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Review

Green Certificates Research: Bibliometric Assessment of Current State and Future Directions

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Abstract: In recent years, sustainability initiatives and the prominence of renewables have emerged as pivotal priorities in addressing environmental, ecological, and socioeconomic challenges. Within this context, green certificates—representing proof of electricity generation from renewable sources—have gained substantial recognition, enabling organizations to demonstrate their commitment to clean energy. This study employs a bibliometric analysis to chart the evolution and current state of green certificates research. Drawing from the Scopus database, we sourced bibliographic data, resulting in a refined dataset of 940 documents spanning from 2000 to 2022. Through performance analysis, we systematically evaluated the landscape of green certificates research, assessing publication trends, identifying influential works, spotlighting prolific authors, highlighting leading academic institutions, mapping regional research hotspots, and pinpointing the top publishing journals in the domain. Employing science mapping techniques—such as co-authorship networks, keyword co-occurrence analysis, and bibliographic coupling—we delineated the collaborative patterns and the conceptual and intellectual structure of the field. This was further augmented by content analysis, revealing four salient research themes, emphasizing the consistent and central focus on support mechanisms and policies for renewable energy sources, sustainable renewable technologies and market dynamics, technological innovations and green certificate trading, and renewable energy sources investment strategies. Building on these findings, the paper concludes by outlining practical implications and prospective research avenues. These encompass a detailed understanding of renewable energy support mechanisms, the pivotal role of electricity disclosure in enhancing transparency, and the transformative potential of emergent technologies, such as artificial intelligence and blockchain, in the green certificate trading landscape. The research also emphasizes the fundamental role of guarantees of origin in advancing sustainability goals, the dynamic discourse on green hydrogen certification standards, and the intricate dynamics of trading mechanisms in shaping investment strategies.

Keywords: renewable energy; green certificates; sustainability; guarantees of origin; renewable portfolio standard; feed-in tariff; power purchase agreement; renewable gas certification; blockchain; bibliometric analysis

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1. Introduction

Over the past decade, the push for companies to adopt sustainable practices in response to environmental concerns has intensified significantly [1]. As a result, sustainability has emerged as a central theme in addressing various environmental, ecological, and socioeconomic issues, prompted by growing awareness of environmental degradation, climate change, resource scarcity, and other challenges [2].

Green certificates, in particular, have gained significant prominence in sustainability discourse, as organizations increasingly acknowledge the critical role of transparency in electricity sourcing and the numerous benefits associated with purchasing green electricity products [3]. These certificates serve as tradable instruments that represent proof that a specific amount of electricity was generated using renewable energy sources [4–6]. In

addition to being held by organizations to demonstrate their commitment to clean energy and efforts to reduce their carbon footprint, green certificates also enable renewable energy producers to sell their guarantees on voluntary markets [7,8]. This allows buyers to use them as evidence of the 'greenness' of their consumed electricity, further enhancing the transparency and reliability of renewable energy claims [9].

The concept of green certificates has evolved to encompass two primary use cases. Firstly, they serve as regulatory support instruments to incentivize the adoption and use of renewable energy sources, particularly in the electricity sector [10,11]. This was initially observed in the early years of renewable energy policy development. Secondly, and more recently, green certificates are used for disclosure purposes, allowing producers of renewable energy to provide verifiable proof of the renewable origin of their electricity [12,13]. Consequently, this mechanism allows consumers and organizations to consciously select energy sources that align with their sustainability goals, thereby enhancing transparency within the energy market [3].

Initially emerging within the European Union (EU) and the United States (US) energy markets, the concept of green certificates rapidly expanded its influence globally. A European Commission [14] white paper was a pivotal moment, signaling a strong commitment to renewable energy as a strategy to address climate change and bolster energy security. With the increasing adoption of renewable energy sources, the EU engaged in a critical debate on the most effective support instruments for boosting renewable electricity uptake. This debate primarily focused on quota obligations with tradable green certificates—a quantity-based approach specifying renewable energy production or consumption quotas—and the feed-in tariff system, a price-based model guaranteeing fixed payments for grid-supplied renewable energy [15–18]. Both methods initially saw widespread adoption, but their popularity fluctuated due to changing market dynamics and shifts in policy objectives [19]. The adoption by the EU of Directive 2001/77/EC in 2001, which introduced the guarantees of origin system, marked a significant milestone, playing a crucial role in verifying the renewable origin of power and establishing a foundation for more robust renewable energy policies across Europe [20]. The Directive 2009/28/EC furthered this initiative by incorporating provisions to standardize renewable energy sources policy through guarantees of origin trading [21]. In the US, the late 1990s marked the emergence of renewable energy certificates to stimulate renewable energy development via market-driven mechanisms, with Iowa establishing the first statewide program in 1999 for issuing certificates per megawatt-hour of renewable electricity [22]. Texas followed in 2001 with a similar initiative, contributing significantly to the growth of the state's wind power market [23]. While these developments in the US evolved independently, they paralleled EU quota obligations, culminating in the US adopting renewable portfolio standards—a strategy with similar objectives of promoting renewable energy integration into state electricity portfolios [24,25].

Following these developments, countries such as China, Australia, South Korea, India, and others initiated their unique green certification schemes. In China, long-standing challenges associated with subsidy payments for wind and solar feed-in tariffs, prevalent since the 1990s, reached a pivotal moment around 2010 with the implementation of more structured subsidized feed-in tariffs [26]. By 2017, China had advanced to a new phase, introducing its Green Electricity Certificate system to bolster wind and solar energy. This move represented a significant paradigm shift, from a reliance on subsidized feed-in tariffs to embracing a market-oriented approach [27]. In parallel, Australia, South Korea, and India also established renewable energy certificate systems. These systems were instrumental in advancing renewable energy development, thereby contributing to a more sustainable energy landscape in these nations [28–30].

As the renewable energy sector expanded, the associated mechanisms and practices of green certificates evolved to align with the dynamic needs of diverse energy markets and policy environments. In the EU, this evolution was evidenced by the continuous updating of renewable energy directives. Notably, significant amendments were made in 2018 with

the Renewable Energy Directive II (RED II) and further in 2023 with RED III. These revisions underscored the commitment of the EU to increasing its share of renewable energy and integrating green certificates more comprehensively into broader energy strategies, such as power purchase agreements [31–33]. In the US, a landmark development occurred with the enactment of the Inflation Reduction Act of 2022. This Act represents the most significant climate legislation in US history, establishing a comprehensive framework for investing in a broad spectrum of programs designed to incentivize clean energy initiatives. This legislative action reflects a strategic shift towards more aggressive climate action and sustainable energy practices [34,35]. Meanwhile, in China, the incorporation of green certificates into the national energy consumption quotas by 2023 marked a substantial shift in policy. This integration represents China's response to the rapid growth and evolving complexities within its renewable energy sector, signaling a move towards more flexible and responsive policy frameworks to accommodate the accelerating pace of change in energy technologies and market demands [36].

The evolution of green certificate mechanisms reflects broader global shifts in environmental and energy strategies, expanding beyond their initial focus on electricity sector incentives to include other sectors, such as green gas production [37]. This expansion not only demonstrates the versatility of green certificates as a policy tool but also underscores their significance in fostering the generation and use of green gases. Alongside this, the role of green certificates in enhancing disclosure and transparency has become increasingly prominent, particularly following the liberalization of electricity retail markets [38]. This evolution empowers consumers to make informed decisions grounded in the sustainability credentials of their energy providers, thereby catalyzing the demand for renewable energy [39]. Furthermore, the synergy between electricity disclosure and tradable green certificates has been pivotal in providing reliable information about the origin of electricity supply, fostering consumer trust and actively engaging them in renewable energy markets [13].

All the above are mirrored in the expanding body of literature on green certificates, reflecting a growing scholarly interest in this field. The complex interactions between various policy incentives and their collective impact on the growth of the renewable sector are key subjects of inquiry [40–44]. The literature also investigates the effectiveness of market-based instruments and policy frameworks, such as tradable green certificates and renewable portfolio standards, in fostering renewable energy integration and promoting equitable and efficient market operations [45–47]. The convergence of blockchain and other digital technologies with green certificate systems is another significant area of focus, revealing a potential for increased efficiency and transparency in sustainable energy practices [48–50]. Furthermore, the research examines the strategic behaviors of market participants, the economic implications of green certificate trading, and the decision-making processes in energy markets [51]. Lastly, the role of green certificates as a catalyst for investment in renewable energy, influencing both market stability and the strategic direction of energy portfolios, is thoroughly explored, providing insights into the economic and policy factors driving the renewable energy transition [52–54].

In light of the rising importance of green certificates, this study seeks to explore the evolution of the literature on this topic, aiming to identify the current state, research clusters, and future research directions. By conducting a thorough examination of publication patterns and citation development in articles pertaining to green certificates up to the end of 2022, we aim to provide valuable insights for academics, policymakers, and industry practitioners interested in understanding the progress and potential of this vital sustainability instrument.

In our endeavor to comprehensively understand the academic landscape surrounding green certificates, we sought to delineate the foundational pillars of this domain. By examining the trajectory of publications, the impact of individual works, and the contributions of authors, institutions, countries, and journals, we aimed to capture a holistic view of the

field's evolution and its key research constituents. Thus, our first six research questions (RQ) are as follows:

RQ 1. *What are the current publication and citation trends in green certificates research?*

RQ 2. *Which are the most influential publications in green certificates research?*

RQ 3. *Who are the most prolific authors of green certificates research?*

RQ 4. *Which are the most prolific institutions publishing research on green certificates?*

RQ 5. *Which are the most prolific countries publishing research on green certificates?*

RQ 6. *Which are the top publishing journals for green certificates research?*

Building on the foundational understanding, we then delved deeper to uncover the collaborative dynamics within the green certificates domain. Recognizing the importance of collaborative efforts in advancing research, we sought to map out the existing collaborative networks. Furthermore, to gain a comprehensive understanding of the field, we aimed to discern both the conceptual and intellectual structures that underpin the vast body of literature on green certificates. Thus, our next three research questions are as follows:

RQ 7. *What is the current state of collaboration in green certificates research?*

RQ 8. *What is the conceptual structure of the green certificates field?*

RQ 9. *What is the intellectual structure of the green certificates field?*

Recognizing the ever-evolving nature of the green certificates field of research, we aim to spotlight areas for future exploration. These emerging areas hold the potential to significantly influence the direction of upcoming research in this domain. Thus, our last research question is as follows:

RQ 10. *What are the prospective avenues for advancing research in the green certificates domain?*

This study marks a significant advancement in green certificates research by offering the first comprehensive bibliometric analysis encompassing a multifaceted exploration of the field's evolution, current state, and future directions. Our approach systematically examines the trajectory of publications, impacts of seminal works, and contributions across various academic dimensions, thereby providing a panoramic view of the field's development. Unique to our research is the intricate mapping of collaborative networks and the elucidation of both the conceptual and intellectual structures of the green certificates literature. This dual analysis of collaboration and intellectual discourse in the domain is a distinctive contribution, offering an enriched understanding of how different research facets interconnect. Further, our study identifies and delineates emerging research themes, setting a new trajectory for future inquiries in the field.

The structure of this study is as follows: Section 2 presents our research methodology, detailing the bibliometric approach used to analyze and map the green certificates domain. Section 3 delves into a performance analysis, examining key research constituents like articles, authors, institutions, countries, and journals within the green certificates research landscape. Section 4 elucidates the cooperative relationships and dynamics in the green certificates field by constructing co-authorship networks, both at the author and country levels. Section 5 delves into a keyword co-occurrence analysis, aiming to discern the conceptual network structure within the green certificates research domain. This section thoroughly maps the structure of topics, emphasizing the interconnectedness of keywords and their significance in representing the primary themes of the field. Section 6 employs a bibliographic coupling analysis to map the intellectual structure of the green certificates research domain, grouping articles into thematic clusters based on shared references, thereby highlighting intellectual similarities and core subjects within the field. Section 7 presents the emerging research themes in the green certificates field, articulating their distinct characteristics and

historical context, as well as aligning them with the specific use cases of green certificates. Section 8 delineates prospective avenues for further exploration within the green certificates domain, spotlighting underexplored areas and emergent inquiries. Section 9 concludes the study by synthesizing the key findings from the bibliometric analysis and discussing the broader implications for academics, policymakers, and industry practitioners. The section also highlights the study's contributions and potential avenues for future research while acknowledging its limitations.

2. Research Methodology

Bibliometrics, rooted in library and information sciences, employs quantitative methods to study and analyze bibliographic material, offering a comprehensive lens to trace the knowledge anatomy of a research domain [55,56]. This analytical approach, extensively practiced and recognized for its efficacy, delves into large sets of aggregated bibliographic data, such as published journal articles and their citations, to identify major themes, thematic shifts, and the overarching structure of a given research field, while also pinpointing current trends and potential future research avenues [57–59]. In the subsequent subsections, we elucidate the data collection process and delve into the specific data analysis methods employed in our bibliometric analysis.

2.1. Data Collection

For the bibliometric analysis of green certificate publications, this study sourced bibliographic data from Elsevier's Scopus database, a leading repository of peer-reviewed literature [60]. Given its widespread recognition and frequent utilization in quantitative analyses [57,61–63], Scopus emerges as an apt choice for this study.

The search process for the bibliometric analysis was conducted in March 2023, using an open starting time to comprehensively capture publications up to December 2022. To ensure the inclusion of full-year data, articles from 2023 were excluded. The earliest relevant article identified dated back to 2000. Informed by the methodologies of Andersen [57], Baker et al. [64], and Mustak et al. [65], our selection of search terms drew from established literature on the topic. We identified several terminologies that the literature employed interchangeably with "green certificates". Consequently, our search string encompassed terms such as "green certificate*", "renewable energy certificate*", "guarantees of origin", and "energy attribute certificate*". Utilizing the "title, abstract, keywords" search function within the Scopus database yielded 1019 documents. This collection comprised 650 articles, 221 conference papers, 63 reviews, 49 book chapters, 17 notes, 6 books, 5 short surveys, 4 conference reviews, 2 errata, and 2 editorials. Echoing the approach of Donthu et al. [61], we initially considered the entirety of these documents. Since we used only one search string, we did not encounter duplicate entries. Subsequently, two co-authors independently reviewed the abstracts, referring to the full text when the relevance was ambiguous, as suggested by Goyal and Kumar [66], Pizzi et al. [67], Vallaster et al. [68], and Xu et al. [63]. This thorough screening refined our dataset, excluding 79 documents deemed outside the study's scope. Our finalized database for analysis consisted of 940 documents, including 597 articles, 203 conference papers, 62 reviews, 43 book chapters, 17 notes, 6 books, 5 short surveys, 4 conference reviews, 2 errata, and 1 editorial. Throughout this phase, we diligently rectified errors and inconsistencies, aligning with best practices highlighted by Pizzi et al. [67].

2.2. Data Analysis

Within bibliometrics, two primary procedures emerge for investigating a research domain: performance analysis and science mapping [69]. Performance analysis evaluates both the productivity and influence of scientific contributors [67]. Productivity is quantified by the volume of publications within a specified timeframe, while influence is assessed by the frequency with which these publications are cited by peers [60]. Science mapping is a bibliometric procedure that visualizes and analyzes the structural and dy-

namic relationships of knowledge within a research field [67]. It employs various graphical representations, such as networks or clusters, to depict the connections between topics, authors, institutions, countries, and journals. By doing so, science mapping offers insights into the main research areas, emerging trends, and the evolution of a field over time. This method aids researchers in identifying key themes, influential works, and potential gaps in the existing literature [57,60,69].

To answer research questions 1 to 6, this study employs performance analysis to systematically evaluate the landscape of green certificates research. We begin by assessing the publication and citation trend in green certificates, aiming to chart the growth trajectory and assess the evolving interest in this domain over time (RQ 1). Our examination of citation counts and patterns leads us to identify the most influential publications on green certificates, spotlighting seminal works that have been pivotal in shaping the field (RQ 2). Further, our analysis extends to individual contributions, allowing us to pinpoint the most prolific authors who have consistently enriched and driven discourse in this area (RQ 3). Venturing into institutional affiliations, we shed light on the academic hubs that are at the forefront of green certificates research (RQ 4). Mapping the geographical distribution of these publications, we gain insights into the most active countries, revealing regional research hotspots (RQ 5). Concluding our analysis, we turn our attention to the outlets of dissemination, identifying the top publishing journals on green certificates (RQ 6).

