

“Renewable energy investments: Exploring the financial landscape through a bibliometric analysis”

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RENEWABLE ENERGY INVESTMENTS: EXPLORING THE FINANCIAL LANDSCAPE THROUGH A BIBLIOMETRIC ANALYSIS

Abstract

As renewable energy is now central to decarbonization and energy security, understanding how financial indices, green bonds, and venture capital steer capital flows has become crucial. This article aims to conduct a comprehensive bibliometric and science-mapping analysis of scholarly research on financial indices, green bonds, and venture capital in the context of renewable energy, to reveal the intellectual structure, thematic trends, and research gaps most relevant to investment management and financial innovations. Based on a Scopus dataset of 299 articles published between 1991 and 2023, the study employs Bibliometrix in R, standard performance metrics, and network-mapping techniques for co-authorship, co-citation, and keyword co-occurrence analysis. The results indicate a marked acceleration in publication activity after 2012, accompanied by rising citation rates and the emergence of a distinct research domain at the intersection of renewable energy and finance. This domain is characterized by a small core of journals and authors that account for a disproportionately large share of output and impact. Country analysis reveals a strong dominance of advanced economies, particularly the United States, China, the United Kingdom, Germany, Australia, and Italy. At the same time, many regions with substantial renewable energy potential remain underrepresented. Thematic and conceptual mapping shows that "investments" form the central organizing concept of the field; financial indices and stock-market linkages between fossil and clean-energy assets constitute a mature, densely connected cluster; green bonds and sustainable finance appear as a rapidly expanding frontier; venture capital and early-stage finance, though still peripheral, are gaining prominence in connection with policy stability, innovation support and market design.

Keywords

investment, financing, green bond, venture capital,
renewable energy, bibliometric analysis

JEL Classification

Q42, Q48, Q56

INTRODUCTION

The financial landscape of renewable energy is undergoing a rapid yet uneven transformation, making its systematic study both timely and policy critical. Global investment in clean energy technologies now exceeds spending on fossil fuels. At the same time, commitments to triple renewable capacity by 2030 underscore the urgency of understanding how financial markets channel and price this capital (IEA, 2024a). Against the backdrop of these trends and the need to align with 1.5°C pathways, understanding how financial markets channel and price this capital becomes a core research task rather than a niche topic.

Within this context, specialized financial indices, green bonds, and climate-oriented venture capital have emerged as key transmission mechanisms between capital markets and real-economy renewable deployment. These instruments shape the cost of capital for renewable

energy companies, influence portfolio allocation decisions, and are increasingly used by regulators as market-based indicators of progress toward the transition. However, their behavior remains sensitive to macro-financial shocks and interest-rate cycles, raising open research questions about volatility, contagion, and the robustness of decarbonization incentives embedded in financial markets.

The current configuration of these financial mechanisms forms a complex, evolving ecosystem that largely determines whether macro-level investment commitments can be sustained and broadened to lagging regions. Research on the financial landscape of renewable energy is therefore highly relevant for identifying how these instruments influence the cost of capital, risk allocation, and spatial distribution of renewable projects; how they respond to macro-financial shocks; and what regulatory or policy frameworks are needed to ensure that record investment volumes translate into an equitable, accelerated, and durable energy transition.

1. LITERATURE REVIEW

Recent assessments of global energy investment provide essential context for understanding the financial landscape of renewable energy. IEA data indicate that global energy investment is expected to exceed USD 3 trillion in 2024, with approximately USD 2 trillion allocated to clean energy technologies and infrastructure, meaning that spending on renewables, grids, and storage is now surpassing total investment in fossil fuels (IEA, 2024b). IRENA's Global Landscape of Energy Transition Finance reports that total energy-transition investments reached about USD 2.4 trillion in 2024, with roughly USD 807 billion flowing specifically into renewable energy technologies, even though the growth rate of renewable spending has started to slow and remains heavily concentrated in advanced economies and China (IRENA and CPI, 2025). Climate-finance monitoring by the IMF indicates that green equity and green bond indices have formed a distinct segment of global capital markets, tracking investor sentiment and risk premiums for low-carbon assets relative to conventional benchmarks (Gautam et al., 2024).

Green bonds have evolved from a niche innovation to a central pillar of renewable energy finance, particularly in Europe. Through the European Green Deal and its sustainable finance strategy, the European Commission aims to mobilize at least EUR 1 trillion of sustainable investment, with NextGenerationEU green bonds channeling capital into clean energy, energy efficiency, and climate adaptation projects (European Commission, n.d.). The introduction of the EU Green Bond Standard establishes a "gold standard" framework

that tightly couples the use of proceeds from bonds to the EU Taxonomy, directly linking financial instruments to technically defined renewable and sustainable activities (Dineen, 2025). At the same time, IMF and IFC analyses indicate that green bond issuance in many emerging and developing economies remains modest, facing fragmentation, regulatory uncertainty, and higher financing costs (Radzewicz-Bak et al., 2024). Venture capital and private equity for climate-tech and renewable energy add another dynamic layer: energy-transition investment trends indicate strong growth in climate-tech venture funding, encompassing solar, wind, storage, hydrogen, and digital optimization of energy systems, although these flows remain cyclical and heavily skewed towards a small number of markets and technologies (BloombergNEF, 2024). These high-risk capital streams are often the main drivers of innovation in early-stage renewable technologies and business models. Yet, the interaction between venture capital, public support schemes, and later-stage green bond or project finance structures remains poorly understood.

The global shift towards renewable energy has transformed questions of energy technology and policy into questions of finance, institutional design, and information flows. Renewable energy is increasingly framed as a means to reconcile economic performance, environmental protection, and energy security across advanced and emerging economies; however, the extent to which this transition can be financed at scale remains contested (Balcerzak et al., 2024; Havrylenko & Myroshnychenko, 2025; Trinh, 2025). Evidence on the relationship between economic growth cycles and environmental pressures underlines that

uncoordinated expansion can intensify ecological burdens, reinforcing the need for deliberate low-carbon investment strategies (Kubatko et al., 2025; Mukhtarov et al., 2024). Composite indices that jointly capture economic, environmental, and energy-security dimensions show that countries are positioned very differently in terms of the structural preconditions for sustainable energy finance, particularly when security of supply, environmental quality, and growth objectives collide (Mentel et al., 2020). Studies of national contexts reveal that green energy in countries such as Ukraine is shaped by a combination of public demand, institutional constraints, and policy instability, which in turn influence investor confidence and capital flows into renewables and household solar projects (Kurbatova et al., 2025; Kuzior et al., 2021). Research on public health and local air pollution adds a layer of urgency by linking renewable-energy deployment directly to health outcomes and social welfare, thereby strengthening the case for sustained green investment (Badreddine & Larbi Cherif, 2024). Taken together, these contributions suggest a complex macro-landscape in which renewable energy finance is shaped by concerns over energy security, institutional quality, and socio-environmental risks (Bai et al., 2024; Ghimire et al., 2025).

Within this broader transition, sustainable finance and green fiscal policy emerge as key mechanisms for directing capital towards low-carbon energy systems. Green fiscal instruments, such as targeted subsidies, tax incentives, and energy-saving policies, aim to reduce pollution and carbon emissions, influencing the relative profitability of fossil and renewable projects and, consequently, the composition of investment portfolios (Bai et al., 2024). Environmental tax reforms designed to internalize ecological costs are shown to alter both firm behavior and the revenue base available for green spending, with composite evaluations highlighting their role in promoting pro-environmental choices and creating fiscal space for transition-supporting measures (Mentel et al., 2020; Samusevych et al., 2024; Vasilyeva et al., 2023). Analyses of sustainable finance in the context of the European Green Deal emphasize that financial markets, regulatory frameworks, and disclosure standards are being re-oriented to align capital allocation with climate and energy

objectives, positioning sustainable finance as a key pillar of the European green course (Streimikiene et al., 2024). At the same time, research on green finance and energy transition reveals that financial flows are unevenly distributed across countries and technologies, and that risk perceptions, policy credibility, and macro-financial conditions significantly condition the scale and direction of green capital (Sang, 2024; Xu et al., 2024). Debt-for-nature swaps and related innovations in sovereign green finance further illustrate how environmental objectives can be embedded in financial contracts, but also highlight the complexity of aligning debt relief, conservation goals, and national development priorities (Oskay, 2025). These strands suggest that renewable-energy finance cannot be separated from broader debates on environmental taxation, fiscal reform, and sustainable finance architecture.

