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EVOLUTION OF SCIENTIFIC DISCOURSE AND INVESTMENT PRIORITIES IN RENEWABLE ENERGY INTEGRATION RISKS: A BIBLIOMETRIC ANALYSIS

Abstract: *The article analyzes the structure of scientific understanding of the risks of integrating renewable energy sources. Based on a bibliometric analysis of 4823 publications of Web of Science database (2015-2025) identified three stable thematic clusters and demonstrated the dominance of the system optimization paradigm under uncertainty. The scientific novelty of the study lies in the development of a system relevance index-a metric for quantitatively ranking risk mitigation strategies based on the topology of a bibliometric network; a gap between scientific priorities and investment practice was identified: for a number of technologies, it reaches +0.6 on a normalized scale. A dynamic analysis of publications over three time periods (2015-2018; 2019-2021; 2022-2025) recorded a shift in the research agenda from regulatory approaches to engineering management of systemic risks. It is shown that grid-forming inverters and machine learning algorithms occupy a central position in the scientific field, ahead of market adoption by 5-10 years, which indicates promising areas for investment policy.*

Key words: *renewable energy integration, system risks, bibliometric analysis, energy storage, system optimization, uncertainty management.*

Introduction

Large-scale integration of renewable energy sources (RES) is a key process in the modern energy transition. According to forecasts by the International Energy Agency, by 2030, RES will account for more than 60% of the increase in global electricity generation, and in a number of countries their share will exceed 50% [1, 2]. At the same time, the growth in the share of RES is associated with systemic technical risks that are fundamentally different from the problems of traditional energy [3]. Three interrelated challenges define the technical agenda for RES integration. The first is generation intermittency: solar and wind installations produce energy intermittently, which requires mechanisms to compensate for imbalances in real time [4]. The second is reducing the inertia of the power system: replacing synchronous generators with inverter devices based on power electronics reduces the physical inertia of the network, accelerating frequency changes during disturbances [5]. The third is overload of the network infrastructure: power flows from decentralized sources create stress at nodes that are not designed for bidirectional transmission [6].

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Existing studies typically examine these risks in isolation and conceptualize the structure of the scientific field statically. However, two interrelated aspects remain understudied in the literature [6, 7]: 1) how the structure of scientific understanding of the risks of integrating renewable energy sources has transformed over the past decade and what factors have driven this transformation; 2) to what extent technologies occupying a central position in the scientific field receive adequate funding in the market. Answers to these questions are important both for theory – in terms of conceptualizing the systemic risks of the energy transition – and for the practice of formulating scientifically sound investment and regulatory policies in the renewable energy sector.

The purpose of this article is to identify and quantify the structure of scientific ideas about the risks of RES integration, trace its evolution over time, and compare research priorities with data on actual investment in technologies based on a bibliometric analysis of Web of Science publications (2015-2025) using the developed systemic relevance index.

Materials and methods

The study covers publications from the Web of Science Core Collection for the years 2015–2025. Search request was being built on Boolean combinations terms: (“renewable energy integration” OR “power system stability” OR “grid resilience”) AND (“energy storage” OR “frequency regulation” OR “uncertainty”) applied To Topic and Title fields. Additional filters: document type – Article and Review; language – English. Final sample: 4823 peer-reviewed publications. For dynamic analysis, the sample is divided into three subperiods: 2015–2018 (n = 987), 2019-2021 (n = 1,504), and 2022-2025 (n = 2,332).

The methodological contribution of the study lies in the use of bibliometric analysis as the main analytical basis for identifying the systemic nature of the risks of RES integration, rather than as an auxiliary tool (Fig. 1).