To address RQ 7, concerning the current state of collaboration in green certificates, we employ science mapping methods, specifically devising co-authorship networks at two distinct levels: authors and countries [60,61,64,70]. This approach enables us to visualize and understand the collaborative dynamics and partnerships that have been instrumental in shaping the discourse on green certificates.

For RQ 8, which seeks to elucidate the conceptual structure of the green certificates field, we employ keyword co-occurrence analysis [57,64–66]. This method, rooted in discerning the conceptual network structure within a research domain, is pivotal in mapping the structure of topics within the green certificates field. By conducting a co-occurrence analysis of keywords extracted from pertinent published works, we are able to identify and categorize distinct thematic clusters that define this knowledge domain.

Turning to RQ 9, which examines the intellectual structure of the green certificates field, we build upon the concept of bibliographic coupling [61,66,67,71]. By grouping articles into thematic clusters, we map the intellectual structure of the green certificates research domain. Specifically, we restrict our bibliographic coupling to articles published from 2020 to 2022, ensuring a chronological context and congruent reference base. This method complements and enriches the insights derived from the keyword co-occurrence analysis, as highlighted by Andersen [57].

To delve deeper into the insights provided by both keyword co-occurrence analysis clusters and bibliographic coupling clusters for RQ 8 and RQ 9, we employ content analysis as a methodological tool. Content analysis, a systematic and objective means of analyzing and interpreting textual information, allows us to extract meaningful patterns and themes from the clusters. By coding and categorizing the content within each cluster, we are able to discern the underlying narratives, trends, and nuances that might not be immediately evident from a surface-level examination. This detailed analysis provides a richer understanding of the conceptual and intellectual structures of the green certificates field.

Lastly, in addressing RQ 10, our focus shifts to the prospective avenues for advancing research in the green certificates domain. Having discerned the major research themes within the green certificates domain—substantiated by both bibliographic coupling and keyword co-occurrence analyses—we embark on delineating prospective avenues for further exploration. Content analysis plays a pivotal role in identifying prospective avenues for research. By analyzing the content of the most prominent and emerging themes within the green certificates domain, we are able to pinpoint areas that have been under-researched or hold potential for novel contributions. This methodological approach ensures that our recommendations for future research are not only rooted in the existing body of knowledge

but also are oriented towards areas of maximum potential impact and relevance in the evolving landscape of green certificates research.

The performance analysis was carried out mostly using MS Excel 2021, whereas science mapping was conducted using the VOSviewer software v.1.6.19 [72]. Specifically, VOSviewer offers a suite of tools tailored for bibliometric mapping and network visualization [73]. For co-authorship networks, VOSviewer aggregates data to visualize connections between authors, highlighting the intensity and frequency of collaborations. In the realm of keyword co-occurrence analysis, the software identifies and maps the relationships between frequently paired keywords, offering a visual representation of dominant themes and their interconnections within the green certificates research. Lastly, when applied to bibliographic coupling, VOSviewer clusters documents that share common references, thereby revealing the intellectual heritage and thematic groupings of the literature. Through these functionalities, VOSviewer provides a holistic and intuitive visualization of the intricate relationships and patterns inherent in the research domain [61,68,70,71].

Figure 1 illustrates our study's research design.

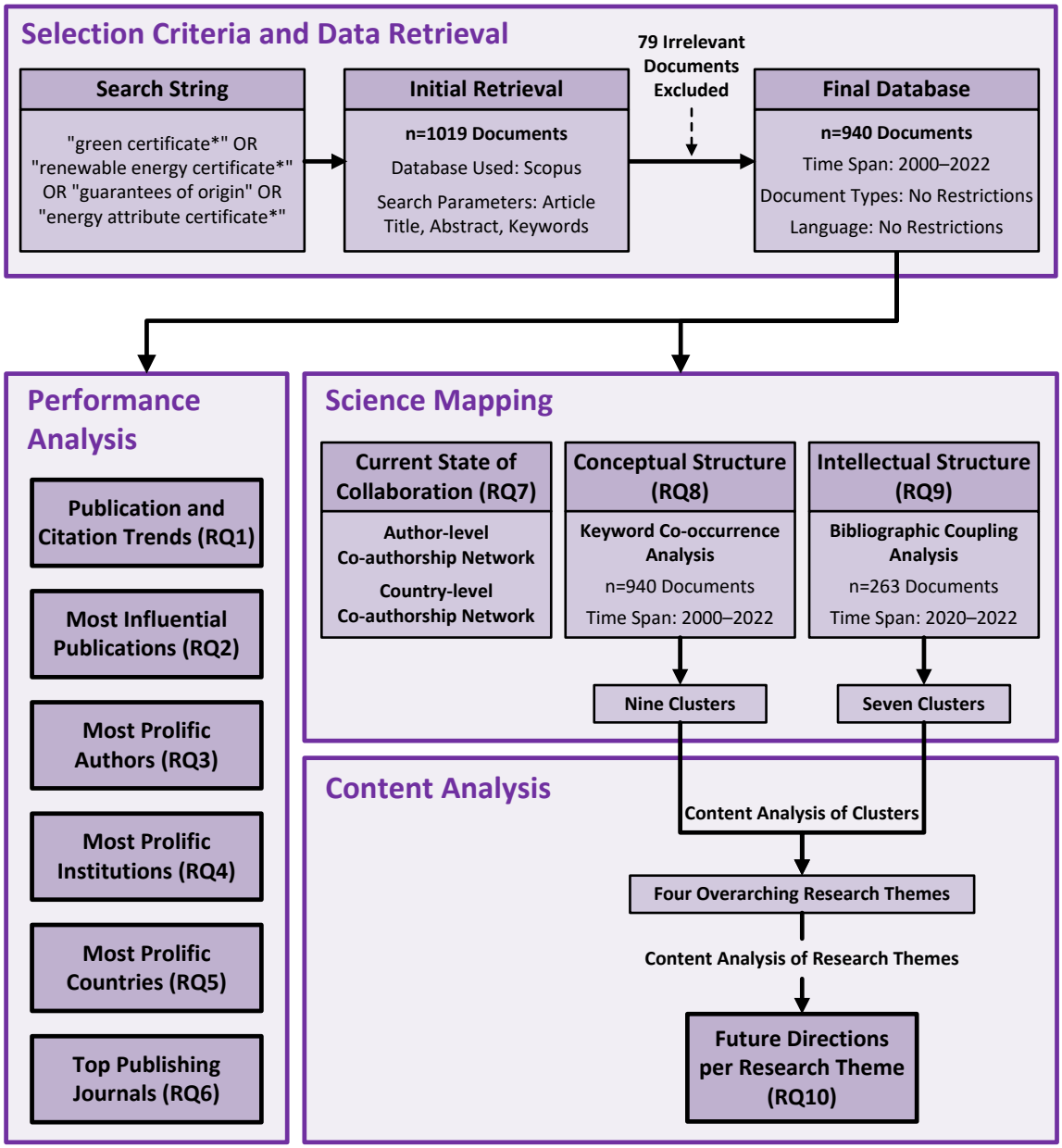

Figure 1. Research design.

3. Performance Analysis

In this section, we commence a comprehensive exploration of the major research constituents within the realm of green certificates research: articles, authors, institutions, countries, and journals. Our analysis is underpinned by a suite of generic metrics, prominently featured in the accompanying tables, such as the total number of publications, total citations, and average citations per publication. To provide a comprehensive understanding tailored to the unique characteristics of each constituent, we also incorporate case-specific metrics. For instance, when evaluating countries, we consider the total number of publications in relation to the country's population, expressed in millions. For journals, we reference both the impact factor and the Scimago journal rank. To quantify the impact of each constituent, we employ the h-index and g-index, further categorizing contributions based on citation thresholds: 100, 50, 10, and 5 citations per publication. Additional metrics, such as the average publication age, which denotes the mean age of individual publications, and the annualized citation rate, which calculates the average number of citations earned per year since publication, further enrich our analysis. In the subsequent subsections, we delve deeper, presenting a detailed analysis of each research constituent, offering a holistic view of the green certificates research landscape.

3.1. Annual Publications and Citations

Table 1 presents the annual publication and citation structure, while Figure 2 illustrates the growth trends of publications and citations per cited publication over a 23-year period (2000–2022). The first article on green certificates appeared in 2000, and since then, the publication trend has followed an exponential growth trajectory ($y = 10.674e^{0.0952x}$; $R^2 = 0.8584$), consistent with the second phase of Price's law, which examines the growth of scientific publications within a specific research domain [74]. With an average of 40.87 articles per year, the number of publications increased from 6 in 2000 to 101 in 2022. The average annual growth rate of publications, calculated using the Compound Annual Growth Rate formula, is 15.64%. Remarkably, 67% of the total articles (630 out of 940) were published within the last decade (2013–2022), and 41% (387 out of 940) emerged in the past five years (2018–2022). This sharp increase in publications after 2010 corresponds to the growing significance of renewable energy and sustainable practices in addressing climate change and facilitating the transition to a low-carbon economy. In terms of quantity, 2022 proved to be the most productive year with 101 publications, reflecting the field's contemporary relevance in light of the evolving renewable energy landscape. The year 2003 was the most influential, garnering 1549 citations and an average of 57.37 citations per publication. By the end of 2022, the cumulative total citations per cumulative total publications reached 16.98. The h-index peaked at 17 for articles published in 2017, indicating that 17 articles published that year received at least 17 citations each. The g-index reached its apex in 2012, with 31 publications cited at least 961 times, equating to 31 squared. Of the 940 articles, 28 (2.98%) accumulated at least 100 citations, 81 (8.62%) were cited a minimum of 50 times, 327 (34.79%) received at least 10 citations, 433 (46.06%) garnered a minimum of 5 citations, and 704 (74.89%) were cited at least once between 2000 and 2022.

Table 1. Annual publication and citation structure between 2000 and 2022.

Year	TP	CP	TC	ACR	C/P	C/CP	*h*	*g*	Publications with Citations ≥			
									100	**50**	**10**	**5**
2000	6	6	178	1.29	29.67	29.67	5	6	1	1	2	4
2001	10	6	252	1.15	25.20	42.00	4	10	1	3	4	4
2002	11	4	146	0.63	13.27	36.50	2	11	1	1	1	2
2003	27	22	1549	2.87	57.37	70.41	16	26	3	9	17	17
2004	22	17	446	1.07	20.27	26.24	10	19	1	4	9	11
2005	29	17	485	0.93	16.72	28.53	9	19	1	4	10	10

Table 1. *Cont.*

Year	TP	CP	TC	ACR	C/P	C/CP	*h*	*g*	Publications with Citations ≥			
									100	50	10	5
2006	20	17	453	1.33	22.65	26.65	10	22	1	3	7	10
2007	31	23	880	1.77	28.39	38.26	14	26	2	5	14	15
2008	29	24	875	2.01	30.17	36.46	16	29	2	4	17	17
2009	30	22	732	1.74	24.40	33.27	12	24	2	4	13	15
2010	23	17	495	1.66	21.52	29.12	9	21	1	4	9	12
2011	31	22	898	2.41	28.97	40.82	13	28	2	3	14	17
2012	41	31	1147	2.54	27.98	37.00	14	31	3	7	17	21
2013	44	29	729	1.66	16.57	25.14	15	25	0	5	20	24
2014	53	44	810	1.70	15.28	18.41	14	25	2	4	19	29
2015	43	38	865	2.51	20.12	22.76	13	27	2	2	18	26
2016	51	40	985	2.76	19.31	24.63	14	26	1	6	26	29
2017	52	48	1055	3.38	20.29	21.98	17	28	2	4	28	37
2018	53	46	841	3.17	15.87	18.28	13	22	0	4	19	28
2019	71	60	820	2.89	11.55	13.67	15	21	0	2	25	35
2020	65	56	666	3.42	10.25	11.89	12	18	0	2	20	30
2021	97	71	481	2.48	4.96	6.77	8	11	0	0	13	31
2022	101	44	172	1.70	1.70	3.91	3	4	0	0	5	9
Total	**940**	**704**	**15,960**	**2.31**	**16.98**	**22.67**	**61**	**96**	**28**	**81**	**327**	**433**

Notes: **TP** = total number of publications; **CP** = number of cited publications; **TC** = total citations; **ACR** = annualized citation rate; **C/P** = average citations per publication; **C/CP** = average citations per cited publication; ***h*** = h-index; ***g*** = g-index.

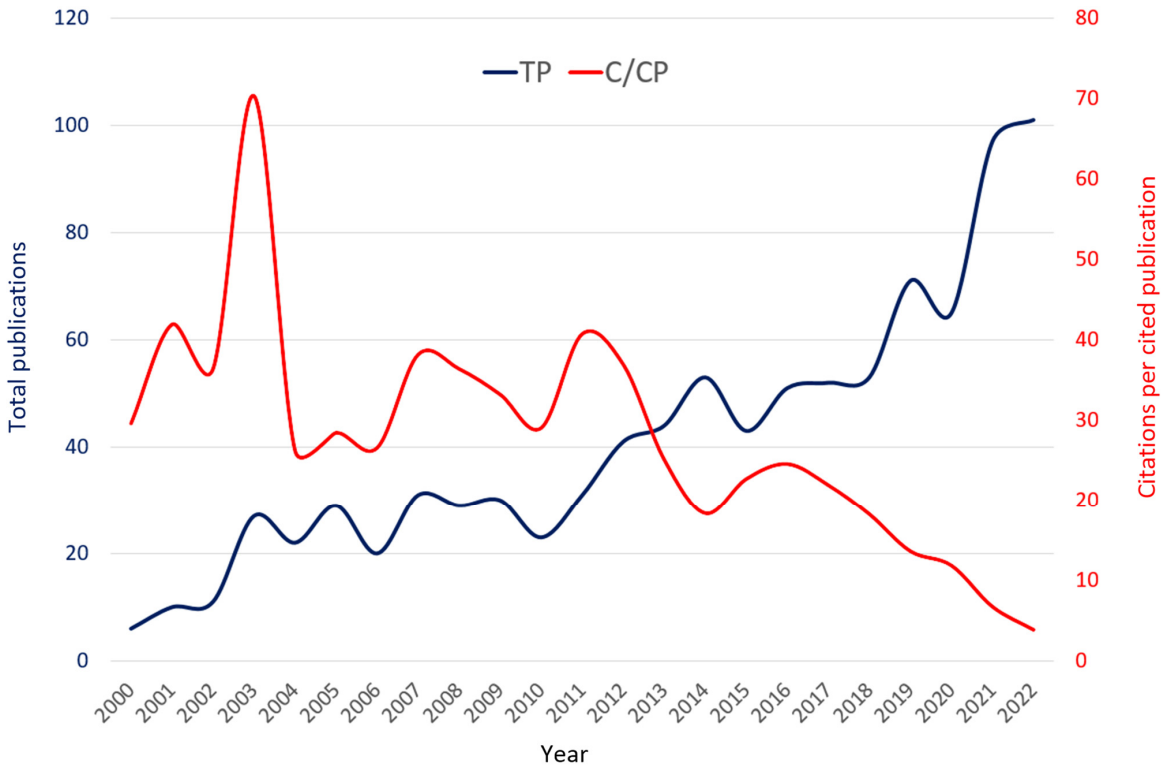

Figure 2. Publication and citation trends between 2000 and 2022.

Notes: TP = total number of publications; **C/CP** = average citations per cited publication.

3.2. Most Cited Publications

The number of citations serves as an indicator of a publication's influence, popularity, and attention within the scientific community, providing a means to identify influential articles across various journals [75]. Table 2 enumerates the 28 most influential publications on green certificates during the period of 2000–2022. The criterion for this distinction is having amassed over 100 citations on Scopus as of the search date. It is noteworthy that the six top-tier articles within this group have surpassed a more stringent benchmark of 200 citations. Seven articles received on average at least 20 citations each year since their publication. Six single-authored publications are included in this list, while the others are all multi-authored. Regarding the document types, there are 20 articles and six reviews, all published in well-reputed academic journals, with two being conference papers.