More specific work addresses how individual financial instruments and market dynamics shape investment in renewable energy. The interaction between commodity markets and clean-energy equities suggests that price movements in oil, gold, and natural gas are transmitted to clean-energy stock prices, with implications for portfolio diversification, risk management, and the cost of capital for renewable firms (Baghirzade & Kosormyhin, 2025). Feed-in tariffs are examined not only as support schemes for renewable producers but also as drivers of green finance, with evidence that stable tariff regimes can incentivize banks and institutional investors to expand their exposure to renewables (Shcherbakova, 2025). In parallel, the role of insurance companies is explored through the lens of how feed-in tariffs alter risk–return profiles, creating conditions under which insurers consider renewables an attractive asset class and thereby broadening the investor base for the sector (Lyeonov et al., 2025a). Studies on environmental taxation and pro-environmental behavior highlight that fiscal and financial incentives interact with household and firm decisions, reinforcing or undermining price-based signals from energy and capital markets (Samusevych et al., 2024; Vasilyeva et al., 2023). This body of work sketches part of the financial landscape surrounding renewable energy – including stock markets, banking, insurance, and public finance – but remains fragmented across instruments and jurisdictions,

leaving open questions about the overall configuration and evolution of renewable-energy finance as a research field.

Entrepreneurship, start-ups, and innovation ecosystems form another crucial layer of the financial landscape. Clean and digital energy start-ups face significant barriers related to access to credit, investor protection, and regulatory burdens, with empirical analyses highlighting how weak protection of minority investors and opaque regulatory environments constrain the ability of innovative firms to secure finance and scale their solutions (Artyukhov et al., 2024; Halynskiy & Telizhenko, 2024; Myroshnychenko et al., 2024). Tax-burden indicators and the ease of tax compliance are also found to influence the development of clean and digital energy start-ups, linking fiscal design directly to entrepreneurship in the energy sector (Halynskiy et al., 2024). At the firm level, principal component analysis of small and medium-sized enterprises reveals heterogeneous progress toward sustainable activities, suggesting that access to finance and policy support for eco-innovations varies substantially, even within integrated markets such as the European Union (Juracka & Valaskova, 2025; Juracka et al., 2024). Household-level solar energy adoption and community-based energy solutions, including energy communities and home energy management systems, further demonstrate how local policy incentives, infrastructure conditions, and financing models interact to shape decentralized renewable energy investments (Delcea et al., 2024; Gualandri & Kuzior, 2023; Kurbatova et al., 2025). In parallel, research on the evolution of green energy sectors in transition economies documents the interplay between state support, public demand, and private initiative, indicating that financing constraints and policy volatility remain binding obstacles to a broader diffusion of renewables (Kuzior et al., 2021). Collectively, these studies demonstrate that the financial landscape of renewable energy encompasses not only large-scale utility projects but also a diverse array of start-ups, SMEs, communities, and households, whose access to finance, risk-sharing mechanisms, and regulatory context are crucial for the transition.

The organizational, behavioral, and communicative dimensions of sustainability provide further insight into how financial incentives and fund-

ing streams translate into tangible outcomes in renewable energy. Organizational values, leadership, and sustainability cultures are shown to be pivotal in embedding environmental objectives into strategic decisions and day-to-day practices, thereby influencing how firms respond to financial incentives and regulatory pressures related to clean energy and public health (Alemu, 2025a, 2025b; Tessema, 2025a, 2025b). Behavioral economics-informed interventions, green promotions, and financial incentives have been identified as effective catalysts for sustainable practices, suggesting that carefully designed monetary and non-monetary signals can shift consumer and organizational behavior in ways that complement broader financial and policy frameworks (Burrell et al., 2025). Communication channels, such as public radio broadcasting and targeted advertising campaigns, play a crucial role in enhancing energy awareness and engagement, particularly in rural areas and among households whose investment decisions significantly impact the adoption of decentralized renewable solutions (Bappayo & Adamu, 2025; Piwowarski, 2024). Narratives of sufficiency and the framing of sustainable lifestyles influence social acceptance of energy transitions, potentially altering preferences for investments in energy efficiency and small-scale renewable energy sources (Korjonen-Kuusipuro et al., 2024). Public administration practices and their paradoxes can either act as enablers or barriers to sustainable development, with governance quality influencing the credibility of green finance policies and the implementation of renewable energy programs (Rosiak et al., 2024). From the user side, determinants of consumer satisfaction with energy services inform understandings of resilience and the perceived value of infrastructure investments, highlighting the importance of aligning financial and service-quality outcomes in the energy sector (Ghimire et al., 2025). These contributions collectively emphasize that the effectiveness of financial mechanisms for renewable energy depends on organizational capabilities, behavioral responses, and communication strategies rather than purely on the availability of capital.

A growing number of studies explicitly employ bibliometric methods to map the intellectual and policy landscapes of green finance, energy transition, and related domains, providing important meth-

odological precedents for analyzing renewable energy finance as a research field. The evolution of green finance has been traced using bibliometric techniques, revealing shifts in thematic focus, influential journals, and collaboration networks over time (Sang, 2024). Complementary work on the research landscape of energy transition and green finance integrates bibliometric analysis with content-based mapping to identify core clusters of topics, regional patterns, and emerging frontiers in the literature (Xu et al., 2024). Bibliometric examinations of debt-for-nature swaps, trade remedies, and innovation marketing demonstrate how these methods can be used to uncover the structure, trends, and intellectual roots of specialized subfields at the intersection of economics, law, and sustainability (Oskay, 2025; Viet & Thanh, 2024; Xolmurotov et al., 2025a). In the renewable energy domain, specifically, bibliometric analysis has been employed to explore regulatory barriers to entrepreneurship and start-ups, shedding light on how research attention has been distributed across legal, financial, and policy obstacles (Myroshnychenko et al., 2024). Studies that combine bibliometric techniques with alternative indicators of public attention, such as Google Trends, reveal that scholarly output on renewable energy does not always align with societal interest, and issues like the shadow economy can be underrepresented despite their importance for investment environments (Lyeonov et al., 2025b). These bibliometric contributions illustrate the value of systematic mapping for understanding how scientific communities conceptualize finance, policy, and technology. However, they have yet to coalesce around a dedicated examination of the financial landscape of renewable energy as a distinct research domain.

The broader sustainability literature also provides background on how organizational transformation, knowledge management, and leadership underpin the capacity of public-health and environmental institutions to design and implement effective financial and governance instruments (Alemu, 2025b; Tessema, 2025b). Work on economic achievements and environmental consequences, as well as the cyclical nature of growth-environment relationships, warns that without robust institutional frameworks and coherent policy mixes, financial flows can reinforce unsustainable

trajectories, even when labelled as ‘green’ (Kubatko et al., 2025; Mukhtarov et al., 2024). Investigations of convergence and divergence in household solar energy, resilience of energy services, and the role of rural media outlets in supporting sustainable development further highlight that financial instruments operate within multi-layered social and territorial contexts (Bappayo & Adamu, 2025; Ghimire et al., 2025; Kurbatova et al., 2025). Sustainable public-policy instruments aimed at the circular economy and eco-innovation, together with environmental tax reforms and green-finance frameworks, thus form a complex policy-finance ecosystem in which renewable-energy investments are embedded (Juracka, Valaskova, & Nica, 2024; Samusevych et al., 2024; Streimikiene et al., 2024).

Existing scholarship offers rich but fragmented insights into the financial dimensions of renewable energy, spanning macro-level green fiscal policy and environmental taxation, sector-specific instruments such as feed-in tariffs and green finance, and micro-level issues of entrepreneurship, consumer behavior, and organizational capabilities (Baghirzade & Kosormyhin, 2025; Bai et al., 2024; Lyeonov, Artyukhov et al., 2025; Shcherbakova, 2025; Xu et al., 2024). Bibliometric studies have demonstrated their usefulness in mapping related areas such as green finance, trade remedies, innovation marketing, and regulatory barriers in renewables, but there remains no comprehensive bibliometric synthesis of the financial landscape of renewable energy as an integrated research field (Myroshnychenko et al., 2024; Sang, 2024; Viet & Thanh, 2024; Xolmurotov et al., 2025a). A dedicated bibliometric analysis of this landscape can therefore contribute by systematically charting how financial instruments, institutions, and behaviors around renewable energy have been conceptualized, where the main thematic and geographic gaps lie, and how future research might better support the design of effective, equitable, and resilient financing architectures for the energy transition.

The reviewed literature shows that the financial landscape of renewable energy is rich, multidimensional, and rapidly evolving, yet conceptually and empirically fragmented across instruments, actors, and governance levels. Existing studies illuminate key elements – from green fiscal policy, environmental taxation, and sustainable finance

to start-up ecosystems, consumer behavior, and organizational capabilities – but they do not yet provide an integrated picture of how these components interact over time. This gap highlights the need for a dedicated bibliometric analysis to systematically map the structure, dynamics, and blind spots of research on renewable energy finance, thereby informing more coherent academic inquiry and better-designed financing architectures for the energy transition.

This study aims to conduct a comprehensive bibliometric and science-mapping analysis of scholarly research on financial indices, green bonds, and venture capital in the context of renewable energy, to reveal the intellectual structure, thematic trends, and research gaps most relevant to investment management and financial innovations in this field.

