewable hydrogen quota mechanism have shown that hydrogen quotas lead to a significant expansion of renewable energy generation capacity to produce renewable hydrogen and synthetic methane using electricity-to-gas technology and that the quotas lead to a redistribution of welfare from these consumers to renewable energy generators and natural gas producers, leading to a significant reduction in total welfare [201]. However, hydrogen-pricing mechanisms involve subsidy policies. Carbon contracts for difference (CFDs) have been used to practically apply green hydrogen [202] to provide cost-competitive supplies of green hydrogen in the transportation and industrial sectors, and sector-specific carbon taxes are needed [203]. Based on the emission reduction mechanism of clean hydrogen, a hydrogen credit trading framework, similar to carbon credits in the international market, was proposed to explore the incentives of the global hydrogen economy and develop new ways to achieve a carbon-neutral future [204]. Wang et al. [205] utilized system dynamics to model the "green hydrogen market–national carbon trading market–electricity market" relationship for modeling and simulation to enrich the green hydrogen trading model and establish a multimarket linkage mechanism.

Notably, at the whole value chain level, the HSC's carbon abatement strategy under a cap-and-trade policy [206] and a study of whole-system value-chain optimization [207] show that carbon abatement efficiency, the hydrogen price, and the carbon trading price have a significant impact on the optimal decision-making of production planning and carbon abatement and that policymakers must pay attention to the abatement benefits of each link of the whole-system value chain to advance incentive policymaking for hydrogen energy technologies.

7. Conclusions and Prospects

7.1. Conclusions

Through bibliometric analysis and systematic evaluation methods, this study systematically analyzes the research hotspots of the environment, technoeconomics, and energy systems that affect the benefits of carbon emission reduction from green hydrogen from the perspective of responding to climate change, discusses the assessment methods, assessment indices, uncertainties, and solutions of carbon emission reduction potential and carbon emission reduction cost, and analyzes the emission reduction effects of the green hydrogen value chain system and obtains revelations. Simultaneously, the trends and potential research directions for the economics of green hydrogen carbon emission reduction are proposed, and the following conclusions are drawn:

(1) After the Paris Agreement was officially signed in 2015, the decarbonization of green hydrogen began to gain attention, and green hydrogen climate change mitigation research expanded from 2020 to the present. Developed countries have clear scientific research strengths, excellent research results, and close partnerships. The application of decarbonization in sectors that have difficulty reducing emissions and the production of green hydrogen is the most important value chain research link; the most common green hydrogen decarbonization application sectors are the transportation, chemical, electric power, iron and steel, and thermal sectors, in which multisector coupling has become a research hotspot;

(2) The hotspots for research on green hydrogen carbon emission reduction are the three main impacts of the environmental, techno-economic, and energy system aspects that are closely related to it. Carbon emission accounting methods and system boundaries are currently not harmonized, and the GWP of hydrogen emissions and the impact of hydrogen leakage on the entire system value chain cannot be ignored. Hydrogen from renewable sources will soon be cost-competitive, with optimization models represented by MILP guiding economically optimal solutions for hydrogen decarbonization pathways. However, the cost of decarbonizing green hydrogen in an energy system is controversial. The key to renewable energy intermittent solutions lies in optimizing system configurations,

and the energy utilization and conversion efficiency of the green hydrogen value chain system constrains the economics of green hydrogen carbon abatement. The multiobjective optimization of the expansion of the hydrogen production system can improve the economic value of green hydrogen abatement;