Menanteau et al.'s [76] article is the most cited in the field, with 545 total citations, averaging about 27 citations per year. In this article, Philippe Menanteau, Dominique Finon, and Marie-Laure Lamy discuss the efficiency of various incentive schemes for promoting the development of renewable energy, including green certificates, and compare them from both theoretical and practical perspectives. The second-most-cited article by Haas et al. [77] provides a historical overview and evaluates the effectiveness of promotion strategies for electricity from renewable energy sources in EU countries, including the use of green certificates. The article by Fouquet and Johansson [78] ranks third and reflects on the differences between national support mechanisms for renewable energy, including green certificates, and the push towards a harmonized EU-wide certificate trade mechanism. In terms of average citations per year (i.e., citations divided by the number of years from publication), Sahu [79] tops the list with 30.38 citations per year. This article discusses the global solar photovoltaic developments, per capita values, government support incentives, and policies of the top ten solar power-producing countries, including their investments in solar energy. Additionally, it explores the instruments used by these countries, such as fulfillment of projections, supportive tariff rates, net metering, and green certificates.

Themes addressed by the remaining articles among the top 28 most influential publications over the past 23 years, which have attracted significant scholarly attention, include green certificates and renewable energy support schemes (e.g., feed-in tariffs, tradable green certificates, and renewable portfolio standards), policy comparisons and the effectiveness of renewable energy subsidies in various countries and regions, interactions between green certificate markets and other energy markets (e.g., power and CO_2 emission markets), technological advancements and applications in renewable energy systems (e.g., energy crop production, data center energy capacity planning, and decentralized energy management through the blockchain), as well as the development and assessment of regional and global renewable energy policies and frameworks.

It should be noted that older publications inherently have a higher likelihood of being cited, compared to more recent publications. Consequently, some recent highly cited articles may not appear in Table 2. In this regard, two recent articles are particularly worth mentioning. Firstly, the article by Velazquez Abad and Dodds [37], which has accumulated 89 citations in just three years, addresses definitions, standards, guarantees of origin, and challenges related to green hydrogen characterization initiatives, including tracking mechanisms such as green certificates. Secondly, the article by Yu et al. [80], having garnered 42 citations in only two years, discusses the integration of two trading mechanisms, namely tradable green certificates and carbon emissions trading, in the Chinese power industry and explores the potential benefits, challenges, and risks associated with these mechanisms.

Table 2. The most influential articles in green certificates research.

Ref.	Author(s)	Title	Document Type	Year	TC	ACR
[76]	Menanteau, P., Finon, D., and Lamy, M.L.	Prices versus quantities: choosing policies for promoting the development of renewable energy.	Article	2003	545	27.25
[77]	Haas, R., Panzer, C., Resch, G., Ragwitz, M., Reece, G., and Held, A.	A historical review of promotion strategies for electricity from renewable energy sources in EU countries.	Review	2011	288	24.00
[78]	Fouquet, D. and Johansson, T.B.	European renewable energy policy at crossroads—Focus on electricity support mechanisms.	Article	2008	245	16.33
[79]	Sahu, B.K.	A study on global solar PV energy developments and policies with special focus on the top ten solar PV power producing countries.	Review	2015	243	30.38
[52]	Boomsma, T.K., Meade, N., and Fleten, S.E.	Renewable energy investments under different support schemes: A real options approach.	Article	2012	232	21.09
[81]	Meyer, N.I.	European schemes for promoting renewables in liberalised markets.	Article	2003	216	10.80
[82]	Kitzing, L., Mitchell, C., and Morthorst, P.E.	Renewable energy policies in Europe: Converging or diverging?	Article	2012	200	18.18
[83]	Haas, R., Resch, G., Panzer, C., Busch, S., Ragwitz, M., and Held, A.	Efficiency and effectiveness of promotion systems for electricity generation from renewable energy sources–Lessons from EU countries.	Article	2011	197	16.42
[18]	Ringel, M.	Fostering the use of renewable energies in the European Union: The race between feed-in tariffs and green certificates.	Article	2006	172	10.12
[84]	Vink, E.T.H., Glassner, D.A., Kolstad, J.J., Wooley, R.J., and O'Connor, R.P.	The eco-profiles for current and near-future NatureWorks polylactide (PLA) production.	Article	2007	165	10.31
[40]	Jacobsson, S., Bergek, A., Finon, D., Lauber, V., Mitchell, C., Toke, D., and Verbruggen, A.	EU renewable energy support policy: Faith or facts?	Article	2009	155	11.07
[85]	Jäger-Waldau, A.	Photovoltaics and renewable energies in Europe.	Review	2007	152	9.50
[86]	Hua, Y., Oliphant, M., and Hu, E.J.	Development of renewable energy in Australia and China: A comparison of policies and status.	Article	2016	145	20.71
[87]	Bergek, A. and Jacobsson, S.	Are tradable green certificates a cost-efficient policy driving technical change or a rent-generating machine? Lessons from Sweden 2003–2008.	Article	2010	145	11.15
[88]	Ren, C., Wang, D., Urgaonkar, B., and Sivasubramaniam, A.	Carbon-aware energy capacity planning for datacenters.	Conference Paper	2012	142	12.91
[89]	Nicolini, M. and Tavoni, M.	Are renewable energy subsidies effective? Evidence from Europe.	Review	2017	140	23.33
[90]	Gerin, P.A., Vliegen, F., and Jossart, J.M.	Energy and CO_2 balance of maize and grass as energy crops for anaerobic digestion.	Article	2008	138	9.20
[8]	Jensen, S.G. and Skytte, K.	Interactions between the power and green certificate markets.	Article	2002	137	6.52
[91]	Frombo, F., Minciardi, R., Robba, M., Rosso, F., and Sacile, R.	Planning woody biomass logistics for energy production: A strategic decision model	Article	2009	136	9.71

Table 2. *Cont.*

Ref.	Author(s)	Title	Document Type	Year	TC	ACR
[23]	Langniss, O. and Wiser, R.	The renewables portfolio standard in Texas: an early assessment.	Article	2003	133	6.65
[92]	Lauber, V.	REFIT and RPS: Options for a harmonised Community framework.	Article	2004	130	6.84
[93]	del Rio Gonzalez, P. and Linares, P.	Back to the future? Rethinking auctions for renewable electricity support.	Review	2014	128	14.22
[51]	Morthorst, P.E.	The development of a green certificate market.	Article	2000	126	5.48
[49]	Imbault, F., Swiatek, M., de Beaufort, R., and Plana, R.	The green blockchain: Managing decentralized energy production and consumption.	Conference Paper	2017	123	20.50
[53]	Abolhosseini, S. and Heshmati, A.	The main support mechanisms to finance renewable energy development.	Review	2014	119	13.22
[94]	Unger, T. and Ahlgren, E.O.	Impacts of a common green certificate market on electricity and CO_2-emission markets in the Nordic countries.	Article	2005	116	6.44
[95]	Reddy, S.S. and Momoh, J.A.	Realistic and transparent optimum scheduling strategy for hybrid power system.	Article	2015	113	14.13
[96]	Amundsen, E.S. and Mortensen, J.B.	The Danish Green Certificate System: some simple analytical results	Article	2001	102	4.64

Notes: Ref. = reference; **TC** = total citations; **ACR** = annualized citation rate.

3.3. Most Prolific Authors

Table 3 highlights the most prolific authors in green certificates research, identified by having contributed a minimum of five articles to the field and garnered at least 50 total citations. Xingang Zhao, affiliated with North China Electric Power University, emerges as the most published author, with 20 contributions from 2013 to 2022. Zhao's influence extends beyond the quantity of his work, as demonstrated by his substantial h-index (11) and g-index (20) standings, reinforcing his prominent role in the field. His colleague, Yuzhuo Zhang, is another significant contributor, producing nine articles. Also noteworthy are the scholarly contributions of Pablo del Rio Gonzalez, from the Spanish Council for Scientific Research, and Dequn Zhou, from China's Nanjing University of Aeronautics and Astronautics, each offering eight articles to the field.

Table 3. The most prolific authors in green certificates research.

Author	Affiliation	TP	CP	FA	TC	APA	ACR	C/P	C/CP	*h*	*g*	Publications with Citations ≥			
												100	50	10	5
Zhao, X.	North China Electric Power University, China	20	20	11	463	4.10	5.65	23.15	23.15	11	20	0	3	13	16
Zhang, Y.	North China Electric Power University, China	9	8	2	288	4.22	7.58	32.00	36.00	8	9	0	2	7	8
del Rio Gonzalez, P.	Spanish Council for Scientific Research, Spain	8	8	7	356	15.25	2.92	44.50	44.50	7	8	1	3	6	7
Zhou, D.	Nanjing University of Aeronautics and Astronautics, China	8	7	0	89	1.38	8.06	11.12	12.71	5	8	0	0	3	5
Zuo, Y.	North China Electric Power University, China	7	7	3	181	3.13	8.26	25.86	25.86	5	7	0	1	5	5

Table 3. *Cont.*

Author	Affiliation	TP	CP	FA	TC	APA	ACR	C/P	C/CP	*h*	*g*	Publications with Citations ≥			
												100	50	10	5
Zhou, Y.	North China Electric Power University, China	7	7	3	160	2.57	8.89	22.86	22.86	6	7	0	1	5	6
Lauber, V.	University of Salzburg, Austria	6	6	2	560	14.33	6.51	93.33	93.33	6	6	2	5	6	6
Ragwitz, M.	Fraunhofer Institute for Systems and Innovation Research, Germany	6	5	2	553	13.00	7.09	92.16	110.60	5	6	2	2	5	5
Resch, G.	Vienna University of Technology, Austria	6	5	0	536	14.67	6.09	89.33	107.20	5	6	2	2	4	5
Morthorst, P.E.	Technical University of Denmark, Denmark	6	6	5	505	19.83	4.24	84.16	84.16	5	6	2	4	5	6
Amundsen, E.S.	University of Bergen, Norway	6	6	5	220	12.00	3.06	36.67	36.67	4	6	1	1	4	4
Bird, L.	National Renewable Energy Laboratory, US	6	4	2	81	11.33	1.19	13.50	20.25	3	6	0	0	2	3
Finon, D.	International Research Centre on the Environment and Development, France	5	5	2	814	16.40	9.93	162.80	162.80	4	5	2	3	4	4
Verbruggen, A.	University of Antwerp, Belgium	5	5	3	359	13.20	5.44	71.80	71.80	5	5	1	4	4	5
Fleten, S.E.	Norwegian University of Science and Technology, Norway	5	5	1	320	8.20	7.80	64.00	64.00	4	5	1	1	3	3
Linnerud, K.	Western Norway University of Applied Sciences, Norway	5	5	3	136	7.60	3.58	27.20	27.20	4	5	0	1	4	4
Gillenwater, M.	Greenhouse Gas Management Institute, US	5	5	4	134	10.80	2.48	26.80	26.80	5	5	0	0	5	5
Ho, M.T. Khorshidi, Z. Wiley, D.E.	University of New South Wales, Australia	5	4	0 5 0	85	8.60	1.98	17.00	21.25	4	5	0	0	4	4

Notes: TP = total number of publications; **CP** = number of cited publications; **FA** = number of publications as first author; **TC** = total citations; **APA** = average publication age; **ACR** = annualized citation rate; **C/P** = average citations per publication; **C/CP** = average citations per cited publication; ***h*** = h-index; ***g*** = g-index.

This notable concentration of prolific authors from China reflects the country's significant engagement with green certificates research. This is largely due to China's policy shift towards renewable energy. Beginning around 2010, China transitioned from subsidized feed-in tariffs to a market-based approach for wind and solar energy. The 2017 implementation of the green electricity certificates system and the subsequent integration of green certificates into China's energy quotas by 2023 further reflect significant policy changes, driving the need for extensive research in this evolving sector.

When considering the total number of citations received—an important metric of impact—Dominique Finon from the International Research Centre on the Environment and Development (France) ranks first, with 814 citations. Volkmar Lauber from the University of Salzburg (Austria) and Mario Ragwitz from the Fraunhofer Institute for Systems and Innovation Research (Germany) follow, each with over 550 citations. Gustav Resch of Vienna University of Technology (Austria) and Poul Erik Morthorst of the Technical University of Denmark complete the top five, each with over 500 citations. Also topping the list, Dominique Finon commands the highest average citations per article, with an impressive 162.80, and leads with the most substantial annualized citation rate at 9.93. It is

noteworthy that, among these leading contributors, nine have authored at least one article that received over 100 citations, and fourteen have at least one article with over 50 citations.

3.4. Most Prolific Institutions

Table 4 enumerates the most prolific institutions in green certificates research, each having published a minimum of nine articles in this field. The list shows a marked geographical concentration: a majority—58.3% or seven institutions—are based in China, with the remainder mainly rooted in Scandinavia (two in Denmark and one each in Norway and Sweden), except for a lone representative from Romania. North China Electric Power University stands prominently at the top of this list, with 56 contributions. This is followed by the State Grid Corporation of China and the Technical University of Denmark, contributing 20 and 18 articles, respectively.

Table 4. The most prolific institutions in green certificates research.

Institution	Country	TP	CP	TC	APA	ACR	C/P	C/CP	*h*	*g*	Publications with Citations ≥			
											100	50	10	5
North China Electric Power University	China	56	46	797	3.45	4.13	14.23	17.33	17	27	0	4	24	31
State Grid Corporation of China	China	20	13	88	2.9	1.52	4.40	6.77	5	9	0	0	3	5
Technical University of Denmark	Denmark	18	17	1199	16.11	4.13	66.61	70.53	13	18	4	10	14	15
Tsinghua University	China	13	11	191	3.54	4.15	14.69	17.36	5	13	0	1	5	5
Shanghai University of Electric Power	China	13	7	38	2.54	1.15	2.92	5.43	3	6	0	0	1	2
Norwegian University of Science and Technology	Norway	12	11	504	7.75	5.42	42.00	45.82	8	12	1	2	8	9
Ministry of Education of the People's Republic of China	China	12	6	72	3.17	1.89	6.00	12.00	3	8	0	1	2	2
Politehnica University of Bucharest	Romania	11	7	39	6.64	0.53	3.55	5.57	3	6	0	0	2	3
Zhejiang University	China	10	7	100	2.5	4.00	10.00	14.29	4	10	0	0	3	4
University of Copenhagen	Denmark	9	9	586	10.22	6.37	65.11	65.11	8	9	2	3	8	8
Lund University	Sweden	9	9	469	12.44	4.19	52.11	52.11	6	9	2	2	6	7
Nanjing University of Aeronautics and Astronautics	China	9	8	106	1.33	8.86	11.78	13.25	5	9	0	0	4	6

Notes: TP = total number of publications; **CP** = number of cited publications; **TC** = total citations; **APA** = average publication age; **ACR** = annualized citation rate; **C/P** = average citations per publication; **C/CP** = average citations per cited publication; ***h*** = h-index; ***g*** = g-index.

Intriguingly, while Chinese institutions manifest prolificacy in production, it is their Scandinavian counterparts that command a more significant influence. The Technical University of Denmark, with fewer than one third of the total publications of North China Electric Power University, leads in accumulated citations, totaling an impressive 1199. Both Danish institutions—the Technical University of Denmark and the University of Copenhagen—register more than 65 average citations per publication. Similarly, Lund University in Sweden and the Norwegian University of Science and Technology mark their significance with averages of 52.11 and 42 citations per publication, respectively. Tsinghua University, China's lead institution by this metric, lags behind, with an average of 14.69 citations per publication. A noteworthy observation is that the nine most-cited publications in the list, each amassing over 100 citations, are all products of the previously

mentioned Scandinavian institutions. This reinforces the substantial scholarly contribution and influence of these institutions in the realm of green certificates research. However, it is crucial to bear in mind that the articles generated by Chinese institutions have, on average, a shorter publication age, a factor that might reasonably contribute to their lower total citation counts at this stage.