2. MATERIALS AND METHODS

Bibliometric analysis provides a quantitative approach to examining scholarly literature, enabling researchers to trace the evolution of scientific communication, identify influential studies and emerging trends through citation counts, co-authorship networks, and publication frequencies. The method has gained substantial traction across scientific fields, with the number of bibliometric studies in Scopus growing by an average of 26% annually since 2003, driven by improved analytical tools, the rise of interdisciplinary research, and the globalization of science (Vasilyeva et al., 2021; Mongeon & Paul-Hus, 2016).

In conducting the literature review for the study, a comprehensive search query was designed and executed in the Scopus database. The query employed a systematic approach to capture relevant peer-reviewed articles, utilizing targeted keywords and Boolean logic to encompass the primary themes and variables of interest within the scope of our research. The applied search request is:

TITLE-ABS-KEY (“renewable energy” OR “clean energy” OR “solar energy” OR “wind energy” OR “green energy” OR “sustainable energy” OR “alter-

native energy” OR “hydro power” OR “geothermal energy” OR “bioenergy” OR “biomass energy” OR “wave energy” OR “tidal energy” OR “hydropower” OR “ocean energy”) AND (“financial indices” OR “stock indices” OR “green bonds” OR “venture capital” OR “private equity” OR “exchange-traded funds” OR “etfs” OR “project finance” OR “commodity prices” OR “carbon market” OR “investment funds performance” OR “yieldcos” OR “infrastructure investment” OR “production and efficiency indices” OR “esg indices” OR “carbon credits” OR “renewable energy certificates” OR “recs” OR “technology-specific indices” OR “government and policy impact indices”) AND (“investment” OR “financing” OR “economic impact” OR “market trend” OR “investment flow” OR “financial analysis” OR “investment attractiveness” OR “financial policy evaluation” OR “financial performance” OR “capital markets” OR “financial viability” OR “investment strategy” OR “return on investment” OR “roi” OR “cost-benefit analysis” OR “financial incentives” OR “economic feasibility”) AND (LIMIT-TO (DOCTYPE , “ar”)) AND (LIMIT-TO (SRCTYPE , “j”)) AND (LIMIT-TO (LANGUAGE , “english”)) AND (LIMIT-TO (PUBSTAGE , “final”))

A detailed breakdown of the used search strategy is as follows:

- *Keyword Selection:* A search query contains a broad array of terms representing various renewable and sustainable energy sources, including “renewable energy,” “solar energy,” “wind energy,” and others. Simultaneously, financial aspects such as “financial indices,” “green bonds,” “venture capital,” and similar terms were integrated. These keywords were linked with the Boolean operator OR, ensuring the inclusion of articles covering any of these energy sources or financial topics.
- *Contextual Focus:* The search was further refined to include articles discussing financial and economic impacts associated with renewable energy investments. This was achieved by adding terms such as “investment,” “financing,” “economic impact,” and others related to the financial and market dynamics of renewable energy, connected to the operator OR.

- *Limitations and Filters:* The search was specifically narrowed to articles indexed as academic research (LIMIT-TO(DOCTYPE, "ar")) and published in scholarly journals (LIMIT-TO(SRCTYPE, "j")). To ensure the inclusion of only fully vetted and peer-reviewed articles, the filter was set to include only those in their final publication stage (LIMIT-TO(PUBSTAGE, "final")).
- *Language and Temporal Scope:* Only articles published in English were considered (LIMIT-TO(LANGUAGE, "english")), ensuring clarity and accessibility of the literature.
- *Execution:* The entire query was encapsulated within TITLE-ABS-KEY to search within article titles, abstracts, and keywords, maximizing the relevance of retrieved documents to the aims of bibliometrics analysis.

The bibliometric analysis conducted in this study was performed using the Biblioshiny application, a user-friendly web interface for the R-package 'bibliometrix'. Biblioshiny offers a comprehensive suite of tools to facilitate quantitative analysis of scientific literature (Aria & Cuccurullo, 2017). The choice of Biblioshiny for this bibliometric study is appropriate due to its robust data handling capabilities, ability to integrate seamlessly with R, and diverse range of analytical functions.

3. RESULTS

Based on the methodology described above, a thematic selection of articles in the Scopus database was formed. Detailed information on this sample is shown in Table 1. Over the past thirty years, from 1991 to the beginning of 2024 (as of April 16), 819 articles, sourced from 299 different journals, have been indexed in the Scopus database. The annual growth rate of published articles is 13.69%. This suggests a steadily increasing interest in the subject matter over time. The average number of citations per paper is 24.29. It demonstrates that papers are significantly impactful and well-regarded within the community.

The dataset under consideration excludes articles that focus solely on developing renewable energy or investigating the creation of a favorable invest-

ment climate. According to the analyzed sample, only publications that study these issues in relation to each other are included.

Figure 1 shows the dynamics of publication activity from 1991 to 2023. Until 2010, the number of articles investigating the financial component of renewable energy development was extremely small. The maximum number of publications where the results of scientific research on this topic were made public was two articles, and in some years (1992, 1993, 1995, and 2005), such publications were absent.

Table 1. Primary data about the article collection for bibliometric analysis

Description	Results
Main information about data	
Timespan	1991:2024
Sources (Journals, Books, etc.)	299
Documents	819
Annual Growth Rate %	13.69
Document Average Age	4.88
Average citations per doc	24.29
References	39572
Document contents	
Keywords Plus (ID)	4577
Author's Keywords (DE)	2437
Authors	
Authors	2388
Authors of single-authored docs	98
Authors collaboration	
Single-authored docs	103
Co-Authors per Doc	3.4
International co-authorships %	34.55
Document types	
Article	819

However, since 2012, there has been a steady increase in the number of publications, which can be attributed to technological shifts in the field of renewable energy that have enhanced the economic prospects for the mass adoption of technologies, both at the industrial level and among households. Accordingly, this led to the search for answers to the question of financial support for market participants to launch and accelerate the mass dissemination of renewable energy technologies. The peak period of publication activity occurred in 2022 and 2023, when the energy industry faced global challenges related to the need to replace a significant amount of fossil fuel ener-

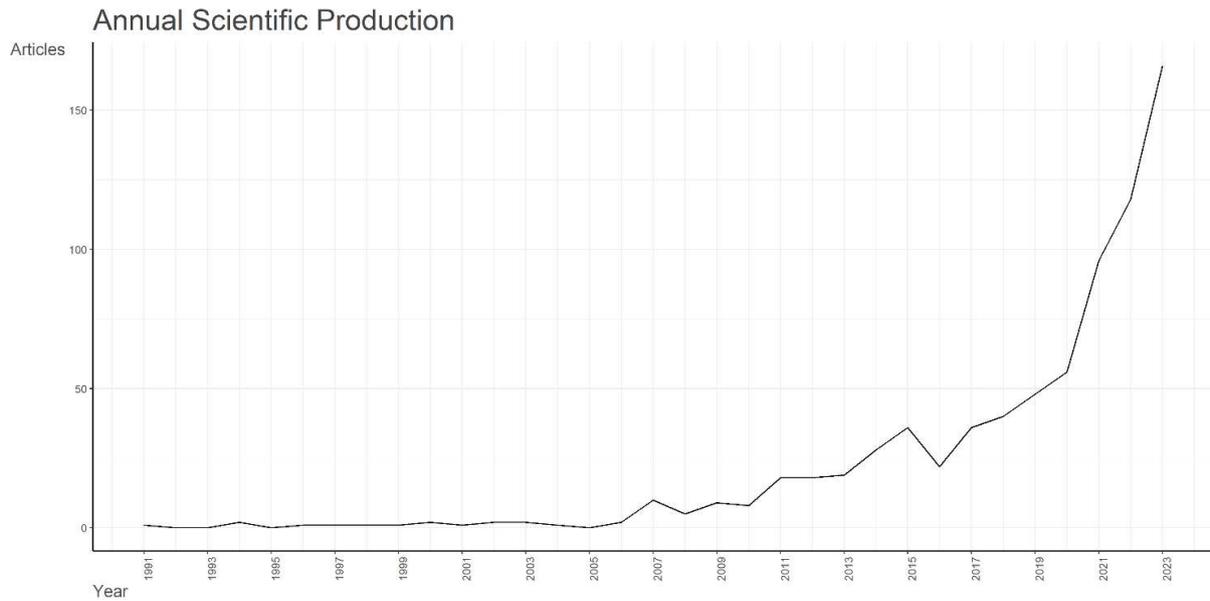


Figure 1. Publication activity for the period 1991–2023

gy resources due to disruptions in logistics chains and the countering of price shocks. This necessity arose due to the disruption of established supply logistics chains and the imperative to counter sharp price shocks in global energy markets. These factors compelled researchers, policymakers, and industrialists to intensify their search for alternative energy sources and methods for their rapid implementation, which was reflected in the growing number of scientific publications and industry reports.