(3) Based on the characteristics of the hydrogen energy value chain, the methodology for assessing the potential for green hydrogen carbon emissions reduction and the cost of carbon emissions reduction mainly adopted a bottom–up analysis model. Green hydrogen carbon emission reduction, which includes carbon avoidance and a carbon-embedded carbon cycle, has great potential; however, there is no perfect emission reduction methodology or economic assessment system for emission reduction to support incentive policies. The indicators and factors affecting the potential for green hydrogen carbon emissions reduction vary along the value chain, and the research process should clarify the use of indicators and scientifically consider the impact of uncertainties. Many uncertainties constrain the role of green hydrogen carbon abatement cost indicators in guiding policies, primarily based on financial analyses. The bottom–up engineering modeling approach can be further improved by considering the characteristics of the hydrogen value chain. To a certain extent, the economic value assessment method of emission reduction based on the SCC promotes the integration of green hydrogen carbon emission reduction with carbon market mechanisms;

(4) The emission reduction effect of green hydrogen decarbonization varies greatly, with renewable power sources, time scenarios, and baseline scenarios being the main influencing factors. The economic impact of emission reduction should be fully considered when promoting the application of green hydrogen. In the application of decarbonization in sectors that have difficulty reducing emissions, green methanol, natural gas systems, and the refining industry have the prospect of prioritizing the application of green hydrogen, as the cost of emission reduction will be zero by 2030 and will be negative in future scenarios. The steel and cement sectors can also prioritize green hydrogen decarbonization applications. The transportation and construction sectors have relatively large abatement costs, and multisector abatement applications have the widest range of abatement costs, considering the integrated system effects and the large number of pathways and technology combinations involved;

(5) The trend of research on green hydrogen carbon emission reduction is, on the one hand, the improvement of its methodological model, especially the solution of uncertainty factors, and on the other hand, the synergistic expansion of green hydrogen emission reduction and the applied research of assessment indicators. Time-technological progress and spatial–geographical variability are research trends and potential directions for addressing the uncertainty in assessing the benefits of green hydrogen emissions reduction. The expansion of green hydrogen system-wide value chain emission reduction involves the synergistic effect of its value chain and the co-benefits of sustainable development and other social benefits. Indicators for assessing the benefits of green hydrogen emission reductions are widely used, and policymakers should focus on the benefits of emission reductions in all parts of the system-wide value chain to guide the development of incentive policies for green hydrogen energy technologies.

7.2. Research Prospects

Through this systematic review, the following problems exist in the study of abatement potentials and economics for climate change mitigation in the green hydrogen total value chain system, and a research outlook is proposed based on these problems:

(1) Study on the Emission Reduction Effect of Green Hydrogen Scale-up Transition Based on top–down integrated assessment modeling. Studies based on the bottom–up approach models to analyze the abatement effects of green hydrogen in the decarbonization sector and integrated energy systems have been gradually conducted and have served as a guide for green hydrogen promotion. To achieve carbon neutrality, there is a lack of research on the comprehensive impacts of green hydrogen energy scaled up from an

emission reduction perspective at the national, regional, and global levels. Top–down integrated modeling can compensate for this lack of research, and macroinput–output modeling studies can also reflect the interactions between the scale-up of green hydrogen developments in different regions;

(2) Research on market mechanisms and international trade impacts based on the green hydrogen carbon emissions reduction methodology. The green hydrogen carbon emission reduction methodology involves basic carbon accounting methods, baseline scenarios, additionality, and other research issues, and a scientific and reasonable methodological system must be established. The definition of the green hydrogen standard has never stopped being debated in many countries or organizations worldwide, and the market or policy application of the green hydrogen emission reduction methodology and emission reduction targets also needs further research. At the same time, as an energy carrier and as a secondary energy source, the impact mechanism of energy prices and carbon tariffs between countries also needs to attract the attention of scholars;

(3) Research on global or regional co-benefits, such as the ecological and social benefits of green hydrogen emissions reduction and sustainable development, should be conducted. While addressing the environmental, economic, and energy dimensions, the potential and economics of emission reduction do not encompass the broader impacts of climate change mitigation. The scaled-up development of green hydrogen is also expected to generate synergies or co-benefits with global or regional ecological and social dimensions. In addition, the sustainable development of green hydrogen is an important future research direction.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su16114602/s1. Table S1: Top 11 most productive journals during 1996–2023; Table S2: Top 13 most productive institutes in research during 1996–2023; Table S3: Top 14 most productive authors in research during 1996–2023. Figure S1: Top 20 author's bibliographic coupling.