3.5. Most Prolific Countries

Of the 940 publications evaluated in this study, 880 are affiliated with 63 distinct countries (the remaining 60 publications do not demonstrate a clear affiliation with any specific country). Table 5 showcases the countries that are most prolific in green certificates research, with each contributing at least 12 articles through their respective institutions and researchers. It is important to note that a single publication may be attributable to multiple countries, due to collaborations among authors from diverse geographies.

Table 5. The most prolific countries in green certificates research.

Country	TP	TP/MH	CP	TC	APA	ACR	C/P	C/CP	*h*	*g*	Publications with Citations ≥			
											100	**50**	**10**	**5**
China	219	0.15	159	2268	3.30	3.14	10.36	14.26	26	40	1	10	64	87
US	103	0.31	77	1754	9.40	1.81	17.03	22.78	21	40	5	9	36	53
UK	53	0.78	44	1850	9.89	3.53	34.91	42.05	21	43	4	10	28	33
Italy	52	0.86	42	1157	12.62	1.76	22.25	27.55	18	33	3	8	24	29
Sweden	47	4.65	41	1711	11.87	3.07	36.40	41.73	21	41	6	10	30	36
Romania	45	2.34	31	250	7.49	0.74	5.56	8.06	9	14	0	2	7	13
India	43	0.03	35	773	7.93	2.27	17.98	22.09	13	27	1	3	17	21
Norway	40	7.38	36	1144	10.15	2.82	28.60	31.78	17	33	2	7	25	29
South Korea	40	0.78	30	405	4.10	2.47	10.13	13.50	8	19	2	2	7	15
Spain	37	0.79	34	838	9.43	2.40	22.65	24.65	16	28	1	6	19	26
Denmark	35	6.04	33	1961	12.97	4.32	56.03	59.42	22	35	6	15	25	26
Germany	35	0.42	31	1140	10.77	3.02	32.57	36.77	14	33	4	5	16	24
Netherlands	35	2.04	31	613	12.91	1.36	17.51	19.77	14	24	1	2	20	23
Australia	34	1.33	29	797	8.47	2.77	23.44	27.48	17	28	1	4	22	24
Belgium	27	2.33	24	1027	13.07	2.91	38.04	42.79	15	27	3	7	15	21
Poland	27	0.71	23	182	5.96	1.13	6.74	7.91	8	12	0	0	7	11
France	21	0.32	19	1089	11.90	4.36	51.86	57.32	9	21	3	5	9	13
Austria	17	1.89	16	1160	11.88	5.74	68.24	72.50	11	17	4	7	11	15
Canada	17	0.45	14	237	7.47	1.87	13.94	16.93	7	15	0	1	5	9
Japan	12	0.09	11	534	7.58	5.87	44.50	48.55	11	12	0	6	11	11

Notes: TP = total number of publications; **TP/MH**: total number of publications divided by the total millions of inhabitants of the country; **CP** = number of cited publications; **TC** = total citations; **APA** = average publication age; **ACR** = annualized citation rate; **C/P** = average citations per publication; **C/CP** = average citations per cited publication; ***h*** = h-index; ***g*** = g-index.

Among the total publications, China dominates with 219 contributions, substantially outpacing other countries. The US ranks second with 103 publications. Although this figure significantly trails China, it surpasses the tallies of the United Kingdom (UK) and Italy, which hold the third and fourth positions, respectively, with 53 and 52 publications. Intriguingly, the Scandinavian countries—Sweden (47), Norway (40), and Denmark (35)—demonstrate

remarkable scholarly output in green certificates research. This prominence becomes particularly striking when accounting for population size.

Countries with a larger number of publications tend to amass a higher count of citations, manifesting an observable correlation. Accordingly, China dominates in total citations (2268) and the h-index (26), while also maintaining a strong standing in the g-index (40). The US, the UK, and Sweden constitute other substantial publishing centers, with each displaying an h-index surpassing 20 and a g-index exceeding 40.

Upon examining the metric of average citations per publication, it becomes evident that European nations command a significant presence. Among the top 20 contributing nations, Austria takes precedence with the highest average of citations per publication, reaching an impressive 68.24, while Denmark and France follow closely, registering averages of 56.03 and 51.86, respectively. Not far behind is Japan, carving its place at fourth with an average of 44.50 citations per publication. These four countries maintain their supremacy even when the results are normalized based on annual citation rate. A subsequent tier of European nations—Belgium, Sweden, the UK, Germany, and Norway—averages between 28 and 38 citations per publication for each country, reinforcing the strong academic influence of Europe in this realm. Further, out of the 47 publications with more than 100 citations appearing on this list, 37 originate from European nations. Sweden and Denmark jointly top this sub-category, each contributing six high-citation publications.

The predominance of the aforementioned countries in leading green certificates research aligns with expectations, given their instrumental role in the formation and execution of progressive policies that stimulate the deployment of renewable energy. These countries extensively deploy green certificate programs as policy tools to encourage renewable energy utilization. The most prevalent among these are the renewable energy certificates in North America, guarantees of origin in the EU, renewable energy guarantees of origin in the UK, green electricity certificates in China, and international renewable energy certificates for other regions, each adhering to its own set of standards. However, it is worth noting the stark underrepresentation of African, South American, and Middle Eastern nations in this arena, both in volume and influence. This discrepancy may be attributed to their less supportive or less developed regulatory frameworks for renewable energy advancement. The development of such frameworks could be a potential avenue for increased contribution to the field in the future.

3.6. Top Publishing Journals

The analysis encompasses 940 publications spread across 434 distinct journals and proceedings. Table 6 showcases the leading journals in green certificates research, each contributing a minimum of eight articles to the field. Astonishingly, the top 14 journals, representing only 3.22% of all journals on the topic, account for over a third of all green certificates publications (328/940).

Topping the list is *Energy Policy*, with a significant contribution of 100 articles, trailed by *Renewable and Sustainable Energy Reviews*, offering 42 articles. Both journals also hold the distinction of being the most cited, averaging above 50 citations per article, underscoring their influence in the field. The prolific citation rates can be attributed to these journals featuring multiple highly cited articles. For instance, out of the 28 most influential articles in the field (see Table 2), eleven and six are published in *Energy Policy* and *Renewable and Sustainable Energy Reviews*, respectively. Unsurprisingly, these two journals also lead in the h-index and g-index categories, with *Energy Policy* scoring 40 and 69, respectively, and *Renewable and Sustainable Energy Reviews* registering 26 and 42.

Table 6. The top publishing journals in green certificates research.

Journal	Publisher	IF	SJR	TP	CP	TC	APA	ACR	C/P	C/CP	*h*	*g*	Publications with Citations ≥			
													100	50	10	5
Energy Policy	Elsevier	9.0	2.292	100	98	5127	12.25	4.19	51.27	52.32	40	69	11	32	83	94
Renewable and Sustainable Energy Reviews	Elsevier	15.9	3.232	42	42	2275	8.81	6.15	54.17	54.17	26	42	6	13	39	41
Renewable Energy	Elsevier	8.7	1.815	28	26	921	7.21	4.56	32.89	35.42	16	28	2	6	20	24
Energies	MDPI	3.2	0.632	24	18	168	3.29	2.13	7.00	9.33	7	12	0	1	4	10
Energy	Elsevier	9.0	1.989	22	20	705	5.55	5.77	32.05	35.25	11	22	1	6	13	18
Energy Economics	Elsevier	12.8	3.039	17	17	580	7.53	4.53	34.12	34.12	13	17	1	4	14	16
Journal of Cleaner Production	Elsevier	11.1	1.981	16	13	376	4.19	5.61	23.50	28.92	10	16	0	3	11	12
Automation of Electric Power Systems	Automation of Electric Power Systems Press	-	0.975	15	12	250	3.47	4.80	16.67	20.83	10	15	0	0	11	12
Sustainability	MDPI	3.9	0.664	14	13	125	3.71	2.41	8.93	9.62	8	11	0	0	5	10
Energy & Environment	SAGE	4.2	0.598	13	10	71	15.00	0.36	5.46	7.10	5	8	0	0	1	6
Power System Technology	Power System Technology Press	-	0.804	11	11	215	3.82	5.12	19.55	19.55	8	11	0	1	8	9
Energy Procedia	Elsevier	-	0.519	10	8	107	8.90	1.20	10.70	13.38	7	10	0	0	5	7
Biomass & Bioenergy	Elsevier	6.0	1.045	8	8	319	13.13	3.04	39.88	39.88	8	8	1	1	8	8
Applied Energy	Elsevier	11.2	2.907	8	8	234	4.00	7.31	29.25	29.25	6	8	0	2	5	7

Notes: **IF** = impact factor (Clarivate Analytics, 2022); **SJR** = Scimago journal rank (2022); **TP** = total number of publications; **CP** = number of cited publications; **TC** = total citations; **APA** = average publication age; **ACR** = annualized citation rate; **C/P** = average citations per publication; **C/CP** = average citations per cited publication; ***h*** = h-index; ***g*** = g-index.

Numerous other publications have also featured in distinct journals, such as *Renewable Energy* (28), *Energies* (24), *Energy* (22), *Energy Economics* (17), and *Journal of Cleaner Production* (16). These top seven journals, collectively, exhibit a formidable average impact factor of 9.95, implying that the sphere of green certificates has garnered recognition from leading journals within the energy management field. A noteworthy addition to this list is *Applied Energy*, with an impact factor of 11.2, which leads in the category of the annualized citation rate with a value of 7.31. This achievement is indicative of its articles' significant appeal and scholarly impact, even though they are relatively recent, as evidenced by their already substantial citation numbers. Other significant journals in this list include *Sustainability* (14), *Energy & Environment* (13), and *Biomass & Bioenergy* (8).

Examining the publishers, Elsevier demonstrates an unequivocal preeminence. Of particular note is the fact that Elsevier's journals secure six of the top seven rankings, comprising the foremost three. In the aggregate list of premier publishing journals, approximately two-thirds (9/14) are Elsevier journals. When assessing total publications among the top-tier publishing journals, Elsevier contributes 251 out of 328 articles, accounting for 76.5% of the total. Elsevier's supremacy extends even further in terms of impact, as it accrues 10,644 out of 11,473 total citations, representing an impressive 92.77%.

4. Co-Authorship Networks

To illuminate the cooperative patterns among authors in the field of green certificates, we devised co-authorship networks at two levels: authors and countries [60,61,97,98].

4.1. Author-Level Co-Authorship Network

Figure 3 depicts the author-level co-authorship network, with the aid of VOSviewer software [72]. To ensure a broad inclusion of contributors, we set a minimum threshold of two documents per author, accommodating those who, albeit through a modest quantity of works, have demonstrated potential for substantial collaboration. Simultaneously, we applied a citation threshold of 25, thereby eliminating authors whose contributions have not yet garnered notable recognition in the field. Further, we excluded authors with a total link strength—quantified as the cumulative weight of an author's collaborative links—of zero or one. This criterion was put in place to exclude those who mostly work in isolation, thereby focusing the analysis on the core network of authors engaged in active collaboration. This refined focus provides a clearer depiction of the co-authorship dynamics within the field. Out of an initial sample of 2104 authors, 134 met these defined parameters. The nodal size, as displayed in Figure 3, was calculated based on each author's total link strength, emphasizing authors with intensive collaborations. The link between any two authors represents their number of co-authorships.

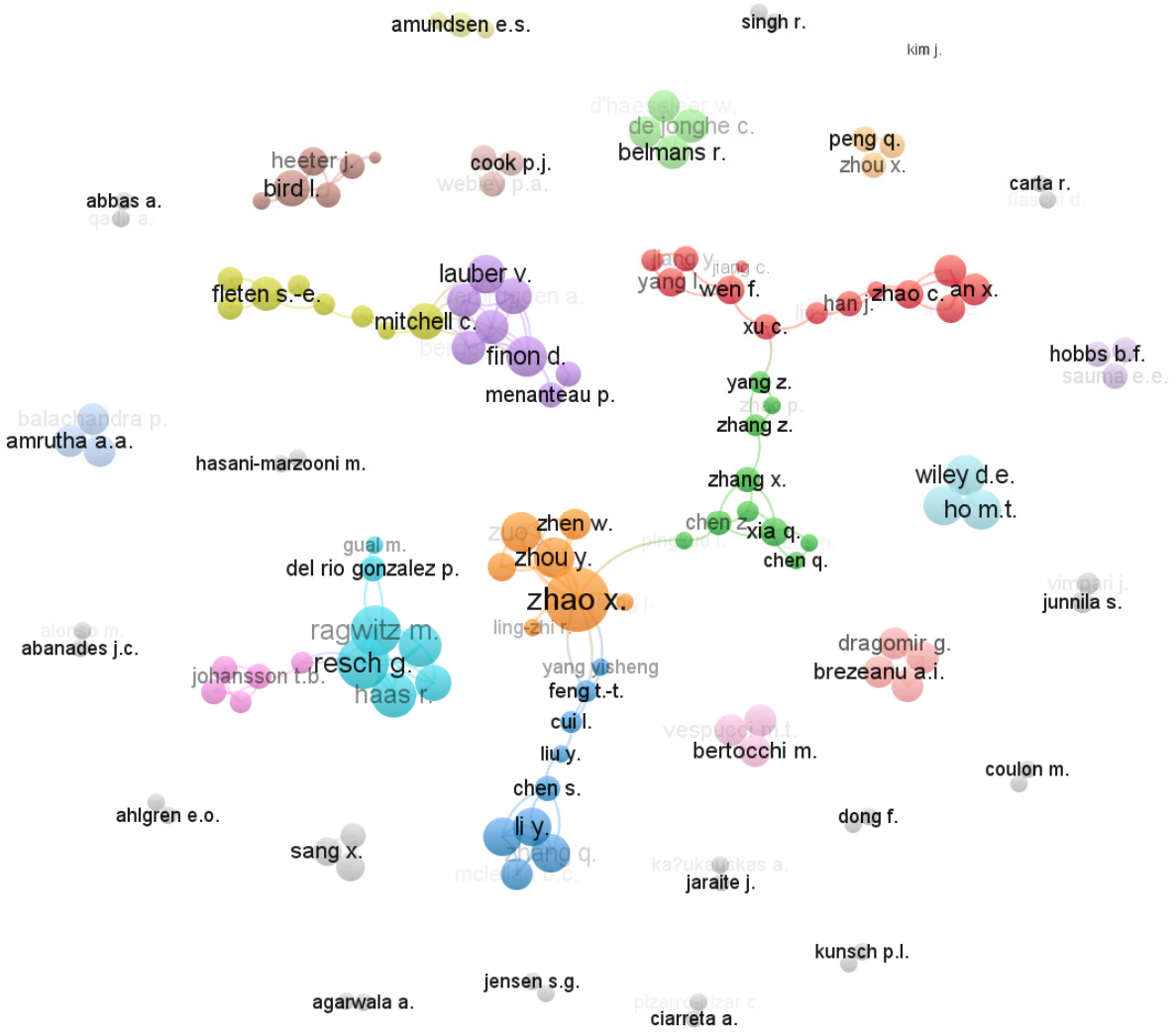

Figure 3. Author-level co-authorship network.

The resultant analysis underscores authors Zhao X., Resch G., and Ragwitz M. as prominent figures in collaborative relationships, with total link strengths of 25, 16, and 15, respectively. The co-authorship network comprises fairly insular clusters, exhibiting minimal to no cross-cluster interactions—indicative of authors' preference for single-team collaboration. The most substantial connected node comprises 39 authors, led by Zhao X.,

and spreads across four distinct clusters predominantly composed of Chinese contributors. Two additional interconnected author sets, primarily European, stand out in the network, each spanning two clusters. The first cluster, centrally featuring authors such as Finon D. and Lauber V., interlinks with another significant cluster that includes Mitchell C. and Fleten S.-E. Likewise, the second connection bridges the cluster prominently involving Resch G. and Ragwitz M., to a cluster that notably includes Johansson T.B., among others. Beyond these, interactions among clusters are non-existent.