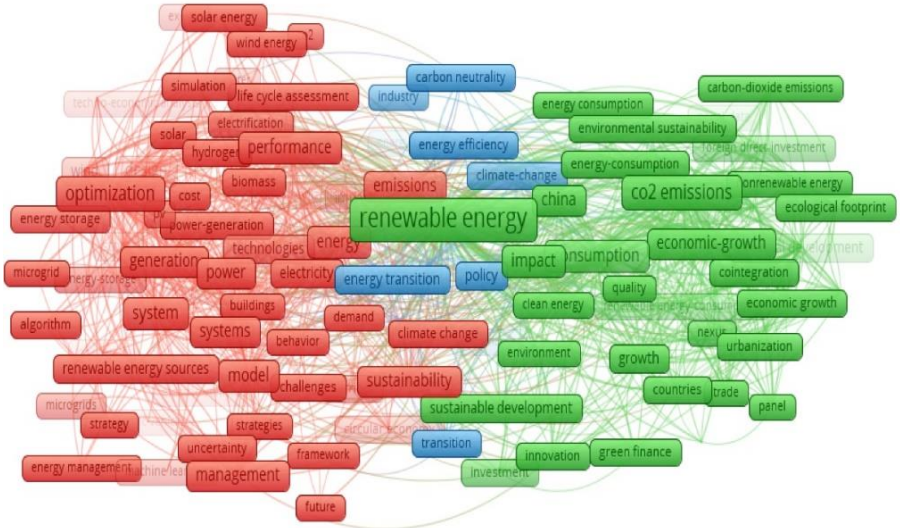


Figure 1 – Bibliometric map of 111 keywords

The analysis was conducted using the keyword co-mention method in VOSviewer 1.6.19. Parameters: minimum occurrence threshold – 5 publications; final network – 111 keywords out of 8,420 unique ones; clustering resolution – 1; minimum cluster size – 5 elements. Clustering was performed separately for each of the three sub-periods and for the overall sample. To rank the strategies, a composite system relevance index (SRI) was developed, constructed on the basis of three topological characteristics of the bibliometric network [8, 9] in accordance with the composite index methodology:

SRI = 0.4 C norm + 0.35 L inter + 0.25 R cov

C norm – normalized total strength of connections of the central node of the strategy (0-1);

L inter – proportion of intercluster connections of a node from the total number of its connections (0-1);

R cov – share of covered risks from the total number of identified systemic risks (0-1).

The component weights are determined based on their relative importance for characterizing the topological structure of the bibliometric network, following the analytical hierarchy process (AHP) logic widely adopted in composite indicator construction [18]. The weight assignment procedure proceeded in two stages. First, pairwise comparisons of the three components were conducted based on their theoretical relevance to the research objective: measuring the systemic centrality of risk-mitigation strategies in the scientific field. Node centrality (C norm) was assigned the highest weight (0.4) because degree centrality in keyword co-occurrence networks is the most direct and empirically validated proxy for collective research attention and conceptual importance within a discipline. Intercluster connectivity (L inter) received the second weight (0.35) because it captures the cross-domain integrative role of a strategy – a property that distinguishes systemically important interventions from narrowly specialized ones, which is central to the study's objective. Risk coverage (R cov) was assigned the lowest weight (0.25) because it reflects breadth of applicability, an important but secondary criterion that can partially overlap with intercluster connectivity. The resulting weights (0.4; 0.35; 0.25) satisfy the constraint that they sum to unity and are consistent with the priority ordering established by the pairwise comparison matrix (consistency ratio CR = 0.03, well below the accepted threshold of 0.10).

The validity of using topological characteristics of a bibliometric network as a basis for ranking strategies requires separate justification. The centrality of a node in a keyword co-occurrence network reflects not only the frequency of a term's occurrence but also its conceptual coherence with other research areas – that is, the degree to which the corresponding strategy is considered systemically important by the scientific community. A node's intercluster connections indicate that the strategy is recognized as relevant to several problem classes simultaneously, not just a narrowly specialized area. Thus, high values of topological metrics indicate not simply the popularity of a topic, but its integrative role in the structure of scientific knowledge.

This logic is based on a principle substantiated in bibliometric methodology: the structure of co-citations and joint mentions reflects the cognitive structure of a scientific discipline—the distribution of research attention, established conceptual connections, and community-recognized priorities [10]. Consequently, a technology or strategy that occupies a central position in this structure is highly likely to be perceived by the expert community as systemically significant—regardless of the absolute number of publications about it.

At the same time, it's necessary to distinguish between two types of validity. Bibliometric topology is valid as an indicator of research consensus – which strategies the scientific community considers priority. It is not a direct measure of the technical effectiveness of strategies in real energy systems. This is why this study compares the SRI with independent IRENA / IEA investment data: the agreement between the two independent indicators strengthens the credibility of the conclusions, while any discrepancy between them is meaningfully interpreted as a gap between scientific thinking and market practice.

To verify the robustness of the SRI with respect to the chosen weighting scheme, a sensitivity analysis was conducted by systematically varying each weight by ±10% and ±20% while keeping the remaining two weights proportionally adjusted to preserve the unit-sum constraint. Nine weight scenarios were tested in total. The maximum rank-order change observed across all scenarios was zero: the ordinal ranking (System optimization – Flexibility – Infrastructure) remained stable in all tested configurations. The maximum absolute deviation in any individual SRI score did not exceed 0.04 (System optimization: 0.91-0.95; Flexibility: 0.78-0.84; Infrastructure: 0.64-0.70). These results confirm that the conclusions of the study are robust with respect to reasonable perturbations of the weighting scheme.