Figure 2 illustrates the citation dynamics of scientific articles in which academics have published research findings on financial instruments that can support and develop renewable energy, as well as the financial and investment environment of the industry. It is worth noting that the Average Citations Per Year indicator is relatively low. However, consider the index of citations on Average Citations Per Article. It is worth noting that even in years when publication activity was minimal, articles on the topic studied in this bib-

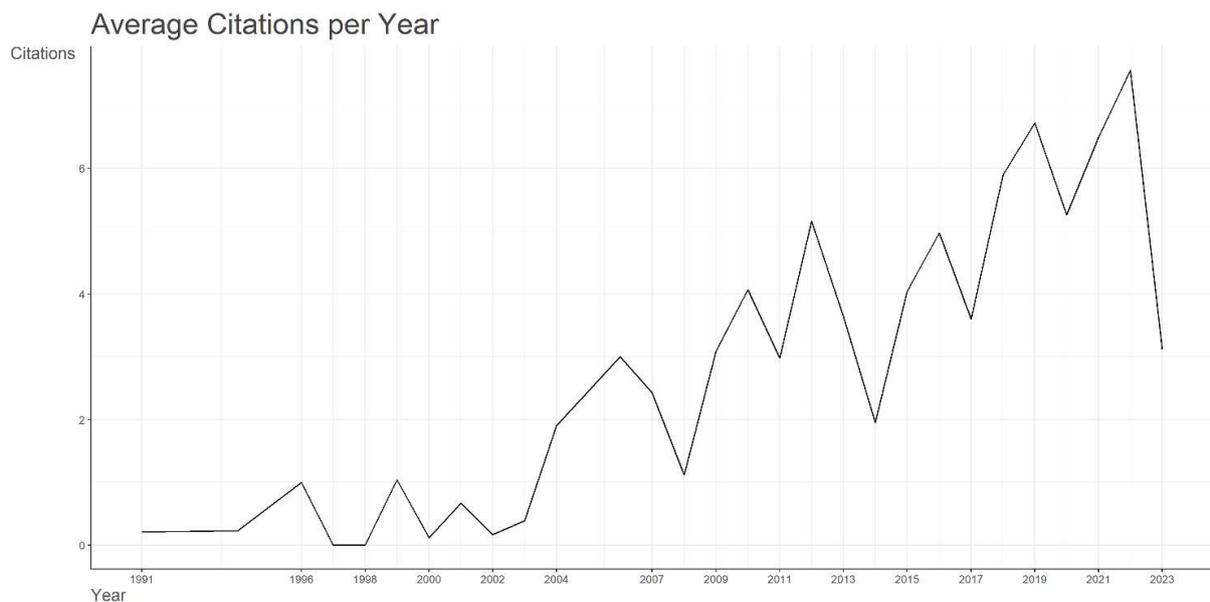


Figure 2. Citation rate of thematic articles for the period 1991–2023

liometric analysis still garnered the scientific community's attention. Such articles include Kahn (1996), which questioned the effectiveness of tax credits for wind turbine manufacturers, thereby updating the debate on effective financial instruments that will promote renewable energy development. Similar problems with the inefficiency of existing financing schemes were highlighted in articles by Briscoe (1999a, 1999b), which used hydropower as an example. The problem of effectively utilizing venture capital was highlighted in a study by scientists from the University of St. Gallen – Moore and Wüstenhagen (2004).

All the articles mentioned above have received a wide response in scientific circles. Still, they are united not only by the topic of the study but also by the fact that they were the only publications on this topic published in recognized journals during the year. This phenomenon suggests that, although the scientific community had begun to recognize and address the issue of financing renewable energy as early as the 1990s and early 2000s, the broader prerequisites for the widespread implementation of renewable energy technologies had not yet been fully developed. The economic, technological, and policy landscapes were still evolving, and the urgency for large-scale adoption of renewable energy was not as pronounced as it would become in later years. Consequently, the time for comprehensive and frequent research on this topic

had not yet arrived, resulting in these isolated but significant publications. Generally, with the increase in the number of publications, their specific citation rate decreases, which is a completely understandable phenomenon.

Publications on the researched topic have been published in 299 scientific articles, indexed in Scopus. However, most publications published one or two articles during the studied period. There are only 20 journals that have five or more articles on the researched topic. Undisputed leadership lies with the scientific journal Energy Policy, which contains the results of 62 studies. The dynamics of publications in the top 5 journals, which include Energy Policy, Energy Economics, Renewable Energy, Energies, and Journal of Cleaner Production, are shown in Figure 3.

Analyzing the distribution of articles among scientific publications, we can state that the situation in this area fully corresponds to Bradford's Law. Thus, we observe a small number of journals that make significant contributions to the problem under study, while other journals make only episodic contributions, which should not be underestimated. According to Bradford's Law, each journal belongs to one of three zones, from the first, characterized by the greatest contribution to the subject area, to the third, which contains journals with a small impact. Table 2 presents publications that

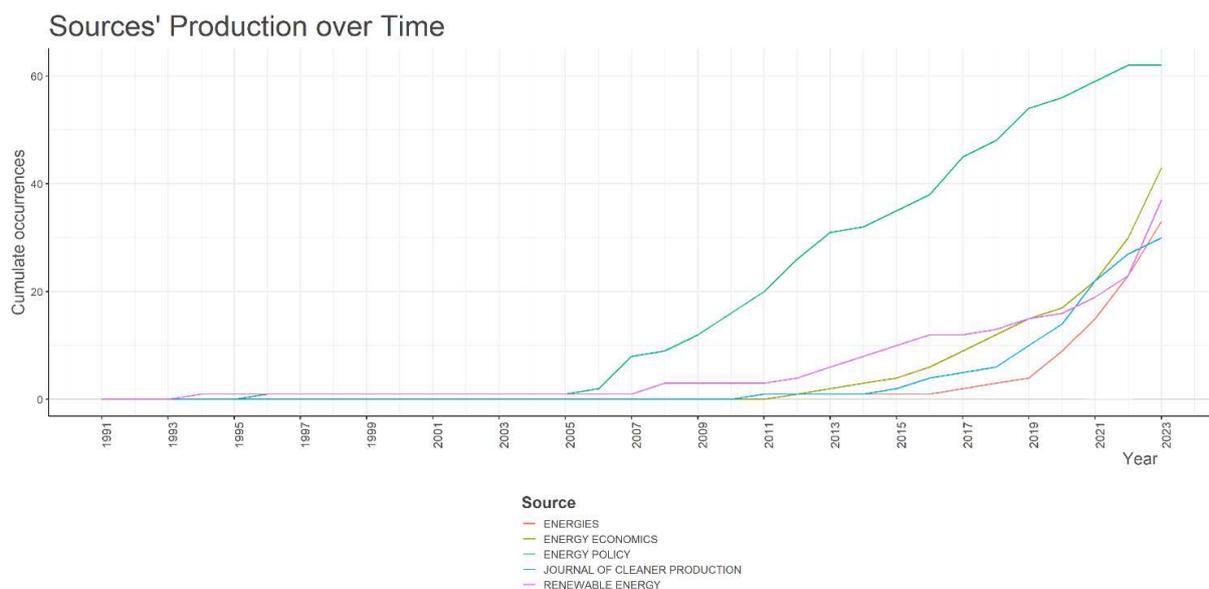


Figure 3. Sources' Production in the period

Table 2. Most relevant sources that have published the greatest number of articles

Scientific journal	Rank	Freq	cumFreq	Zone
Energy Policy	1	62	62	Zone 1
Energy Economics	2	43	105	Zone 1
Renewable Energy	3	37	142	Zone 1
Energies	4	33	175	Zone 1
Journal Of Cleaner Production	5	30	205	Zone 1
Sustainability (Switzerland)	6	25	230	Zone 1
Energy	7	24	254	Zone 1

Table 3. Sources' Local Impact indicator (fragment)

Journal	h_index	g_index	m_index	TC	NP	PY_start
Energy Policy	32	57	1,103	3354	64	1996
Energy Economics	24	45	1,846	2075	49	2012
Journal of Cleaner Production	17	31	1,214	1383	31	2011
Renewable Energy	17	33	0,548	1127	39	1994
Applied Energy	16	29	1,067	845	30	2010
Energy	14	24	1,4	609	25	2015
Resources Policy	14	25	2,8	666	28	2020
Energies	12	20	0,923	434	34	2012
Energy Conversion And Management	10	12	0,833	564	12	2013
Sustainability (Switzerland)	9	16	0,818	301	25	2014

belong to Zone 1, along with the number of thematic publications within each zone. Accordingly, out of 299 publications, only seven belong to Zone 1. 52 publications belong to Zone 2, and the rest are in Zone 3.

Table 3 contains the data necessary to determine the local impact of journals. It is advisable to conduct a local impact analysis to supplement the journal's significance results, as per Bradford's Law.

Considering several metrics provided to determine the Local Impact indicator is necessary.