4.2. Country-Level Co-Authorship Network

Using the same methodological criteria initially established for the author-level co-authorship network, we subsequently applied this approach to a country-level co-authorship network, resulting in an interconnected network of 28 countries. This cross-national web of collaboration is graphically represented in Figure 4. While China leads in total publications (see Table 5), its fourth position in total link strength, at 28, indicates a relative lack of international collaborations compared to its counterparts. Indeed, the collaboration patterns of Chinese researchers seem predominantly confined within their national boundaries, corroborating our earlier findings as portrayed in Figure 3. In stark contrast, the UK emerges as the central node in the network, with a noteworthy total link strength of 50. The US and Germany trail close behind, with link strengths of 38 and 33, respectively. These countries serve as significant hubs for co-authored publications within the field. In terms of interconnections, the UK and Germany share a cluster where collaborations flourish, also encompassing several other European nations: Austria, Belgium, Denmark, Sweden, Spain, and France. China's cluster, influenced by geographic proximity, includes countries such as Taiwan, Japan, Australia, and Singapore. We further identify three additional clusters, led by the US, the Netherlands, and Denmark, in terms of collaborative relationships. The underrepresentation of African, South American, and Middle Eastern nations, as noted earlier in Section 3.5 regarding publication volume and influence in the field, is further corroborated in this context of international collaborative endeavors, as reflected in our network analysis.

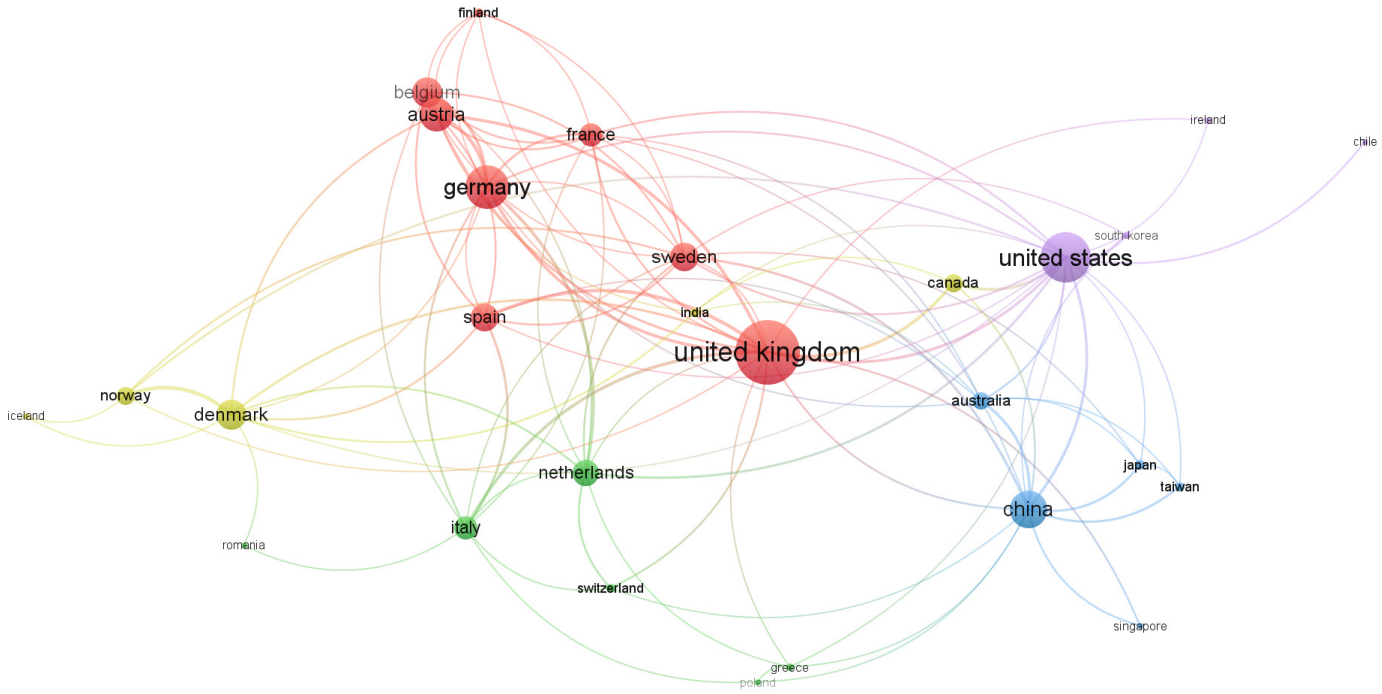

Figure 4. Country-level co-authorship network.

5. Keyword Co-Occurrence Analysis

Keyword co-occurrence analysis, a method employed to discern the conceptual network structure within a research domain [99], forms the basis of this section. This analysis is rooted in the principle that the co-presence of words within diverse documents signifies an interrelation between the underlying concepts, effectively facilitating the identification of a research specialty via the unique associations established between its keywords [100]. Essentially, the observed conjunction of terms within a literature corpus [65] underscores the potency of co-occurrence analysis. This interconnectedness reaffirms the premise that authors' chosen keywords reliably encapsulate the primary themes of their articles [64,101]. Herein, we apply this method to map the structure of topics within the field of green certificates, utilizing a co-occurrence analysis of keywords from pertinent published works.

To conduct the keyword co-occurrence analysis, we initially extracted the authors' keywords from each document within our dataset and then refined these keywords to minimize redundancy, as recommended by Hallinger and Kovačević [102]. Plural terms were rendered singular (e.g., "electricity markets" became "electricity market"), British spelling variants were Americanized (e.g., "harmonisation" became "harmonization"), abbreviations were spelled out in full (e.g., "RPS" was expanded to "Renewable Portfolio Standard"), and synonyms were unified under a single term (e.g., both "feed in tariff" and "feed-in-tariff" were standardized to "feed-in tariff"). These transformations were implemented in accordance with the guidelines set forth in earlier studies [57,67,103]. Adhering to the approach proposed by Andersen [57], we further filtered the keyword set to exclude words not denoting a distinct concept, such as countries and regions. Furthermore, as is common practice in social network analysis, we excluded from our study the keywords employed in the search string (detailed in Section 2.1), since these tend to appear in most articles within the dataset by default [2,57]. For instance, the terms "green certificate" or "tradable green certificate" are found in 255 articles, while the synonymous term "renewable energy certificate" appears in 102 articles. If included in the co-occurrence analysis, these terms would disproportionately clutter the network map and be arbitrarily assigned to a specific cluster [57].

Following this stringent refinement process, we were left with 1856 keywords. To ensure the analysis focused on core concepts within the green certificates field, we only included keywords appearing in at least five publications. A total of 79 keywords satisfied this criterion, with the most frequently occurring being "renewable energy" (137 instances), "renewable portfolio standard" (116 instances), and "feed-in tariff" (63 instances).

Figure 5 visually communicates the keyword co-occurrence network map, spotlighting the most prominent terms. Constructed with the aid of VOSviewer software [72], each node on the map signifies a keyword, and the lines or links connecting them represent their co-occurrences across a range of articles. The relative size of a node corresponds to the frequency of the associated keyword; a larger node indicates a more frequently mentioned term. Moreover, the distance separating two nodes reflects their interrelation, with a shorter span implying a tighter relationship. In a similar vein, the thickness of the interconnecting line represents the degree of keyword co-occurrence, with a denser line indicating more frequent co-occurrence. This map's structure is designed to elucidate the domain's collective knowledge, informed by the patterns and strengths of the keyword connections. Additionally, distinct thematic clusters within this knowledge domain are delineated by variations in node colors.

Upon examination, the keyword co-occurrence network map shown in Figure 5 discloses nine unique clusters. To organize the nine identified clusters, we first analyzed their content, yielding a preliminary grouping into four research themes. Given the inherent subjectivity of this task, we sought additional validation by examining the clusters' relative positions on the map. Finding that our content-derived groupings mirrored the spatial proximity of clusters on the map, we gained further confidence in the validity of our thematic categorization. Table 7 catalogues the keywords associated with each cluster and theme, alongside their metrics of occurrence (the keyword frequency) and total link

strength (signifying the keyword's importance within the field, with a higher value denoting extensive and frequent linkage with other terms). A short discussion of each cluster ensues in subsequent subsections.

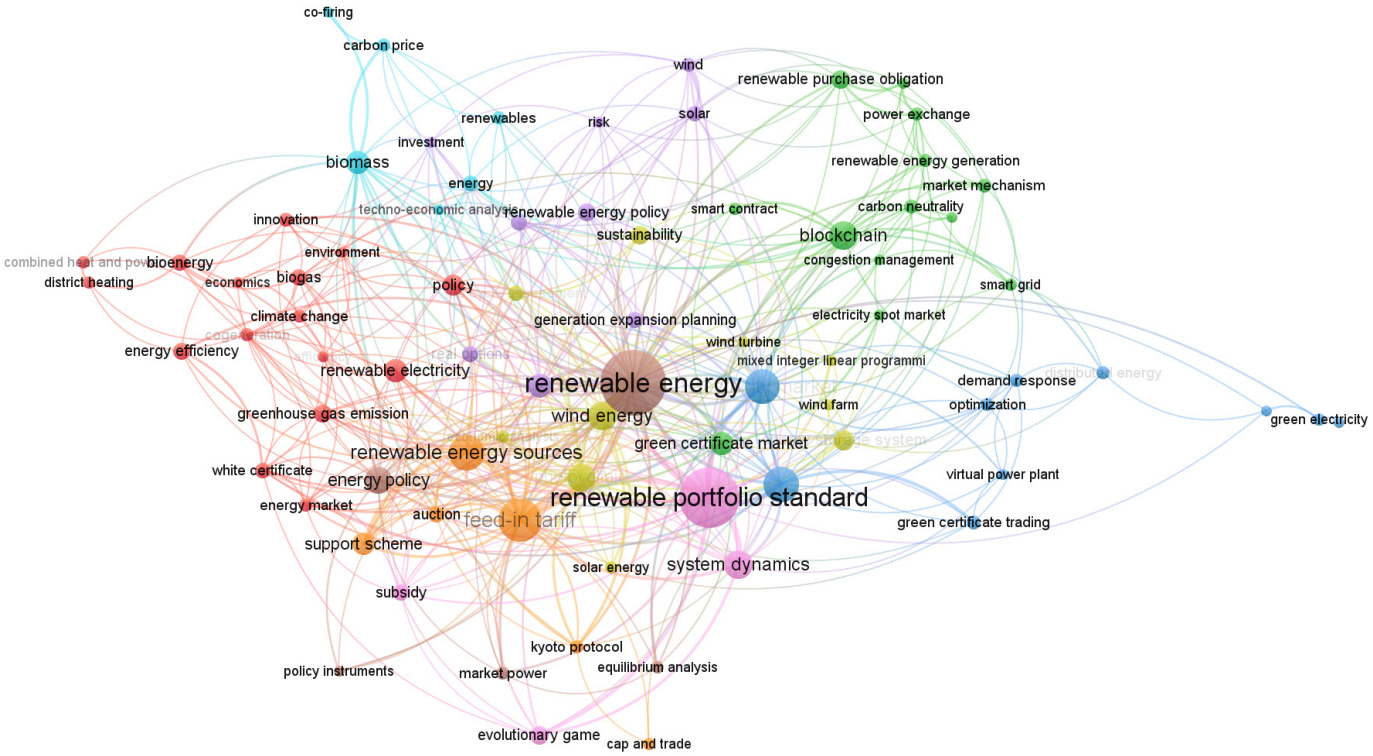

Figure 5. Keyword co-occurrence network.

Table 7. Keyword co-occurrence clusters themes.

Research Theme	Cluster	Keywords	OC	TLS
Research theme A: Support mechanisms and policies for renewable energy sources; positioned at the bottom of the map.	**Cluster 7 (**orange**):** Renewable energy policies and strategies.	feed-in tariff	63	103
		renewable energy sources	44	54
		support scheme	18	25
		auction	10	18
		Kyoto protocol	7	22
		cap and trade	6	3
	Cluster 9 (pink**):** Modeling renewable energy policy approaches.	renewable portfolio standard	116	128
		system dynamics	29	45
		evolutionary game	13	21
		subsidy	10	16

Table 7. *Cont.*

Research Theme	Cluster	Keywords	OC	TLS
Research theme B: Tradable green certificates, sustainable renewable technologies, and market dynamics; positioned centrally and on the map's left side.	**Cluster 1 (**red**):** Policy-driven innovations and efficiency in renewable energy systems.	renewable electricity	20	15
		policy	16	19
		greenhouse gas emission	12	18
		energy efficiency	11	12
		bioenergy	10	18
		biogas	10	17
		white certificate	9	19
		innovation	8	13
		energy market	7	19
		cogeneration	7	17
		climate change	7	10
		district heating	6	7
		combined heat and power	6	6
		economics	5	9
		efficiency	5	9
		environment	5	9
	Cluster 6 (light blue**):** Co-firing strategies in the transition towards more sustainable energy solutions.	biomass	20	43
		energy	9	13
		carbon price	7	12
		renewables	7	6
		co-firing	5	6
		techno-economic analysis	5	5
	Cluster 8 (brown**):** Insights into renewable energy market dynamics.	renewable energy	137	177
		energy policy	26	47
		market power	7	12
		equilibrium analysis	6	10
		policy instruments	5	7
Research theme C: Technological innovations and green certificate trading; positioned on the map's right side.	**Cluster 2 (**green**):** Technological and regulatory frameworks in green certificate trading.	blockchain	29	36
		green certificate market	20	28
		renewable purchase obligation	13	19
		carbon neutrality	8	12
		market mechanism	8	10
		power exchange	7	16
		renewable energy generation	7	10
		smart grid	6	10
		smart contract	6	8
		central electricity regulatory commission	5	12
		congestion management	5	11
		electricity spot market	5	11
		quota system	5	7

Table 7. *Cont.*

Research Theme	Cluster	Keywords	OC	TLS
Research theme C: Technological innovations and green certificate trading; positioned on the map's right side.	**Cluster 3 (**dark blue**):** Strategic market interactions and innovations in green energy distribution.	carbon emission trading	44	60
		electricity market	42	60
		green certificate trading	8	11
		optimization	7	11
		demand response	7	10
		distributed energy	7	7
		green electricity	6	5
		virtual power plant	5	7
		game theory	5	5
		electricity disclosure	5	1
Research theme D: Tradable green certificates and renewable energy sources investment strategies; positioned centrally and at the top of the map.	**Cluster 4 (**yellow**):** Advancing sustainability in renewable energy.	wind energy	29	48
		photovoltaic	28	50
		energy storage system	15	20
		sustainability	13	11
		life cycle assessment	9	10
		economic analysis	6	12
		solar energy	6	7
		wind turbine	5	10
		mixed integer linear programming	5	9
		wind farm	5	5
	Cluster 5 (purple**):** Renewable energy policies and investment analysis.	electricity	21	38
		renewable energy policy	12	16
		real options	10	17
		uncertainty	10	16
		generation expansion planning	10	12
		solar	9	18
		wind	8	19
		investment	5	14
		risk	5	11

Notes: OC = occurrence; **TLS** = total link strength.

5.1. Research Theme A: Support Mechanisms and Policies for Renewable Energy Sources

This research theme delves into the various strategies, policies, and models that promote and underpin the development of renewable energy sources. With a primary focus on support mechanisms, it critically examines the historical and innovative policy approaches that have been designed to foster the growth of green energy.

5.1.1. Cluster 7: Renewable Energy Policies and Strategies

This cluster evaluates the different mechanisms and strategies put in place to promote renewable energy sources. It looks at the "feed-in tariff" system, where producers are paid a set rate for the renewable energy they feed into the grid. Additionally, it assesses the various "support schemes" in place, along with the "auction" processes that are used to allocate renewable energy projects. An understanding of international agreements, such as

the "Kyoto protocol", and market-based solutions like "cap and trade", further underscores this cluster's comprehensive view on the methods used to foster renewable energy.