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Abbreviations

ALK	**Alkaline**
CAC-1	Carbon avoidance cost
CAC-2	Carbon abatement cost
CCS	Carbon capture and storage
CDM	Clean Development Mechanism
CFDs	Carbon contracts for difference
FCCVs	Fuel cell commercial vehicles
GAC-1	GHG abatement cost
GAC-2	GHG avoidance cost

GHG	Greenhouse gas
GHGE	Greenhouse gas emission intensity of electricity
GIS	Geographic information system
GWP	Global Warming Potential
GWP100	The 100-year global warming potential
HSC	Hydrogen supply chain
IEA	International Energy Agency
IF	Impact factor
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCCM	Levelized cost of carbon mitigation
LCOE	Levelized cost of energy
LCOH	Levelized cost of hydrogen
LEAP	Long-range energy alternative planning system
MAC	Marginal abatement cost
MILP	Mixed integer linear programming
PEM	Polymer electrolyte membrane
PTG	Power-to-gas
PTL	Power-to-liquids
PTX	Power-to-X
PV	Photovoltaic
RCP	Representative concentration pathway
RES	Renewable energy sources
SCC	Social cost of carbon
SCIE	Science Citation Index Expanded
SDGs	Sustainable development goals
SMR	Steam methane reformation
SSCI	Social Science Citation Index
WOS	Web of Science

Appendix A

Table A1. Principles and results of the literature extraction, purification, and review.

Steps	Principles	Results	Description
Develop a search string to ensure that all relevant papers are extracted	TS = (“Renewable hydrogen” OR “Green Hydrogen” OR “Low Carbon Hydrogen” OR “Electrolytic water Hydrogen” OR “Clean Hydrogen” OR “Hydrogen*”) AND TS = (“Climate Change “OR “Energy transition” OR “Climate* Change Mitigation “OR “decarbonization*” OR “Environmental*”OR “Carbon*Reduction” OR “Sustainability” OR “Emission* reduction”) AND TS = (“ Abatement Costs” OR “benefit” OR “Economy* “OR “Cost*” OR “Cost effectiveness”)	Extracted 7060 documents from 1996 to June 2023	The field label TS (=Topic) containing the title, abstract, and keywords is used to create the query, and was created on 17 August 2023. The earliest publication in the literature that matched the research topic search is 1996, so the timeframe begins in 1996. The deadline is 30 June 2023. The research language and type are restricted to ‘English’ and ‘Article’, respectively.
The literature purification	WC = (Energy Fuels or Environmental Sciences or Green Sustainable Science Technology or Engineering Environmental or Environmental Studies or Economics or Meteorology Atmospheric Sciences or Operations Research Management Science or Management or Behavioral Sciences or Urban Studies or Social Sciences Interdisciplinary or Political Science or Development Studies or Construction Building Technology or Ecology or Social Issues or Business Finance) AND SC = Energy Fuels or Engineering or Environmental Sciences Ecology or Science Technology Other Topics or Business Economics or Meteorology Atmospheric Sciences or Behavioral Sciences or Development Studies or Operations Research Management Science or Social Issues or Social Sciences Other Topics	Access to 4189 published documents	
The literature review	The researchers conducted a full-text review of each of these studies, excluding irrelevant studies.	706 publications were screened for relevance to the research topic	

Table A2. Information on the literature on the economics of green hydrogen carbon emission reductions, 1996–2023 (as of 30 June 2023).

The Literature	Data
Timespan	1996:2023
Sources (Journals)	97
Documents	706
Annual growth rate %	19.17
Document average age	2.76
Average citations per doc	29.51
References	31,621
Authors' keywords (DE)	1815
The sum of the times cited	20,836
Authors	2359

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