H-index: Reflects the number of articles (h) that have received at least h citations. It is an indicator of both the productivity and citation impact of a scientist's or scholar's publications.

G-index: Represents the global citation performance of a set of articles, where (g) articles have received together at least g^2 citations.

M-index: This is typically the h-index divided by the number of years the author has published papers, indicating the impact over time.

Total Citations (TC): This represents the sum of citations all articles from a specific source have received.

Number of Publications (NP): This indicates the number of articles published by a specific source.

Start Year of Publications (PY_start): Indicates the year the source started publishing.

According to the specified metrics, the journals with the greatest Local Impact based on H-index are shown in Figure 4.

Along with the analysis of the influence of the publications in which the articles are published, a geographical analysis is important, as it gives an idea of which countries the research issue has the greatest relevance.

Table 4 presents the productivity of scientists from various countries, as reflected in the number of publications. This is an absolute indicator of which of the two largest economies in the world - the USA and China - are leaders. Scientists from the United Kingdom, India, Germany, Australia, and Italy have conducted extensive research.

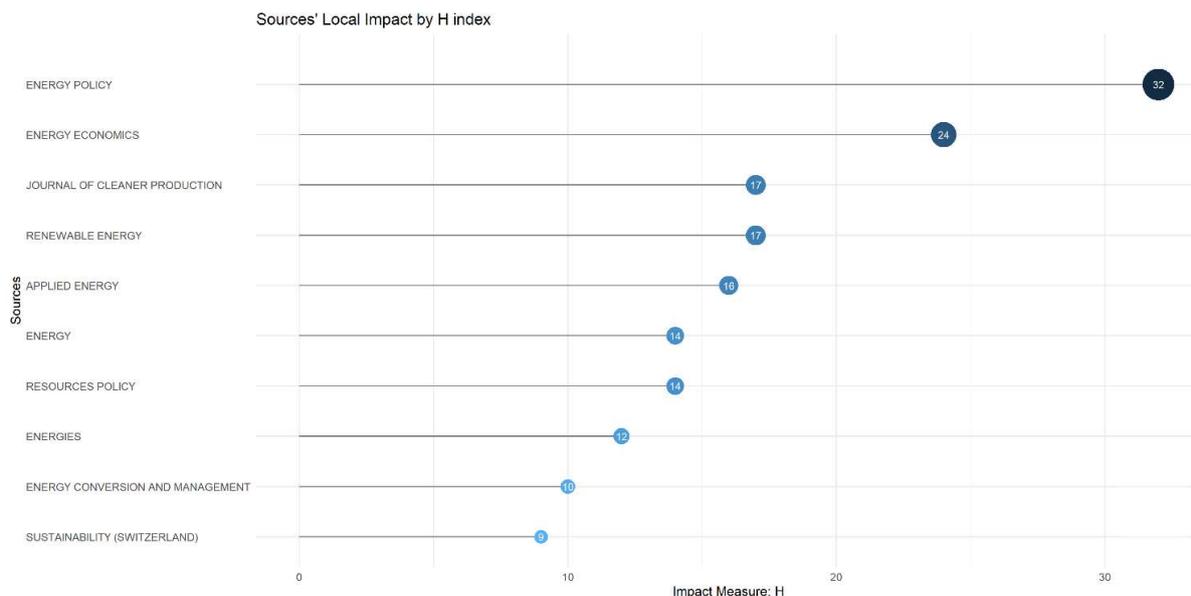


Figure 4. Sources' Local Impact in the field of financial instruments and mechanisms for renewable energy

Table 4. Countries' Scientific Production for the period 1991–2023

Country	Freq	Region	Freq
China	437	Greece	38
USA	362	France	33
UK	162	Portugal	31
India	123	Turkey	30
Germany	108	Sweden	28
Australia	105	Thailand	25
Italy	102	Iran	24
South Korea	78	Saudi Arabia	23
Spain	69	Switzerland	23
Brazil	65	Bangladesh	22
Canada	47	Finland	21
Netherlands	47	Malaysia	21
Japan	44	Norway	21
Pakistan	43	Ireland	20

However, although the number of publications indicates scientific interest in the issue, a more complete picture is obtained by considering this indicator in conjunction with indicators of scientific research citation.

The cumulative number of scientific research citations is shown in Table 5. These data indicate that the countries with the largest number of publications, as a rule, are also in the lead regarding aggregate citations.

Table 5. Global citation metrics: Country-based scientific publication citations in 1991–2023

Country	Total citation tally	Country	Total citation tally
China	3287	Pakistan	514
USA	1882	Netherlands	426
United Kingdom	1210	Canada	410
Japan	908	Italy	350
Australia	742	Spain	350
Switzerland	663	Belgium	309
India	621	Austria	293
Germany	568	Norway	265
Lebanon	537	Sweden	261
France	517	Singapore	245

An indicator of research influence is the number of citations per article. Data for the countries with the highest indicator are contained in Table 6.

However, it is worth considering that this indicator can also be used with certain caveats. In particular, a situation arises when a country's scientists have published a limited number of articles that are frequently cited by many researchers in their works. Such situations should be singled out because they are not indicative. However, they testify to high-quality, episodic research work in this country. An example of such a situation in our case is Israel, whose scientists published on-

ly one article that was included in the analyzed sample. This is an article by Parag and Ainspan (2019), which was published by researchers from the School of Sustainability, The Interdisciplinary Center (IDC) Herzliya and is devoted to the study of “the costs and benefits associated with microgrid development relative to the costs and benefits of conventional generation interconnected to a bulk transmission and distribution grid” (Parag & Ainspan, 2019).

Table 6. Comparative International Citation Frequencies for Scientific Articles for the period 1991–2023

Country	Avg. Citations	Country	Avg. Citations
Belgium	103,00	Philippines	46,00
Switzerland	82,90	France	43,10
Israel	79,00	Netherlands	38,70
Lebanon	76,70	Chile	38,00
Saudi Arabia	69,00	Sweden	37,30
Cyprus	68,50	Luxembourg	34,00
Pakistan	64,20	United Kingdom	33,60
Singapore	61,20	Greece	31,60
Japan	50,40	Georgia	31,50
Austria	48,80	Norway	29,40

Although such studies are significant and contribute to the subject area, acting as an important link in the chain of research and reducing the number of unexplored questions and gaps (Figure 5), they do not constitute a systematic study of a scientific problem at the national level.

Scientific research on financial mechanisms for supporting renewable energy is closely tied to technological advancements in this field. On the one hand, research provokes the emergence of new technologies. On the other hand, they are a reaction to these changes and a reflection of the need for new solutions in response to the altered existing conditions. In the case of studies of economic direction, the second case prevails. The emergence of breakthrough technologies and the achievement of significant technological improvements alter the prospects for market implementation of technologies and the scaling of projects, prompting scientists, politicians, and other stakeholders to seek more effective solutions for financial support and investment mechanisms to promote the spread of renewable energy. Accordingly, by dividing the time of more than 30 years from the begin-

Source: Formed by the authors using Connectedpapers (2024)