5.1.2. Cluster 9: Modeling Renewable Energy Policy Approaches

This cluster dives deep into the modeling and analytical methods used to understand and shape renewable energy policies. Central to this is the "renewable portfolio standard", which mandates a certain percentage of energy to come from renewable sources. To dissect the behavior and outcomes of these policy measures, methodologies like "system dynamics" and "evolutionary game" theories are employed. The role of "subsidies" as an influential tool in promoting renewable energy is also examined, highlighting its impact and implications in the broader renewable energy policy landscape.

5.2. Research Theme B: Tradable Green Certificates, Sustainable Renewable Technologies, and Market Dynamics

This research theme investigates the intersections of green certificates with sustainable renewable technologies (highlighted by keywords like "cogeneration", "bioenergy", and "biogas") and the market dynamics surrounding them. It delves into policy-driven innovations, transitions to more sustainable energy solutions through strategies such as "co-firing", and sheds light on the insights gained from studying renewable energy market dynamics.

5.2.1. Cluster 1: Policy-Driven Innovations and Efficiency in Renewable Energy Systems

This cluster focuses on the innovations prompted by renewable electricity policies aimed at reducing greenhouse gas emissions. It examines "energy efficiency" and the integration of "bioenergy" and "biogas" in the broader energy market. With tools like the "white certificate" to promote energy-saving measures, the cluster also looks at "cogeneration", where electricity and useful heat are simultaneously produced. Approaches such as "district heating" and "combined heat and power" are explored, all while considering the economic, efficiency, and environmental implications of these systems in the context of "climate change".

5.2.2. Cluster 6: Co-Firing Strategies in the Transition towards More Sustainable Energy Solutions

This cluster delves into the integration of "biomass" with other energy sources in "co-firing" setups to produce electricity, examining its impact on carbon pricing and its contribution to renewables. It performs a "techno-economic analysis" to understand the feasibility and profitability of these strategies, keeping in mind the broader goals of sustainability and reducing carbon emissions.

5.2.3. Cluster 8: Insights into Renewable Energy Market Dynamics

This cluster analyzes the intricacies of the renewable energy market, evaluating the influence of "energy policy" and potential "market power" wielded by dominant entities. Utilizing "equilibrium analysis", it seeks to understand the balance and interactions in the market, particularly in the face of different "policy instruments" aimed at promoting and regulating renewable energy sources.

5.3. Research Theme C: Technological Innovations and Green Certificate Trading

This research theme delves deep into the intersection of cutting-edge technological innovations with green certificate practices, emphasizing their role in fostering sustainable energy practices. Key focal points include the adoption of "blockchain" in green certificate trading, the role of regulatory frameworks in shaping the market, and the strategic interactions and innovations that steer the green energy distribution landscape.

5.3.1. Cluster 2: Technological and Regulatory Frameworks in Green Certificate Trading

This cluster focuses on how technologies, especially "blockchain", are revolutionizing the "green certificate market". "Smart contracts" on the "smart grid" are being used

to automate and secure renewable energy transactions. This is further augmented by mechanisms like the "renewable purchase obligation" aiming for "carbon neutrality". It also takes a closer look at the "power exchange" systems, "renewable energy generation", and the role of regulatory bodies, like the "central electricity regulatory commission", in shaping these market mechanisms. Concepts such as "congestion management" in the "electricity spot market" and the "quota system" underscore the intricate balance between technological advancements and regulatory guidelines.

5.3.2. Cluster 3: Strategic Market Interactions and Innovations in Green Energy Distribution

This cluster explores the intricate strategies at play in the green energy market. With the advent of "carbon emission trading", the "electricity market" is undergoing significant shifts. A significant focus is placed on "green certificate trading" and its integration into these markets. Advanced techniques, such as "optimization" and "game theory", are used to understand the dynamics of "demand response", "distributed energy", and the rise of "virtual power plants". Additionally, the cluster examines the role of "green electricity" in this evolving landscape, highlighting the increasing need for transparent "electricity disclosure" to consumers.

5.4. Research Theme D: Tradable Green Certificates and Renewable Energy Sources Investment Strategies

This research theme delves into the intricate relationship between green certificate trading and the strategies that drive investments in renewable energy sources. It highlights the economic, technological, and policy factors that shape investment decisions, with a focus on assessing the sustainability of renewable energy projects and understanding the uncertainties and risks associated with such investments.

5.4.1. Cluster 4: Advancing Sustainability in Renewable Energy

This cluster concentrates on furthering sustainability within the renewable energy sector, with a pronounced focus on "wind energy" and "photovoltaic" systems. The integration of "energy storage systems" and their role in enhancing the efficiency of renewable sources like "solar energy" and "wind energy" is explored. Comprehensive tools like "life cycle assessment" provide insights into the environmental impacts, while "economic analysis" assesses the viability of projects like "wind farms". Advanced computational methods such as "mixed integer linear programming" further help in optimizing the design and deployment of systems, ensuring a harmonious blend of sustainability and economic viability.

5.4.2. Cluster 5: Renewable Energy Policies and Investment Analysis

This cluster delves into the decision-making process behind investments in the renewable energy sector, particularly "solar" and "wind" energies. A central theme is the role of "renewable energy policy" and the instruments that facilitate or deter investments. The cluster brings to the fore tools like "real options", which help in evaluating investment opportunities in the face of "uncertainty". Additionally, it investigates the complexities of "generation expansion planning" to ensure a stable energy supply. The ever-present factors of "investment" and "risk" are explored in-depth, offering a comprehensive understanding of the landscape that shapes and directs investments in renewable energy.

6. Bibliographic Coupling Analysis

Bibliographic coupling, as introduced by Kessler [104], is a bibliometric method that identifies intellectual similarities between scientific works based on their shared references. The underlying assumption of this technique is that documents with common literature references are likely to have related content or themes [105,106]. This intellectual resemblance is manifested through patterns of referencing, where articles that cite similar sources are termed bibliographic couples [107]. The strength of association between two documents

is reflected through the number of shared references, with a higher number indicating a greater degree of thematic similarity [105,108].

Building on the concept of bibliographic coupling, we mapped the intellectual structure of the green certificates research domain by grouping articles into thematic clusters [109]. For meaningful comparison based on bibliographies, it is essential that the articles originate from a similar chronological context, ensuring they reference a congruent body of research [57,107,110]. As such, our focus narrowed to a subset of the entire research body: specifically, the 263 articles published from 2020 to 2022. Utilizing VOSviewer software [72], we crafted a visual representation of these articles' interrelationships (see Figure 6). Within this network, each node symbolizes an article. A node's circle size illustrates its relative connection frequency to other articles, its color denotes its intellectual cluster, and the thickness of the connecting lines reflects the count of mutual references. To enhance clarity, we omitted articles with a link strength of three or fewer, ensuring the analysis emphasizes the most influential and interconnected works in the field.

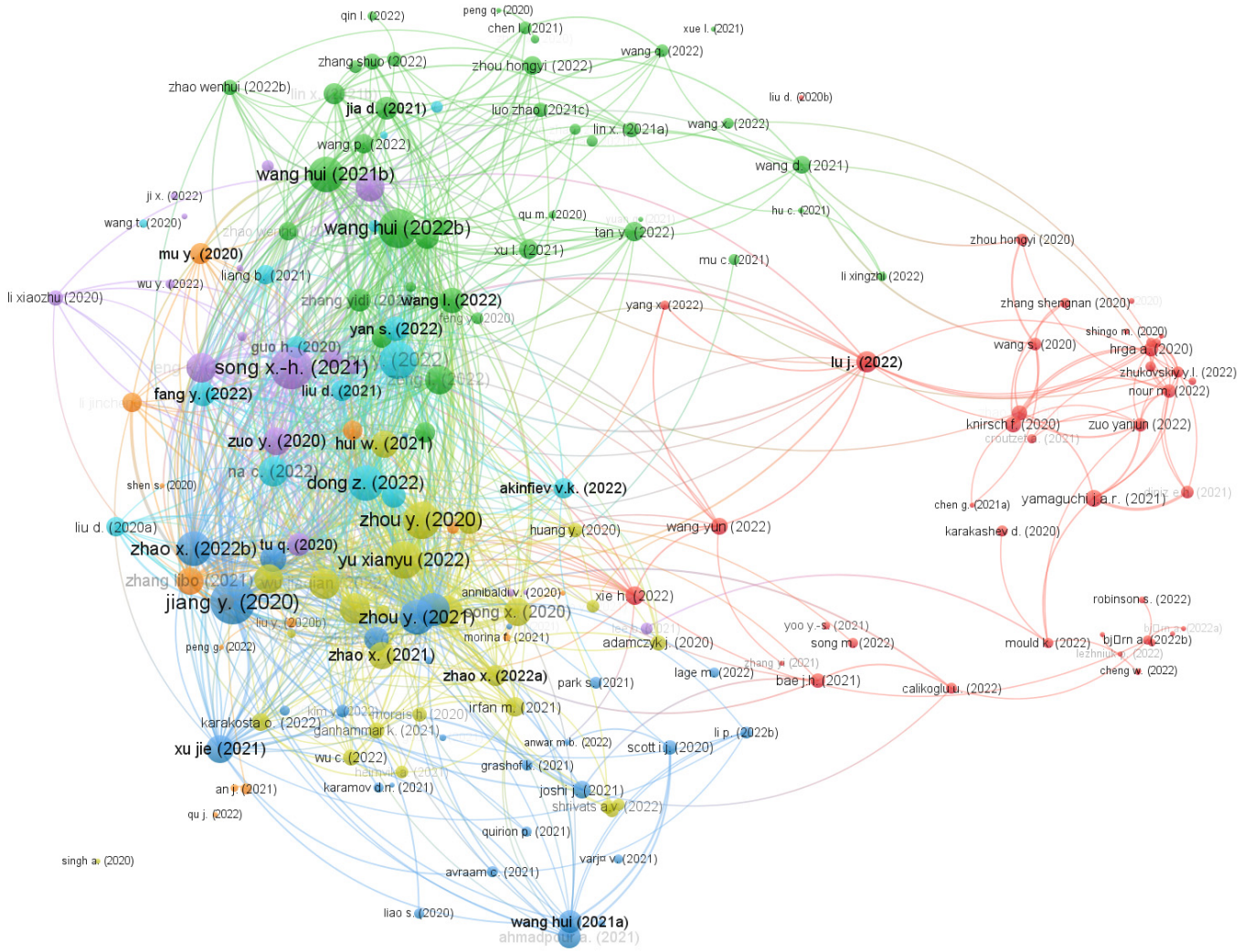

Figure 6. Bibliographic coupling network.

To prepare for this analysis, a rigorous data curation process was undertaken to address discrepancies in the raw Scopus citation data. Specifically, we identified and rectified many instances where the same source was cited inconsistently—owing to variations in referencing styles—which the VOSviewer software initially misinterpreted as distinct citations. This harmonization of citation data was an essential step to ensure the integrity

and validity of the bibliographic coupling analysis, providing a reliable foundation for identifying the thematic clusters within the research domain.

Bibliographic coupling analysis identified seven distinct clusters, encompassing 182 of the 263 articles (approximately 70%) published from 2020 to 2022. To discern the core content of each cluster, we thoroughly examined the articles they contained. We selected a representative subset of the most influential and interconnected articles within each cluster to determine central subjects. Subsequently, we designated names to the clusters based on these identified subjects. This methodology aligns with approaches adopted in previous research [111,112]. Specifically, we selected the top ten most-cited articles and the top five articles with the highest link strength from each cluster. As a result, our analysis encompassed a range of 10 to 15 articles per cluster, contingent upon the overlap between the most influential and interconnected articles. Detailed content analyses for each cluster are elaborated upon in the following subsections.

6.1. Cluster 1: Emerging Technologies on Green Certificates

This cluster, consisting of 41 articles, sheds light on the synergy of blockchain and other technological innovations, emphasizing their transformative capacity in reshaping green certificate systems and bolstering the evolution of sustainable energy practices. Blockchain emerges as a transparent, decentralized, and immutable platform for applications like green certificate trading and carbon emission trading [48,113–118]. Diniz et al. [50] explore its potential to streamline the Greenhouse Gas Protocol Program, specifically in scope 2 emissions. This is complemented by Knirsch et al. [119], who introduce a decentralized system for green energy certificates, and Hrga et al. [120], who discuss the broader applications of distributed ledger technologies in the energy sector. On the data front, Olindo et al. [121] call for improved databases and calculation rules in life cycle assessments, especially for electric vehicles and electrolytic hydrogen. This aligns with the discourse on green hydrogen standards and guarantees of origin [37,122]. FinTech's role in renewable energy adoption is also highlighted, particularly in crowdfunding and blockchain-based certificates [123]. Liu et al. [124] further examine the operational frameworks for entities like charging load aggregators in green certificate trading.

6.2. Cluster 2: Market-Based Mechanisms for Renewable Energy Market Optimization

This cluster, consisting of 39 articles, investigates the application of market-based mechanisms, particularly tradable green certificates, and their role in optimizing renewable energy markets, also exploring integrated approaches and various methodologies pertinent to the deployment and effectiveness of these mechanisms. Wang and Li [125] and Zeng et al. [45] lay the foundation by using bi-level decision-making models to achieve social welfare and cost-effective renewable portfolio standards targets. Zhang et al. [126] and Wang et al. [127] build upon this by employing simulation methods to explore renewable energy consumption and trans-provincial electricity market dynamics. Luo et al. [128,129] and Lin et al. [130] introduce integrated frameworks that merge carbon–green certificate trading with electricity spot markets, aligning with the insights of Wang et al. [131] and Qu et al. [132] on consumer preferences and provincial responsibilities. Peng et al. [133] extend the discussion by proposing coordinated mechanisms between national green certificate trading and provincial electricity markets. Incorporating technological innovations, Luo et al. [134] and Hongliang et al. [135] delve into the potential of blockchain and virtual power plants to enhance market efficiency and transparency. Game theory models by Liu et al. [136] and Zhou et al. [137] analyze the equilibrium strategies of market participants under renewable portfolio standards and tradable green certificates. Liu et al. [138] conclude the cluster by introducing compensation ancillary service schemes based on green certificates to incentivize service providers.

6.3. Cluster 3: Policy-Driven Strategies for Renewable Energy Advancement

This cluster, consisting of 30 articles, explores the role of policy-driven strategies, notably renewable portfolio standards and green certificates, in advancing renewable energy initiatives. Initiating the discussion within the Chinese context, Zhou et al. [139] and Zhao et al. [140] argue for the importance of scientifically designed renewable portfolio standards incentive mechanisms. This is further elaborated by Xu et al. [141] and Jiang et al. [142], who call for efficiency and fairness in renewable portfolio standards quota allocation. Zhou et al. [143] and Zhao et al. [144] broaden the scope by comparing the effectiveness of feed-in tariffs and renewable portfolio standards in achieving social welfare and grid parity within China. Expanding geographically, Joshi [25] provides evidence from the US that renewable portfolio standards significantly enhance renewable electricity capacity, particularly in the solar and wind sectors. Avraam et al. [145] examine the impact of renewable portfolio standards on the North American natural gas market, while Scott et al. [43] investigate the influence of long-term uncertainty on renewable energy market modeling. Specialized insights are offered by Ahmadpour et al. [42], who assess the social welfare implications of renewable energy certificates, and Wang et al. [146], who explore energy trading strategies in regional integrated energy systems.

6.4. Cluster 4: The Complex Interplay of Policies and Incentives in Renewable Energy

This cluster, consisting of 26 articles, explores the intricate interplay between various policies and incentives, such as feed-in tariffs and renewable portfolio standards, in the renewable energy sector. Zheng et al. [147] and Wu et al. [148] explore the intricacies of China's tradable green certificate market, focusing on social influence and policy coupling. Karakosta and Petropoulou [149] evaluate how national tradable green certificate systems align with broader EU renewable energy goals. Yu et al. [150] and Zhu et al. [151] delve into the effectiveness of integrating tradable green certificates with other policy instruments like feed-in tariffs and renewable energy certificates. Yu et al. [80] offer a specialized look at the integration of tradable green certificate trading with carbon emissions trading in China. Feng et al. [4] contribute to this context by discussing policy synergy and market optimization. Hui et al. [152] and Zhao and Zhou [153] analyze market behavior, focusing on the strategic actions of market participants and the effectiveness of renewable portfolio standards in China. Zhou et al. [154], Song et al. [155], and Xin [156] extend this by examining demand-side incentives and market efficiencies within China's tradable green certificate framework. Irfan [157] provides an Indian perspective, focusing on the market integration between electricity and renewable energy certificates. Adamczyk and Graczyk [41] conclude the cluster with a critique of Poland's green certificate system.