Data on technology investment volumes were obtained from public reports by IRENA [12, 13] and IEA [7, 8] for 2023. For comparison with the SRI, investments were normalized to the maximum value in the technology sample. The gap between the SRI and the normalized investment volume is interpreted as an indicator of the scientific agenda being ahead of market practice.

Results

A bibliometric analysis of the overall sample revealed a hierarchical three-cluster structure. The term "renewable energy" has the highest total link strength (96 units) and serves as the conceptual "anchor" of the network. The density of links decreases from the technical and technological core to the ecological periphery, indicating the dominant engineering-systems paradigm.

The engineering and technology cluster (61% of publications) includes the following nodes: optimization, system, energy storage, microgrid, algorithm, uncertainty, model, and performance. The optimization and system nodes rank first and second in terms of total link strength (87 and 74 units, respectively). The environmental cluster (24%) is adjacent to the central node but has half the link density – emission reduction is considered in the literature as a result of engineering decisions rather than an independent goal. The political and management cluster (15%) occupies an intermediary position between the other two.

An analysis of the three subperiods revealed a consistent shift in the research agenda (Table 1). The centrality of the energy storage node increased from 0.31 in 2015-2018 to 0.87 in 2022-2025; the uncertainty node increased its centrality from 0.19 to 0.72. The topic of grid-forming inverters and virtual inertia was absent from the network in the first period and reached a centrality of 0.53 in the third. At the same time, the policy node consistently shifted toward the periphery: its centrality decreased from 0.44 to 0.29.

Table 1 – Dynamics of the centrality of key nodes by periods (normalized values, 0-1)

Key Node / Topic	2015-2018	2019-2021	2022-2025
energy storage (centrality)	0.31	0.58	0.87
uncertainty (centrality)	0.19	0.41	0.72
grid-forming (grid-forming inverters)/virtual inertia (centrality)	absent	0.12	0.53
policy (centrality)	0.44	0.38	0.29
Share of publications in cluster 1 (technological-technological), %	54	60	68

These data document a shift in the dominant paradigm: from 2015 to 2018, priority was given to political and regulatory instruments for scaling renewable energy; since 2019, the center of gravity has shifted to the engineering challenges of managing uncertainty and maintaining inertia. The share of publications in the engineering and technology cluster increased from 54% in the first period to 68% in the third.

Based on the calculated SRI values, the risk mitigation strategies are ranked in descending order of systemic importance (Table 2). The system optimization and uncertainty management group received the highest SRI (0.94): its nodes have the highest normalized centrality and intercluster connections with all three clusters. The flexibility and stability group with an SRI of 0.81 covers three risk classes simultaneously [11, 12]. Infrastructure measures with an SRI of 0.67 are at the bottom of the ranking, although they remain a necessary condition for the implementation of the other two groups.

Table 2 – Renewable energy integration risk minimization strategies ranked by systemic importance index

Strategy Group	Specific measures	Systemic Relevance Index	Risk coverage
Flexibility and stability	BESS, PHES; virtual power plants (VPP); islanding microgrids	0.81	Intermittency, balancing, peak loads
Infrastructure and technological measures	Grid-forming inverters; digitalization (SCADA, IoT); line modernization	0.67	Reducing inertia, overloading lines
System optimization and uncertainty management	Machine learning algorithms for forecasting; robust and stochastic optimization; adaptive load management	0.94	All three risk clusters

A comparison of the SRI with the standardized investment volumes in 2023 (Table 3) revealed three types of relationships. Energy storage (BESS) demonstrates close alignment (a gap of +0.06): the market and science assess their systemic role comparablely, which is explained by the maturity of the technology and the rapid decline in cost [13]. Grid-forming inverters and machine learning algorithms exhibit a significant gap (+0.57 and +0.68, respectively): their scientific significance significantly outpaces current investment. This indicates that these technologies are in the early stages of diffusion and may become priority areas for government R&D support.