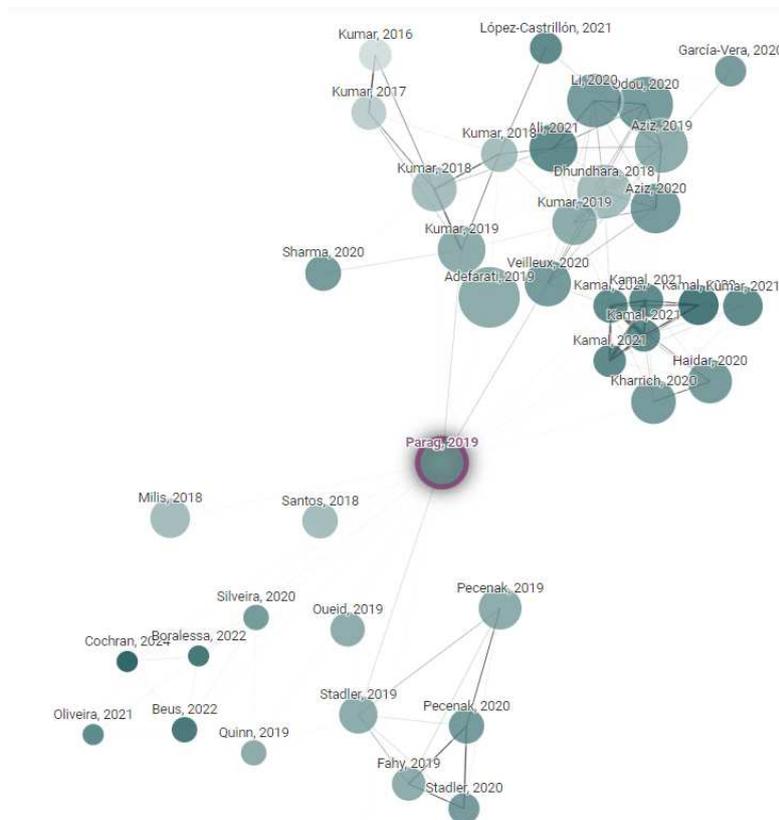


Figure 5. Interconnectedness of scientific research

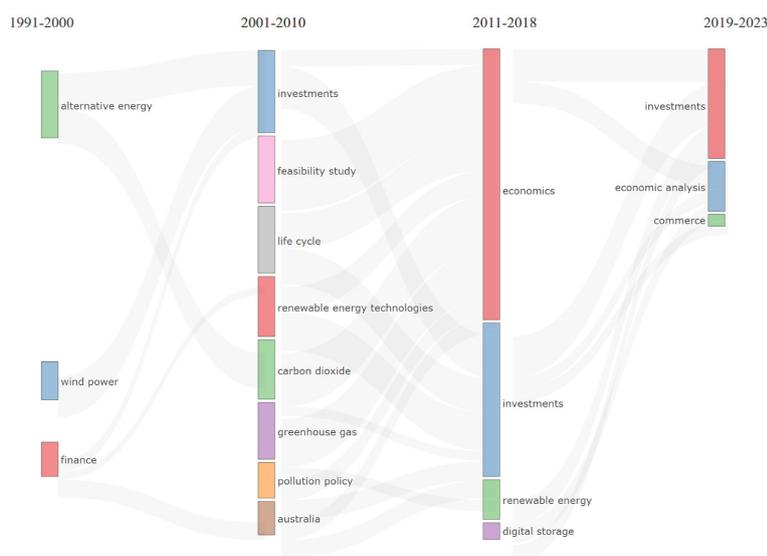


Figure 6. Thematic evolution in the field of financial instruments and mechanisms for renewable energy

ning of the 1990s, it is possible to follow changes in the vector and priorities of scientific research. Figure 6 visualizes the keywords that were dominant in four time periods, characterized by different statuses of development of renewable energy technologies.

As noted earlier, the 1990s and early 2000s were relatively sparse in publications that contributed to the search for financial instruments and mechanisms to support renewable energy. Accordingly, the research topics were not too diverse. A typical situation was the authors' focus on a specific technology, such as wind turbines, with the prospect of commercial implementation, and analyzing ways to support manufacturers working in this field, including through tax incentives. The second stage of research evolution was characterized by the introduction of a motivational component for the development of renewable energy, which, combined with technological successes, catalyzed the industry's popularization and growth. It is about the connection between implementing renewable energy technologies and achieving the climate goals outlined in climate policy, which aims to combat the negative and threatening effects of climate change. It was the consideration of the question from the perspective of the long-term effectiveness of renewable energy for humanity that was the subject of many articles that allowed

to expand the understanding of the financial component of the process because the economic benefit was complemented by assessments of environmental and social benefits from the growth of the share of renewable energy in the structure of its consumption and production. Support for the course on environmentally safe energy and achieving climate policy goals has been enriched through the popularization of motivational economic instruments in scientific, political, and societal circles, such as the green tariff and trading of carbon emission quotas.

In the studies of the following periods, a narrowing of the subject area is observed. This is quite understandable because the key approaches and mechanisms for promoting the development of renewable energy have been thoroughly described in scientific works, and practical applications have been implemented in several policies. Accordingly, the economic evaluation of the policy's effectiveness in the renewable energy sector, as well as the implementation of individual projects and their scaling, took center stage. It should be noted that case studies supporting renewable energy in recent years have migrated to the financial and economic research sector, focused on the analysis of effective investment strategies and maintaining a healthy investment and financial environment in response to current and strategic threats that

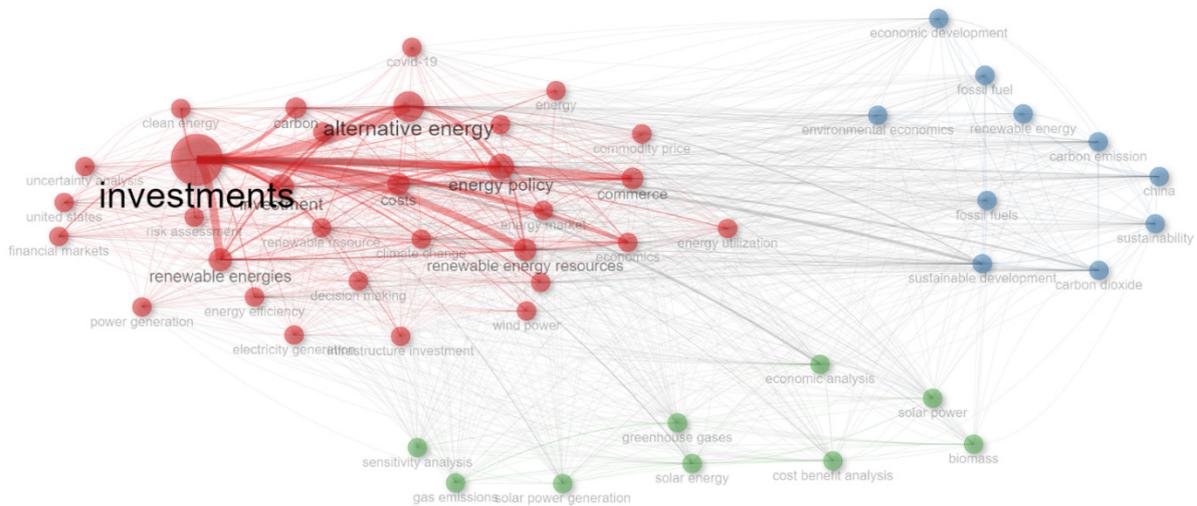


Figure 7. Thematic clustering of studies in the field of financial instruments and mechanisms for renewable energy

have intensified with the COVID-19 epidemic and global economic instability due to the growing threat of global conflicts.

Figure 7 illustrates a network map that visualizes the interconnections between various terms related to scientific research in the energy sector. This form of bibliometric analysis determines the structure and trends within a field of study. Each node (circle) represents a term or a concept, and the lines (edges) indicate relationships or co-occurrences of these terms in scientific literature.

According to Figure 7, the term “investments” is central and large. It is a primary focus within the research network. This indicates a strong emphasis on the economic aspects of energy, particularly the financing of different energy types. Other terms include “alternative energy,” “renewable energies,” and “energy policy,” which highlight the research focus on non-traditional energy sources and the policies that govern them.

There are distinct clusters around “investments,” each color-coded, representing sub-themes or specific focus areas within the research network. The red cluster, which includes “alternative energy” and “carbon,” represents research on investment in low-carbon and renewable energy sources. The blue and green clusters correspond to specific areas, such as environmental economics and climate action, and cost-benefit analysis is related to

different energy sources, including solar and biomass energies.

The density and strength of connections between the nodes suggest a highly interdisciplinary field of research. For instance, “alternative energy” is closely tied to “carbon,” indicating a significant overlap between economic investment considerations and environmental concerns related to carbon emissions.

The presence of “COVID-19” suggests that recent literature has explored the impacts of the pandemic on energy investments. The “Uncertainty” and “Risk Assessment” nodes connected to “Financial Markets” reflect a focus on the economic risks and uncertainties in energy sector investments, which are influenced by fluctuating policies, market conditions, and technological advancements.

Figure 8 is a Sankey diagram that illustrates the relationship between research institutions (on the left) and the specific research topics they focus on (on the right). The width of the bands represents the volume of research or the intensity of the institution’s focus on a particular topic.

From the left, we have a list of universities and research institutions. These institutions are linked to the right side of the figure, which lists various research topics, including renewable energy, green bonds, bioenergy, climate change, and many others.

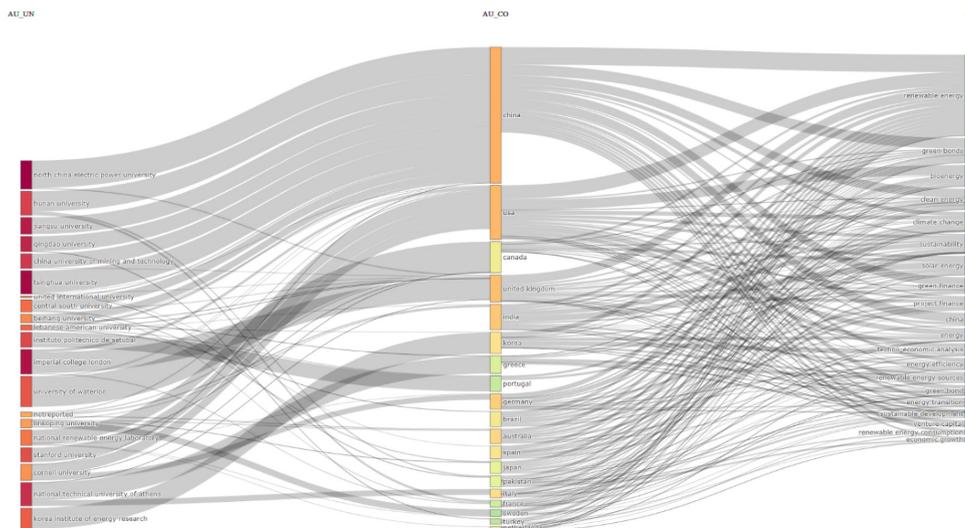


Figure 8. Leading research institutions and the specific topics they focus on

Research institutions from various countries contribute to the body of work on energy and related financial topics. According to the data presented in Figure 8, Chinese institutions make significant contributions to research on these topics.