6.5. Cluster 5: Impact of Tradable Green Certificates on Market Dynamics

This cluster, consisting of 17 articles, highlights the pivotal role of tradable green certificates in shaping market dynamics, offering stakeholders a range of models and strategies to navigate the complexities introduced by policy changes. Wang et al. [158] and Leng et al. [159] lay the foundation by examining how tradable green certificates influence trading decisions and market efficiency, particularly in medium- and long-term electricity markets. Fan et al. [160] and Song et al. [161] build upon this by exploring optimization models that assess the role of tradable green certificates in market profitability and stability. Yan et al. [162] and Li et al. [163] add depth by incorporating carbon trading and dynamic environmental economic dispatch into these models. While the majority of the studies focus on China, Marinescu [164] provides insights from Romania, emphasizing how policy changes affect renewable energy producers and the role of green certificates. Annibaldi et al. [165] broaden the scope with a review of renewable energy policies, including the role of tradable green certificates. Zuo et al. [166] and Tu et al. [167] delve into the design parameters of tradable green certificate systems, aiming for social welfare maximization and grid parity for solar photovoltaic power. Zhao et al. [168] and Lee et al. [169] further enrich the discussion by exploring ladder bidding strategies in thermal power and

the economic feasibility of hydrogen energy storage systems, respectively, both within the context of tradable green certificates.

6.6. Cluster 6: Economic Incentives and Behavioral Dynamics in Renewable Energy Markets

This cluster, consisting of 15 articles, explores the role of economic incentives and behavioral dynamics in shaping renewable energy markets, particularly through the use of tradable green certificates and renewable portfolio standards. Yan et al. [170] and Yu et al. [171] delve into the economic aspects, proposing robust trading models and optimal dispatch strategies that incorporate green certificates and carbon emission rights. These frameworks are further refined by Hu et al. [172], who advocate for region-specific policies to enhance the effectiveness of renewable portfolio standards and tradable green certificates. On the behavioral front, Na et al. [173] and Liang et al. [174] employ evolutionary game theory to investigate the decision-making processes of green power plants and electricity retailers. Fang et al. [175] extend this approach by using a networked evolutionary game to study the impact of dynamic renewable portfolio standards on renewable energy diffusion. Dong et al. [46] offer a unique angle by examining the synergistic evolution of feed-in tariffs and renewable portfolio standards. Liu et al. [176,177] focus on market behavior and policy optimization, particularly in relation to quota systems and the role of thermal power plants under renewable portfolio standards. Wang et al. [178] introduce the concept of power insurance to optimize trading decisions, while Guo et al. [179] model the strategic behaviors of renewable energy in both energy and tradable green certificate markets.

6.7. Cluster 7: The Transformative Role of Green Certificates in Renewable Energy Investment

This cluster, consisting of 14 articles, delves into the transformative impact of tradable green certificates on investment strategies in the renewable energy sector. Starting with the foundational role of policy incentives, Peng et al. [180] and Zhang et al. [54] explore how tradable green certificates shape investment decisions in wind power and renewable energy portfolios. Wang et al. [181] and Qu and Jeon [182] further examine the transition to competitive electricity markets, emphasizing the stabilizing influence of renewable energy certificates in the face of subsidy and price volatilities. Safarzadeh et al. [183] argue for the efficacy of mandatory fines over subsidies in guiding traditional energy suppliers toward renewable alternatives. In the context of China's renewable energy landscape, Zhang et al. [47] and Chong et al. [184] explore the viability of renewable energy without subsidies, emphasizing the role of tradable green certificates and renewable energy quotas. Morina et al. [185] extend the scope to European firms, demonstrating that tradable green certificate schemes enhance long-term profitability. Shen et al. [186] and Mu et al. [187] contribute by investigating the economic efficacy of tradable green certificate markets and multi-market trading strategies under renewable energy quotas. Finally, Li et al. [188] and Liu et al. [189] explore investment strategies for thermal generation companies and the feasibility of achieving wind power grid parity, both through the lens of green certificate trading.

6.8. Alignment of Bibliographic Coupling Clusters with Keyword Co-Occurrence Themes

Our content analysis of the bibliographic coupling clusters reveals a strong alignment with the themes delineated in the keyword co-occurrence analysis, as detailed in Section 5.

Clusters 3 and 4 extensively explore the role of policy-driven strategies, incentives, and support mechanisms in advancing renewable energy initiatives. Both clusters delve into the intricacies of various policies, such as tradable green certificates and renewable portfolio standards, highlighting their significance in fostering the growth of green energy. This focus aligns seamlessly with Theme A, which emphasizes the importance of strategies, policies, and models that underpin the development of renewable energy sources.

Clusters 2, 5, and 6 extensively explore the role and impact of tradable green certificates in optimizing and shaping renewable energy market dynamics. These clusters delve into the intricate interplay of market mechanisms, economic incentives, and behavioral dynamics,

emphasizing the transformative influence of tradable green certificates on renewable energy markets. This comprehensive exploration aligns well with Theme B, which investigates the intersections of green certificates with sustainable renewable technologies and the associated market dynamics.

Cluster 1 extensively investigates the transformative role of blockchain and other emerging technologies in the realm of green certificates and renewable energy trading. The emphasis on the integration of these technological innovations with green certificate practices aligns directly with the focus of Theme C. Both the cluster and the theme underscore the pivotal role of cutting-edge technologies in enhancing sustainable energy practices, particularly in the context of green certificate trading.

Cluster 7 delves deeply into the profound influence of tradable green certificates on shaping investment strategies within the renewable energy sector. This exploration, which encompasses the economic, policy, and technological dimensions of investment decisions, aligns closely with the core tenets of Theme D. Both the cluster and the theme emphasize the pivotal role of green certificates in guiding and optimizing investment strategies, ensuring a sustainable transition in the energy landscape.

While the groupings may seem subjective, their validity is reinforced by the clusters' spatial positions on the map. For instance, the close proximity of clusters 3 (dark blue) and 4 (yellow) in the lower-left corner corresponds to Theme A. Similarly, clusters 2 (green), 5 (purple), and 6 (light blue) in the upper-left corner align with Theme B. Cluster 1 (red) on the map's right and Cluster 7 (orange) on the left resonate with Themes C and D, respectively. The reader can refer to Table 8 for an overview of these clusters within the aforementioned research themes. The table includes the top five references for each cluster, ranked by citation count, with the total link strength also provided for each article.

Table 8. Bibliographic coupling clusters within green certificates research themes.

Research Theme	Cluster	Lead Publications	TC	TLS
Research theme A: Support mechanisms and policies for renewable energy sources; positioned at the lower-left corner of the map.	**Cluster 3 (**dark blue**):** Policy-driven strategies for renewable energy advancement.	[142]	27	357
		[42]	22	96
		[144]	19	115
		[25]	16	61
		[141]	15	140
	Cluster 4 (yellow**):** The complex interplay of policies and incentives in renewable energy.	[80]	42	110
		[4]	34	32
		[154]	23	248
		[155]	21	146
		[151]	17	154
Research theme B: Tradable green certificates, sustainable renewable technologies, and market dynamics; positioned at the upper-left corner of the map.	**Cluster 2 (**green**):** Market-based mechanisms for renewable energy market optimization.	[138]	18	33
		[133]	17	6
		[137]	13	16
		[130]	10	47
		[134]	10	39
	Cluster 5 (purple**):** Impact of tradable green certificates on market dynamics.	[163]	53	44
		[167]	45	97
		[160]	13	11
		[164]	12	4
		[161]	11	315

Table 8. *Cont.*

Research Theme	Cluster	Lead Publications	TC	TLS
Research theme B: Tradable green certificates, sustainable renewable technologies, and market dynamics; positioned at the upper-left corner of the map.	**Cluster 6 (**light blue**):** Economic incentives and behavioral dynamics in renewable energy markets.	[179]	29	89
		[46]	8	226
		[176]	5	82
		[178]	5	16
		[175]	3	111
Research theme C: Technological innovations and green certificate trading; positioned on the map's right side.	**Cluster 1 (**red**):** Emerging technologies on green certificates.	[37]	89	4
		[114]	40	34
		[123]	26	17
		[48]	22	48
		[124]	15	5
Research theme D: Tradable green certificates and renewable energy sources investment strategies; positioned on the map's left side.	**Cluster 7 (**orange**):** The transformative role of green certificates in renewable energy investment.	[47]	15	135
		[54]	15	14
		[185]	8	14
		[189]	6	22
		[182]	4	4

Notes: TC = total citations; **TLS** = total link strength.

7. Emerging Green Certificates Research Themes

This section is devoted to explicating the unique attributes and historical context of each research theme associated with green certificates. Additionally, it demonstrates how they align with the specific use cases of green certificates, either as regulatory support instruments or as mechanisms for transparency and disclosure.

Research theme A (support mechanisms and policies for renewable energy sources) is unique in its comprehensive examination of the strategic and policy frameworks that underpin the growth of renewable energy. Unlike other themes, it delves deeply into the historical evolution and innovative approaches of policy development. Its focus on support mechanisms, including the intricate dynamics of policies, distinguishes it from other themes which might concentrate more on technological aspects or market dynamics.

Research theme B (tradable green certificates, sustainable renewable technologies, and market dynamics) uniquely bridges the gap between the conceptual framework of green certificates and their practical application in sustainable renewable technologies and market dynamics. It goes beyond mere policy analysis to explore how green certificates function in real-world market scenarios, considering the environmental, social, and governance objectives. The integration of complex market dynamics with sustainable renewable technologies sets this theme apart.

The distinctive aspect of research theme C (technological innovations and green certificate trading) lies in its focus on the intersection of cutting-edge technological advancements, such as blockchain and artificial intelligence, with the realm of green certificate trading. This theme advances our understanding of how these technologies can revolutionize the trading of green certificates, offering new insights into the efficiency, transparency, and reliability of green energy distribution. Its focus on the practical application of emerging technologies in green certificate trading makes it a unique and forward-looking area of study.

Research theme D (tradable green certificates and renewable energy sources investment strategies) stands out for its exploration of the complex relationship between green certificate trading and investment strategies in renewable energy sources. It uniquely combines economic, technological, and policy perspectives to analyze how green certificates

influence investment decisions. Its emphasis on the sustainability of renewable energy projects, as well as the uncertainties and risks involved in these investments, provides a comprehensive understanding of the financial aspects of green energy, distinguishing it from other themes which may focus more on policy or technology.

Moving beyond individual descriptions, it is crucial to understand how each research theme correlates with the two primary use cases of green certificates. Research theme A aligns with the first use case, where green certificates act as regulatory support instruments. It delves into the strategic and policy development from the early years of renewable energy policy, where green certificates began as tools for regulatory support. In contrast, research theme B corresponds with the second use case of green certificates, focusing on their role in enhancing transparency and disclosure in renewable energy markets. It extends beyond policy analysis to explore real-world applications and market dynamics, reflecting the certificates' use in providing verifiable proof of renewable energy sources. Similarly, research theme C aligns with the disclosure and transparency aspects of the second use case. It explores how emerging technologies like blockchain and AI intersect with green certificate trading, enhancing the transparency and reliability of energy sourcing. This focus on innovative technologies positions it at the forefront of the disclosure role of green certificates. Lastly, research theme D uniquely combines elements of both use cases. It examines how green certificates, as regulatory tools, influence investment strategies, tying in the regulatory aspect. Simultaneously, its focus on sustainability and risk analysis in investments reflects the disclosure role of green certificates in the renewable energy market. This dual alignment allows for a comprehensive understanding of green certificates' impact on financial decisions in the renewable energy sector. Together, these research themes comprehensively cover the spectrum of green certificates' applications, from regulatory support to market transparency and investment strategies, showcasing their evolving role in the renewable energy sector.

8. Future Directions on the Green Certificates Research Themes

After discerning the four pivotal research themes within the green certificates domain—substantiated by both bibliographic coupling and keyword co-occurrence analyses—we turn our attention to delineating prospective avenues for further exploration, tailored to each theme. Drawing from a thorough examination of contemporary seminal works pinpointed through our bibliographic coupling analysis, we aim to bridge the gaps in the existing body of knowledge by spotlighting underexplored areas and emergent inquiries. This section serves as a compass, guiding scholars towards relatively uncharted territories in the ever-evolving landscape of green certificates research. Table 9, which is presented at the end of this section, provides a structured overview of the future directions in green certificates research across the four identified themes.

8.1. Research Theme A: Support Mechanisms and Policies for Renewable Energy Sources

As the realm of renewable energy expands, the role of green certificates and their associated support mechanisms and policies becomes increasingly paramount. Both countries and companies, in their pursuit of sustainability, must grasp the intricacies of these mechanisms and policies.

The policy landscape for renewable energy is vast, encompassing a range of support mechanisms from investment-based incentives to production-based mechanisms, like tradeable green certificates and renewable portfolio standards. Understanding how these mechanisms, in conjunction with price-based approaches such as fixed and variable subsidies, shape the renewable energy landscape is essential. Furthermore, insights into their interplay with guarantees of origin, especially their hourly based variants, and their synergy with power purchase agreements, can offer a deeper understanding of their influence on corporate sustainability initiatives.

Drawing from the experiences of leading renewable energy countries, both developed and developing, can offer invaluable insights into optimizing governmental tools for

maximum renewable energy production. A global comparative analysis of support mechanisms, including feed-in tariff systems, and auction processes, can provide a comprehensive understanding of their effectiveness in varied socio-economic and political contexts.

Delving further into the subject matter, tradable green certificates stand out as a significant area of focus. A comparative study of tradable green certificate markets, especially between emerging economies and established players, can reveal best practices and areas ripe for innovation. Furthermore, the dynamics of renewable energy certificate tracking systems, especially in the context of potential governmental interventions, present another promising research avenue.

Small and medium-sized enterprises (SMEs) play a pivotal role in the renewable energy landscape. Delving into the factors influencing SMEs' adoption of green electricity across different industrial sectors can illuminate pathways to broader green electricity adoption, aligning with overarching governmental sustainability goals.

From a theoretical standpoint, while system dynamics and evolutionary game theories have provided valuable insights, there is potential to delve into other advanced modeling techniques or even to combine multiple methodologies for a holistic understanding of renewable energy policies.

Finally, in advancing research within the green energy sector, a paramount focus should be on fostering transparency and trust, especially concerning electricity disclosure. The rising significance of electricity disclosure is instrumental in cultivating trust. For this process to gain consistent credibility, the establishment of rigorous guidelines and standards is imperative. Furthermore, aligning the trade of energy certificates with tangible capacities is essential for market transparency and reliability, thereby enabling consumers to make well-informed decisions. Emphasizing total disclosure, which includes all energy sources and their environmental footprints, is vital. Such an approach not only amplifies sustainability initiatives but also strengthens trust with stakeholders.

8.2. Research Theme B: Tradable Green Certificates, Sustainable Renewable Technologies, and Market Dynamics

The global energy landscape is in the midst of a transformative shift, with a growing interest in tradable green certificates, especially within the domains of sustainable renewable technologies and market dynamics. As we transition towards a more sustainable future, understanding the complex nuances of these dynamics is of utmost importance.

The interplay between the harmonization of the European guarantee of origin markets and overarching environmental, social, and governance objectives represents a pivotal avenue for upcoming research endeavors. A critical examination of how a cohesive guarantee of origin market, aligned with environmental, social, and governance benchmarks, can catalyze international collaboration and promote equitable renewable energy distribution is imperative. Furthermore, the significance of corporate sustainability reporting directives in reinforcing this alignment warrants in-depth exploration. The integration of machine learning with sustainability insights offers a robust approach to fortify this harmonization, acting as a safeguard against deceptive tactics such as greenwashing. Concurrently, it is essential to probe the evolving paradigms of corporate theories, including corporate social responsibility, to discern their influence on renewable energy practices in firms, thereby shedding light on their role in shaping the sustainable energy landscape in corporate contexts.