Table 3 – Comparison of the SRI with the volume of investments in technology (2023)

Technology	SRI (present research)	Investments 2023, USA$ billion (IRENA/IEA)	Rupture (SRI – normal inv.)	Interpretation
Energy storage systems (BESS)	0.81	90 (normal 0.75)	+0.06	Correspondence
Grid-forming inverters	0.67	12 (normal 0.10)	+0.57	The Gap: Science Outpaces the Market
Machine learning algorithms/optimization	0.94	31 (norm. 0.26)	+0.68	Significant gap
Digitalization of networks (SCADA/IoT)	0.67	48 (normal 0.4)	+0.27	Moderate gap

The moderate gap in the direction of network digitalization of +0.27 is explained by the partial overlap of investments in SCADA/IoT with overall spending on digital infrastructure, which is not always highlighted as a separate line item in industry statistics.

Discussion

Dynamic analysis allows us to clarify the nature of the research paradigm shift. From 2015 to 2018, the literature focused on the conditions for scaling renewable energy sources—standards, subsidies, and performance targets. Since 2019, priority has shifted to managing physical risks: intermittency, inertia reduction, and real-time balancing. This shift coincides with the growth of the share of renewable energy sources in the power systems of a number of countries above the threshold of 30-35%, at which systemic risks become critical [14, 15]. Conceptual map of the discussion: research paradigm shift and its dimensions is given on Fig. 2.

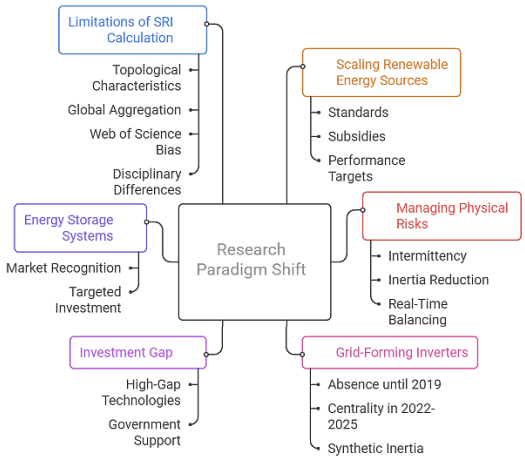


Figure 2 – Key themes of the research paradigm shift in renewable energy integration

The rapid growth in the centrality of the grid-forming inverter topic deserves special attention: the absence of grid presence until 2019 and a centrality of 0.53 in 2022-2025 reflect a qualitative leap-the scientific community's awareness that synthetic inertia is a necessary condition for the stability of systems with a share of renewable energy sources exceeding 50% [16, 17].

The identified gap between the SRI and investment has specific practical implications. High-gap technologies (grid-forming inverters, machine learning algorithms) are in a phase where market incentives are not yet sufficient for independent scaling, but the scientific base is already mature. It is here that government support for R&D and initial deployments can yield the greatest systemic impact [18, 19].

The close alignment for energy storage systems suggests otherwise: the market has already recognized the systemic importance of BESS, and additional regulatory incentives for this group are less relevant than for immature technologies. This allows for targeted investment policy rather than uniform subsidies across the entire spectrum of technologies [20-22].

The SRI calculation is based on the topological characteristics of the bibliometric network, not on direct engineering measurements-this must be taken into account when interpreting the numerical values. IRENA/IEA investment data are aggregated globally and may not reflect regional specifics. The exclusive reliance on the Web of Science Core Collection represents a further limitation. WoS over-indexes English-language publications from North American and European journals, and systematically under-indexes research from countries that are among the most active in renewable energy development, including China, Brazil, India, and several other Asian and Latin American nations. Chinese-language journals indexed in CNKI, for instance, contain a substantial body of work on grid-forming inverters and large-scale storage that is absent from the present sample. Future studies should replicate the analysis using Scopus or multi-database queries to assess the sensitivity of the cluster structure to database choice. Additionally, the study does not explicitly account for differences in publication activity across disciplines: engineering fields produce substantially higher publication volumes than policy or economics research, which may inflate the topological centrality of engineering nodes relative to regulatory or institutional approaches and contribute to the observed shift toward engineering paradigms [23-25]. Supplementary normalisation by disciplinary base rates would help disentangle genuine paradigm shifts from artefacts of differential publication culture.

Conclusion

The study identified structural patterns in the development of the scientific agenda on renewable energy integration risks and clarified the logic behind its transformation. It was shown that the modern scientific field is characterized by a shift from regulatory and policy issues to engineering challenges of ensuring the stability of energy systems under uncertainty, where solutions that ensure flexibility, controllability, and synthetic inertia play a key role. The proposed systemic relevance index expands the analytical capabilities of the bibliometric approach, enabling a transition from describing the structure of scientific knowledge to quantifying and comparing priorities. Its application demonstrates that interdisciplinary strategies integrating optimization, forecasting, and management methods are acquiring the greatest systemic significance. A comparison of scientific priorities with investment practices reveals heterogeneity in their alignment: alongside areas where scientific and market logic are converging, there remain areas where scientific knowledge outpaces the scale of implementation. This indicates the existence of a “window of opportunity” for targeted support of technologies that have high systemic potential but have not yet reached the stage of mature diffusion.