Institutions have specific focus areas, but some publish a broader range of topics, while others specialize in their areas of interest. Along with numerous research directions on studying renewable energy, several issues are connected to the economic and financial dimensions of energy, including green bonds, project finance, venture capital, and economic growth. This means the importance of economic research in energy, which studies funding, investment, and market development.

Scientific institutions and universities with the highest publication activity in the study of financial aspects of renewable energy are shown in Table 7.

Table 7. Most relevant affiliations

Affiliation	Articles	Affiliation	Articles
North China Electric Power University	18	Instituto Politécnico De Setúbal	12
Tsinghua University	18	Stanford University	12
Imperial College London	14	University of Waterloo	12
Jiangsu University	14	Korea Institute of Energy Research	11
Qingdao University	14	Lebanese American University	11
National Technical University of Athens	13	Central South University	10
China University of Mining and Technology	12	National Renewable Energy Laboratory	10
Hunan University	12	United International University	10

However, it is worth noting that the number of authors with a significant number of publications on this topic is relatively low.

Thus, Lotka’s Law is fully confirmed, which says that few researchers produce many papers while the majority publish only a few (Figure 9). Only one author has more than ten articles on the given topic, and another 16 authors have more than five publications. At the same time, 1954 authors have only one thematic publication each, and another 175 authors have two.

However, even a significant number of thematic publications by one author does not indicate that this is the focus of his research work. After all, it should be considered that some researchers have numerous publications but lack a clear research profile. This may indicate their participation in most publications as a decimator for research results obtained mainly by other co-authors of a scientific article. In this case, we are dealing with a situation just like this.

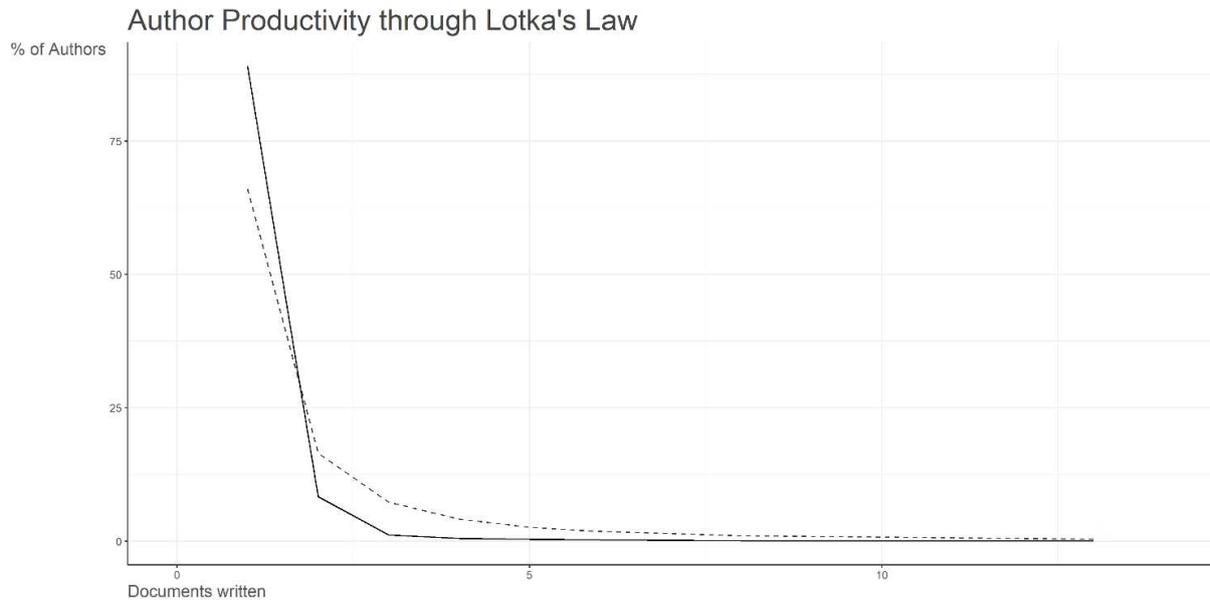


Figure 9. Author Productivity on financial instruments and mechanisms for renewable energy

Figure 10 shows a visualization of a co-authorship network among researchers. Each node (circle) represents an individual researcher, and the edges (lines) connecting the nodes signify collaborative relationships, indicating that the researchers linked by these edges have co-authored one or more papers together.

The most influential is the network in which Elie Bouri from the Lebanese American University (Lebanon) and Anupam Dutta from the University of Vaasa (Finland) take center stage. A research network formed by these researchers and their collaborators analyzes the energy asset market

(Ferreira et al., 2022; Saeed et al., 2020). Their research focuses on volatility (Wang et al., 2022; Dutta, 2020a), returns, and risks associated with net and renewable energy (Dutta et al., 2020b), as well as the interrelationships between energy markets and broader financial markets.

The research network centered around Farhad Taghizadeh-Hesary from Tokai University (Japan) has a similar research focus, focused on a multifaceted approach to understanding and leveraging green finance as a means to foster the growth of renewable energy sectors (Taghizadeh-Hesary et al., 2022, 2023), ensure their economic sustainability (Li et al.,

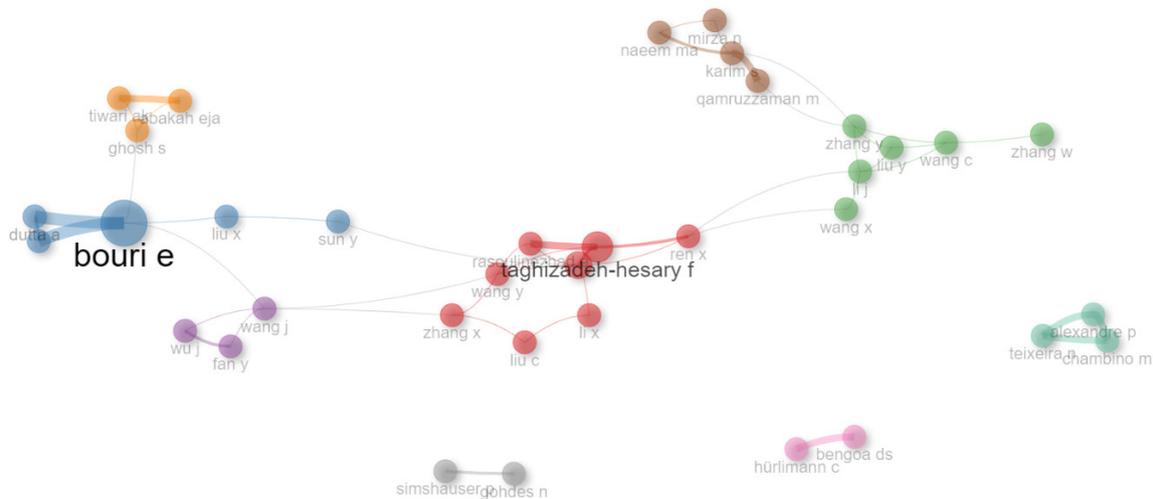


Figure 10. Research collaboration networks

Table 8. Most global cited documents on financial instruments and mechanisms for renewable energy

Paper	Total Citations	TC per Year	Normalized TC
Kumar et al. (2012)	373	28,69	5,56
Bürer & Wüstenhagen (2009)	308	19,25	6,23
Yin & Powers (2010)	284	18,93	4,65
Boomsma et al. (2012)	258	19,85	3,85
Liao & Shi (2018)	257	36,71	6,23
Zamalloa et al. (2011)	245	17,50	5,86
Gianfrate & Peri, 2019	241	40,17	5,98
Rasoulnezhad & Taghizadeh-Hesary (2022)	227	75,67	10,01
Saeed et al. (2021)	209	52,25	8,05
Ahmad et al. (2021)	202	50,50	7,78

2023), and understand their interaction with global financial markets.

Other research networks also significantly contribute to the study of financial support for the development of renewable energy. However, based on the publication activity of the authors, it is rather difficult to determine the researcher around whose name the publication activity is concentrated, specifically in the dissemination of the results of scientific research by researchers in these networks.

Suppose it is accepted as an axiom that the citations of publications reflect their influence in scientific circles. In that case, it is appropriate to consider the most cited scientific articles published in peer-reviewed scientific journals indexed by Scopus (Table 8).