The role of green gas certificates in quantifying energy supply and assessing the sustainability of renewable gases from diverse sources is another pivotal area of exploration. A comprehensive understanding of all process stages, from production to consumption, is essential for crafting a robust certification framework for renewable gas.

Central to the renewable energy discourse is the role of green hydrogen standards. The complexities surrounding the potential requirement for guarantees of origin to encompass carbon intensity details necessitate a deep dive into hydrogen pathways. This includes understanding cost structures, greenhouse gas emissions, and the implications of adopting

varied definitions. Such insights are pivotal for crafting robust certification frameworks. The momentum towards future hydrogen strategies, which encompasses the value chain, technological dominance, geopolitical dynamics, and water resource implications, calls for a comprehensive global strategy. This strategy should aim to develop low-carbon hydrogen pathways and foster international cooperation. Furthermore, the discourse on green hydrogen standards and guarantees of origin presents a unique challenge. The potential of these standards to enhance customer choice, compared with the risk of confusion due to varied hydrogen labels, underscores the importance of understanding their impact on consumers.

The integration of CO_2 capture and storage in energy production presents an intriguing avenue for future research. This includes exploring certification processes using guarantees of origin, which could offer insights into the sustainability and traceability of this technology. Further investigation into the challenges and potential of green hydrogen blending in gas-to-power technologies is also crucial. Additionally, the role of nuclear power, particularly in the context of producing green hydrogen as per the new EU taxonomy, warrants exploration. These technologies, while varied in their nature, contribute to a more comprehensive understanding of the renewable energy landscape. Utilizing equilibrium analysis can illuminate how different policy instruments influence the balance and interactions in this market. Furthermore, economic incentives, especially those related to tradable green certificates and renewable portfolio standards, are pivotal in shaping the renewable energy landscape. Evaluating the long-term impact of these incentives on market dynamics remains essential for understanding future investment portfolios and the evolving energy sector.

The liquidity of green power markets and the influence of tradable green certificates on transparent price discovery present another promising avenue for academic exploration. Delving into the potential trade-offs, competition with other market and policy objectives, and the broader impact of tradable green certificates on renewable energy market dynamics is crucial. Additionally, the interplay between green energy expansion and economic growth, especially when integrated with econometric methods and system dynamics models, can provide a richer understanding of the prevailing dynamics.

Finally, the shift towards competitive electricity markets, underscored in contemporary literature, is abundant with challenges and opportunities. Exploring the nuances of this transition, particularly when compared with tradable green certificate trading, can reveal the complexities of market dynamics, regulatory hurdles, and the investment landscape.

8.3. Research Theme C: Technological Innovations and Green Certificate Trading

Technological innovations, particularly in the realm of green certificate trading, are taking center stage in shaping the future of sustainable energy. As we transition towards a greener future, understanding the multifaceted dynamics of this domain is essential.

The rapid evolution of technologies such as artificial intelligence and blockchain promises to reshape the energy sector. These technologies, combined with innovative model-building methods like integration flows modeling, are set to redefine the design and operation of future smart energy systems. Investigating the potential and implications of these advancements is vital for the future trajectory of green certificate trading.

Blockchain's potential in reducing transactional costs, especially in guarantee of origin schemes, promoting compliance, streamlining trading, and enhancing transparency is undeniable. Furthermore, blockchain and microgrid solutions are at the forefront of energy sector innovations. Ensuring their successful adoption necessitates robust stakeholder engagement, encompassing both energy consumers and producers. Building trust and raising awareness about the benefits of these technologies can catalyze their widespread acceptance. Additionally, understanding blockchain's impact on "24/7" certification, demand response, and the implications of this certification scheme across regions is essential.

Additionally, the intersection of artificial intelligence and greenwashing presents a unique research avenue. Exploring data-driven methods for sourcing and reporting envi-

ronmental information and investigating data authentication techniques related to green claims can offer a holistic perspective on greenwashing dynamics. However, challenges persist, including the need for regulatory support, industry collaboration, and further technological refinement.

Furthermore, the increasing significance of power-to-gas, gas-to-power, and gas-to-gas systems in energy markets highlights the importance of green hydrogen. Crafting a comprehensive green hydrogen guarantee of origin scheme, which addresses its definition, carbon intensity details, and production–consumption dynamics, is crucial. Moreover, the role of consistent policy frameworks and international collaborations cannot be understated, especially in promoting economic growth, facilitating hydrogen trade, and safeguarding producers.

Finally, an in-depth examination of the complex interactions among tradable green certificate prices, carbon within the EU emissions trading system, and electricity in energy exchanges is paramount to elucidate their sustained interactions. As global momentum shifts towards carbon peak and neutrality targets, comprehending stakeholder decision-making processes in the realms of green certificates, green electricity, and carbon trading becomes ever more vital. The intricate dynamics inherent in these trading mechanisms present a fertile ground for scholarly investigation.

8.4. Research Theme D: Tradable Green Certificates and Renewable Energy Sources Investment Strategies

The intricate interplay between tradable green certificates and renewable energy sources investment strategies is gaining prominence in the academic realm. As the global thrust towards sustainability intensifies, delving deep into this multifaceted domain is of paramount importance.

Central to this exploration is the life cycle assessment of renewable energy projects. Understanding the long-term environmental consequences, especially when intertwined with tradable green certificates, can offer a holistic view of the environmental footprint from inception to decommissioning. Such insights are pivotal for investors and policymakers aiming for environmentally conscious decisions.

The transformative power of renewable energy policy in steering investments is another recurrent theme. Delving deeper into the efficacy of various policy instruments, especially their differential impacts across regions or countries, can illuminate the nuances of policy-induced renewable investments. This includes understanding the role of tradable green certificates in shaping investment strategies, particularly in nascent markets.

The crossroads faced by traditional energy suppliers, notably thermal generation entities, also warrants attention. Exploring avenues for these leaders to capitalize on tradable green certificate trading to pivot towards greener energy sources can chart the course for the sector's transformation.

Furthermore, a compelling area of research is the comparative efficacy of mandatory penalties versus subsidies. By analyzing the repercussions of diverse policy tools on steering energy suppliers towards green alternatives, future research can identify the most effective strategies to promote green energy adoption.

The aftermath of COVID-19 has reshaped the parameters of the green finance landscape. Investigating the socio-economic consequences of the pandemic, especially set against the backdrop of green finance policies and the evolution of a low-carbon economy, can shed light on the resilience of green finance mechanisms amidst global disruptions.

Finally, the constraints spotlighted in current literature, encompassing uncertainties in financing costs, energy consumption, and evolving policies, emphasize the imperative for robust research methodologies. Future endeavors can address these gaps by integrating more reliable data streams, broadening the certificate spectrum, and crafting scientific scenarios rooted in industry evolution and policy recalibrations.

Table 9. Future research directions in green certificates across major research themes.

Research Theme	Key Directions for Future Research
Research Theme A: Support mechanisms and policies for renewable energy sources	➢ Comparative analysis of support mechanisms in varied contexts. ➢ Tradable green certificate market studies between emerging and established economies. ➢ Dynamics of renewable energy certificate tracking systems. ➢ Factors influencing SMEs' adoption of green electricity. ➢ Potential of advanced modeling techniques in understanding renewable energy policies. ➢ Importance of electricity disclosure and total disclosure.
Research Theme B: Tradable green certificates, sustainable renewable technologies, and market dynamics	➢ Interplay between European guarantee of origin markets and environmental, social, and governance objectives. ➢ Role of corporate sustainability reporting directives. ➢ Influence of corporate theories on renewable energy practices. ➢ Role of green certificates in renewable gas certification. ➢ Complexities surrounding green hydrogen certification standards. ➢ Potential integration of various energy sources into future portfolios. ➢ Influence of tradable green certificates on transparent price discovery. ➢ Transition challenges towards competitive electricity markets and tradable green certificate trading.
Research Theme C: Technological innovations and green certificate trading	➢ Potential of technologies like artificial intelligence and blockchain in reshaping the energy sector and green certificate trading. ➢ Role of blockchain in guarantee of origin schemes. ➢ Impact of blockchain on "24/7" certification. ➢ Intersection of artificial intelligence and greenwashing. ➢ Importance of power-to-gas, gas-to-power, and gas-to-gas systems. ➢ Examination of interactions among tradable green certificate prices, EU emission trading system, and energy exchanges.
Research Theme D: Tradable green certificates and renewable energy sources investment strategies	➢ Life cycle assessment of renewable energy projects. ➢ Role of renewable energy policy in investment decisions. ➢ Role of tradable green certificates in investment strategies. ➢ Potential avenues for traditional energy suppliers in tradable green certificate trading. ➢ Comparative efficacy of penalties versus subsidies. ➢ Impact of COVID-19 on the green finance landscape. ➢ Addressing uncertainties in financing, consumption, and policies.

9. Discussion and Conclusions

The urgent need for sustainable practices has grown exponentially in recent years, driven by escalating environmental concerns. Green certificates, as tradable commodities representing proof of electricity generation from renewable sources, have become instrumental in this context. They enable organizations to demonstrate their commitment to clean energy and sustainable practices, especially in the face of the global push towards a low-carbon economy.

This study employed a comprehensive bibliometric analysis to explore the literature on green certificates. The research was guided by ten research questions, covering various facets of the domain, from publication patterns and influential works to collaborative dynamics and overarching conceptual and intellectual structures. The literature data were collected from the Scopus database, and 940 related publications were obtained after cleaning the data.

Our comprehensive performance analysis of green certificates research revealed significant insights into the field's evolution and current state. The publication trend has experienced exponential growth since the first article appeared in 2000, with a notable surge in publications after 2010, reflecting the increasing importance of renewable energy and sustainable practices.

By 2022, the field had produced 940 articles, with 67% of these published in the last decade, highlighting the topic's contemporary relevance. The most influential articles

have primarily addressed green certificates and renewable energy support schemes, policy comparisons, and interactions between green certificate markets and other energy markets. China emerged as the dominant contributor in terms of publications, while European nations, particularly Scandinavian countries, demonstrated significant academic influence. The journals *Energy Policy* and *Renewable and Sustainable Energy Reviews* stood out as leading platforms for disseminating influential research in this domain.

The co-authorship networks in the realm of green certificates research highlight distinct patterns of collaboration at both the author and country levels. At the author level, the network showcases certain key figures, such as Zhao X., Resch G., and Ragwitz M., as central to collaborative endeavors. However, the network also reveals a tendency towards insular clusters, with limited cross-cluster interactions, suggesting a preference for consistent team collaborations. On a country level, while China leads in total publications, it exhibits a relative insularity in international collaborations. In contrast, the UK, the US, and Germany emerge as central nodes, fostering extensive international collaborations.

The keyword co-occurrence analysis, employed to map the conceptual structure of green certificates research, revealed a complex array of interconnected themes. Through rigorous refinement, 79 core keywords were identified, with terms like "renewable energy", "renewable portfolio standard", and "feed-in tariff" emerging as the most frequent. The resultant network map unveiled nine distinct clusters, which were further grouped into four overarching research themes: "support mechanisms and policies for renewable energy sources", "tradable green certificates, sustainable renewable technologies, and market dynamics", "technological innovations and green certificate trading", and "tradable green certificates and renewable energy sources investment strategies".

The bibliographic coupling analysis was employed to map the intellectual structure of green certificates research. Focusing on articles from 2020 to 2022, the analysis identified seven distinct clusters. These clusters were thoroughly examined to discern their core content, leading to their categorization into specific themes. Notably, the emergence of these clusters provided further validation for the four major research themes previously identified in the keyword co-occurrence analysis. This alignment underscores the robustness and consistency of the identified themes, reaffirming their significance and centrality in the broader green certificates research domain.

Several implications emerge from this study, impacting the academic community, policymakers, and industry practitioners. Academically, our comprehensive bibliometric analysis offers a significant advancement in understanding green certificates, revealing notable gaps in the literature and serving as a foundational reference for future research. The study emphasizes the transformative role of green certificates in the renewable energy discourse. From a policy and managerial perspective, the findings underscore the pivotal role of green certificates in shaping renewable energy markets. Their profound influence on investment decisions, market dynamics, and policy frameworks suggests that policymakers and industry practitioners can benefit from these insights. The study also highlights the importance of transparency, robust certification frameworks, and a harmonized approach to integrating green certificates into the broader renewable energy landscape.

This study has highlighted several avenues for future exploration in the realm of green certificates. Among the most prominent directions identified are the comprehensive understanding of support mechanisms for renewable energy, with a focus on the interplay between feed-in tariff, renewable portfolio standards, and guarantees of origin. The increasing importance of electricity disclosure and the need for rigorous guidelines and standards to foster transparency and trust in the green energy sector are also underscored. The harmonization of the European guarantee of origin markets with environmental, social, and governance objectives, and the potential of machine learning to combat deceptive practices like greenwashing, are pivotal areas for future research. The discourse on green hydrogen standards, the complexities of their potential requirements, and the momentum towards future hydrogen strategies highlight the evolving nature of the renewable energy sector. The potential of emerging technologies, such as artificial intelligence and blockchain,

in reshaping the energy sector and their implications for green certificate trading are also emphasized. Furthermore, the liquidity of green power markets, the influence of tradable green certificates on price discovery, and the intricate dynamics of trading mechanisms offer rich avenues for academic exploration. Lastly, the life cycle assessment of renewable energy projects and the role of tradable green certificates in shaping investment strategies provide a holistic perspective on the environmental footprint and investment dynamics in the realm of green certificates.

While this study offers a comprehensive bibliometric analysis of the green certificates domain, it is not without its limitations. One primary constraint is the reliance on a single database, Scopus, for sourcing the research articles. This could potentially overlook significant contributions from other databases or platforms. Additionally, the study's methodological approach, while rigorous, might have inherent biases due to the chosen software and tools, such as VOSviewer for bibliometric mapping and network visualization. Furthermore, the content analysis, despite its thorough approach, inherently relies on the researchers' interpretations of the data. This subjective nature can introduce biases, as interpretations might vary even from the same set of data. Additionally, the clustering methodology used in our study has its own limitations. The unique allocation of keywords or articles to single clusters and the natural overlaps among thematic clusters are inherent to the bibliometric analysis. These constraints may sometimes limit the multi-dimensional relevance of certain topics and result in overlaps in thematic categorization. Such overlaps, while reflecting the interconnected nature of the green certificates field, may obscure the distinct boundaries of our identified research themes. Despite our best efforts to address these limitations, some level of constraint is unavoidable in such an extensive bibliometric study.

Nevertheless, by providing a holistic perspective using a comprehensive bibliometric analysis, we feel that our study offers a number of important contributions in the green certificates field. Firstly, the identification of four overarching research themes provides a 'big picture' view of the field, marking a significant advancement in understanding green certificates. This was achieved using a dual-method approach of keyword co-occurrence analysis and bibliographic coupling analysis, enhancing the robustness and depth of our findings. Secondly, our systematic examination of publication trajectories, the impact of seminal works, and the contributions of authors, institutions, countries, and journals has led to the first panoramic view of the evolution of the green certificates field. Thirdly, the study illuminates the collaborative dynamics within the field, revealing complex patterns of author- and country-level interactions, and delineating the key nodes and networks shaping the field's academic community. Finally, our thematic approach to proposing future research directions is among the most exhaustive and forward-looking within the existing literature, adding substantial value to the domain.

In the journey towards a sustainable and low-carbon economy, green certificates play an indispensable role. They serve as a testament to the global commitment to renewable energy and underscore the importance of sustainable practices in energy consumption and production. As the discourse around green certificates continues to evolve, it is imperative for continued research and collaboration. Academics, policymakers, and industry practitioners alike must join forces to further the understanding and adoption of green certificates, ensuring that they remain at the forefront of the transition to a greener future.

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