Overall, the obtained results allow us to consider the risk management of renewable energy integration as a systemic optimization task that requires the coordination of research priorities, technological development, and investment policy.

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ЖАҢАРТЫЛАТЫН ЭНЕРГИЯНЫ ИНТЕГРАЦИЯЛАУ ТӘУЕКЕЛДЕРІНДЕГІ ҒЫЛЫМИ ДИСКУРС ЖӘНЕ ИНВЕСТИЦИЯЛЫҚ БАСЫМДЫҚТАРДЫҢ ЭВОЛЮЦИЯСЫ: БИБЛИОМЕТРИЯЛЫҚ ТАЛДАУ

Мақалада жаңартылатын энергия көздерін интеграциялау тәуекелдерін ғылыми түсіну құрылымы талданады. Web of Science дерекқорының (2015–2025) 4823 басылымының библиометриялық талдауы негізінде үш тұрақты тақырыптық кластер анықталды және белгісіздік жағдайында жүйені оңтайландыру парадигмасының басымдығы көрсетілді. Зерттеудің ғылыми жаңалығы жүйенің өзектілік индексін – библиометриялық желінің топологиясына негізделген тәуекелдерді азайту стратегияларын сандық бағалауға арналған метриканы әзірлеуде жатыр; ғылыми басымдықтар мен инвестициялық тәжірибе арасындағы алшақтық анықталды: бірқатар технологиялар үшін ол нормаланған шкала бойынша +0,6-ға жетеді. Үш кезеңдегі (2015-2018; 2019-2021; 2022-2025) жарияланымдардың динамикалық талдауы зерттеу күн тәртібіндегі реттеуші тәсілдерден жүйелік тәуекелдерді инженерлік басқаруға ауысуды тіркеді. Тор түзетін инверторлар мен машиналық оқыту алгоритмдері ғылыми салада орталық орын алатыны, нарыққа енуден 5–10 жылға озып кететіні көрсетілген, бұл инвестициялық саясаттың перспективалы бағыттарын көрсетеді.

Түйін сөздер: *жаңартылатын энергия көздерін интеграциялау, жүйелік тәуекелдер, библиометриялық талдау, энергияны сақтау, жүйені оңтайландыру, белгісіздіктерді басқару.*

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ЭВОЛЮЦИЯ НАУЧНОГО ДИСКУРСА И ИНВЕСТИЦИОННЫХ ПРИОРИТЕТОВ В ОБЛАСТИ РИСКОВ ИНТЕГРАЦИИ ВОЗОБНОВЛЯЕМЫХ ИСТОЧНИКОВ ЭНЕРГИИ: БИБЛИОМЕТРИЧЕСКИЙ АНАЛИЗ

В статье анализируется структура научного понимания рисков интеграции возобновляемых источников энергии. На основе библиометрического анализа 4823 публикаций базы данных Web of Science (2015-2025) были выявлены три устойчивых тематических кластера и продемонстрировано доминирование парадигмы системной оптимизации в условиях неопределенности. Научная новизна исследования заключается в разработке индекса релевантности системы – показателя для количественного ранжирования стратегий снижения рисков на основе топологии библиометрической сети; был выявлен разрыв между научными приоритетами и инвестиционной практикой: для ряда технологий он достигает +0,6 по нормализованной шкале. Динамический анализ публикаций за три периода времени (2015-2018; 2019-2021; 2022-2025) выявил сдвиг в программе исследований от нормативных подходов к инженерному менеджменту.

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INFLUENCE OF MICRO-ARC OXIDATION PROCESSING PARAMETERS ON THE STRUCTURE AND PROPERTIES OF ALUMINOSILICATE COATINGS FORMED ON AMG6 ALUMINUM ALLOY

Abstract: *The work presents a comprehensive study of the formation processes, structure, phase composition, and performance properties of oxide coatings produced on the AMG6 aluminum alloy by the micro-arc oxidation method. The treatment was carried out using a laboratory setup equipped with a pulsed power supply and a temperature control system, ensuring stable electrical and thermal regimes. The use of silicate-alkaline electrolytes of various compositions made it possible to purposefully control the morphology*

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