The most cited article published in 2012 is Kumar et al. (2012). The article investigates the impact of oil and technology market dynamics on the stock prices of clean energy firms, hypothesizing that higher costs of conventional energy or carbon pricing would boost clean energy investments. The researchers found no significant correlation between carbon prices and the valuations of clean energy stocks. In another, one of the most cited publications, Boomsma et al. (2012) also investigated various renewable energy support schemes. These studies were extremely timely for updating the discussion about the financial component of renewable energy development.

The second most cited publication is Bürer and Wüstenhagen (2009). The article explores the policy preferences of private investors in clean energy technology firms. The authors concluded that feed-in tariffs are the most effective policy for stimulating investment interest, particularly among European

investors with significant involvement in the clean energy sector. This research contributes to the arguments in favor of a feed-in tariff as a crucial component of energy policy. At the same time, Liao and Shi (2018) offer a broader perspective on renewable energy investment incentives, empirically demonstrating that public support influences green investment, which in turn promotes growth through increased local environmental regulations.

The third most cited publication, Yin and Powers (2010), deals with the impact of renewable portfolio standards on renewable energy development. Ahmad et al. (2021) approach this issue from the perspective of innovation support.

Zamalloa et al.'s (2011) publication is a frequently used approach to publishing research results in technical fields when the research subject is very concrete and specific. A similar approach is used by Zamalloa et al. (2011) to determine the "techno-economic potential of renewable energy through the anaerobic digestion of microalgae." The high citation of articles results from well-conducted research, timeliness, and the ability to answer topical questions. Thus, the research topic of Gianfrate and Peri (2019) is not new. Still, it answers the modern questions of financiers, particularly showing arguments regarding the prospects of green bonds. Researching green bonds, Rasoulnezhad and Taghizadeh-Hesary (2022) add that a positive effect on renewable energy and the environment can be observed exclusively due to their long-term use. In Saeed et al. (2021), researchers explain the economic motivations of energy market participants by analyzing the relationship between clean and conventional energy investments under normal economic conditions and during times of crisis. The authorship of this study belongs to the researchers of one of the research networks identified earlier.

4. DISCUSSION

The discussion of this study's findings shows both continuity with and added nuance to earlier work on green finance, energy transition, and bibliometric mapping. The post-2012 surge in publications and citations, and the consolidation of a distinct renewable-energy–finance domain, broadly confirms prior bibliometric evidence on green finance and energy transition, as well as general regularities of a small, highly productive core and a long tail of occasional contributors (Sang, 2024; Viet & Thanh, 2024; Xolmurotov et al., 2025a; Xu et al., 2024). What differentiates this domain is its strong interdisciplinarity, spanning energy economics, finance, environmental policy, and management, which helps explain the coexistence of a recognizable core with considerable fragmentation across peripheral outlets.

The dominance of advanced economies in authorship and impact – particularly the United States, China, the United Kingdom, Germany, Australia, and Italy – mirrors patterns in bibliometric studies of green finance and related fields (Sang, 2024; Xu et al., 2024), yet sits uneasily alongside empirical work documenting acute renewable-energy and energy-security challenges in lower-middle-income and transition economies (Havrylenko & Myroshnychenko, 2025; Trinh, 2025). Evidence on green energy in Ukraine, convergence and divergence in household solar deployment, and context-specific transition issues further underlines that many critical dynamics arise in countries underrepresented in the mapped literature (Kurbatova et al., 2025; Kuzior et al., 2021). This geographic skew echoes similar imbalances found in trade remedies and debt-for-nature swaps (Oskay, 2025; Viet & Thanh, 2024), suggesting that research agendas do not fully align with the regions where renewable-energy finance is most constrained.

The thematic structure identified here refines earlier bibliometric mappings. The central role of “investments” and the mature cluster around financial indices and stock-market linkages between fossil and clean-energy assets are consistent with empirical studies on clean-energy stock pricing and energy-mix management

(Baghirzade & Kosormyhin, 2025; Balcerzak et al., 2024), while the rapid rise of green bonds and sustainable finance accords with work on fiscal reform and the European Green Deal's financial architecture (Bai et al., 2024; Samusevych et al., 2024; Streimikiene et al., 2024; Vasilyeva et al., 2023). At the same time, venture capital and early-stage finance emerge as only a peripheral, though growing, theme despite strong evidence that regulatory barriers, minority-investor protection, and tax-compliance conditions critically shape clean and digital energy start-ups (Artyukhov et al., 2024; Halynskiy et al., 2024; Halynskiy & Telizhenko, 2024; Myroshnychenko et al., 2024). This gap suggests that risk capital for renewable energy innovation remains underexplored, given its practical importance.

Finally, the bibliometric maps show that organizational, behavioral, and communicative dimensions of sustainability occupy relatively marginal positions, even though other strands of the literature highlight their centrality for translating financial incentives into real outcomes. Studies on leadership, culture, agile mindsets and knowledge management stress that internal capabilities condition the effectiveness of financial instruments and policies (Alemu, 2025a, 2025b; Tessema, 2025a, 2025b), while work on behavioral economics, public broadcasting, sufficiency narratives and energy awareness demonstrates the role of social norms and communication in driving uptake of renewable solutions (Bappayo & Adamu, 2025; Burrell et al., 2025; Korjonen-Kuusipuro et al., 2024; Piwowski, 2024). Evidence that scholarly attention to renewable energy and the shadow economy does not always match public interest, alongside findings on institutional quality and cyclical environmental pressures, further suggests that governance and informality are critical but under-integrated elements of the financial landscape (Kubatko et al., 2025; Lyeonov, Serhienko et al., 2025; Mentel et al., 2020; Mukhtarov et al., 2024; Rosiak et al., 2024). Overall, the comparison indicates that while research on financial indices, green bonds, and venture capital in renewable energy has expanded rapidly, it remains unevenly developed, pointing to clear opportunities for future work that better connects financial innovation with policy design, early-stage financing, and institutional and behavioral contexts

This study has several limitations. The analysis is based solely on a Scopus-derived corpus of 299 English-language journal articles (1991–2023), which may omit relevant work indexed in other databases, published in languages other than English, or disseminated through books, reports, working papers, and industry studies. The search strategy, focused on renewable energy, financial indices, green bonds, and venture capital, may under-represent studies using different terminology and leaves other important financial channels for renewables (for example, bank lending, project finance, blended finance, or carbon markets) largely outside the scope.

Bibliometric and science-mapping methods also have inherent constraints. Publication and citation indicators, as well as h- and g-indices, and Local Impact, capture academic visibility rather than research quality or real-world policy and investment impact, while co-authorship, co-citation, and keyword networks depend on specific parameter and clustering choices. Finally, the study provides a retrospective snapshot up to 2023 in a rapidly evolving field; emerging instruments, regulatory changes, and new geopolitical conditions may quickly reshape both renewable energy finance practice and the associated research agenda.

CONCLUSIONS

This study aimed to conduct a comprehensive bibliometric and science-mapping analysis of scholarly research on financial indices, green bonds, and venture capital in the context of renewable energy, to reveal the intellectual structure, thematic trends, and research gaps most relevant to investment management and financial innovations in this field.

The results reveal a distinct research domain emerging after 2012, characterized by accelerating publication and citation activity. A small core of journals in energy economics, sustainable finance, and environmental policy dominates the output, while research impact is concentrated in the United States, China, the United Kingdom, Germany, Australia, and Italy, leaving many regions with high renewable potential underrepresented. Authorship patterns follow Lotka's law, characterized by a few repeat contributors and a relatively small expert community. Thematically, "investments" serves as the central organizing concept, linking clusters on stock-market indices, fossil–clean asset linkages, feed-in tariffs, and carbon pricing. Green bonds are a rapidly growing sub-theme, whereas venture capital remains more peripheral but increasingly prominent in discussions of policy stability and innovation support.

These findings have several implications for policy and financial practice. First, the dominance of a narrow set of countries, journals, and research networks highlights the need for international initiatives that support knowledge production and data availability on renewable energy finance in underrepresented regions, particularly where capital scarcity and institutional fragility hinder the energy transition. Second, the strong thematic focus on listed-asset indices and green bonds indicates that policymakers and regulators should prioritize transparent, taxonomy-aligned standards for green bond issuance and index construction, in order to reduce greenwashing risks, lower information asymmetries, and ensure that these instruments genuinely channel capital into additional renewable-energy projects. Third, the comparatively modest but growing attention to venture capital and early-stage finance highlights the importance of stable support schemes, the protection of minority investors, and blended-finance mechanisms that can de-risk innovative renewable energy business models and technologies. Finally, by clarifying who publishes what, where, and with whom, this bibliometric mapping can inform the design of targeted research programs and policy dialogues that bridge academic insights and the practical needs of investors, supervisors, and energy policymakers, thereby contributing to more coherent and effective financial architectures for the global renewable energy transition.

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Writing – review & editing: Serhiy Lyeonov, Ihor Vakulenko, Vahan Avetikyan, Kateryna Levchenko.

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