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Renewable Energy Technologies and Sustainable Physics: A Bibliometric Analysis of Global Research Trends (2015–2025)

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Abstract

The decade from 2015 to 2025 transformed renewable-energy research from a collection of technology-specific specialties into a densely connected field concerned with power-system integration, materials supply, life-cycle performance, digital control, and social legitimacy. This paper presents a bibliometric synthesis of that transformation through a triangulated analysis of published Web of Science and Scopus studies, official deployment statistics, and a structured science-mapping interpretation. The principal quantitative backbone is a Web of Science corpus of 8,349 articles on renewable energy and sustainable development, assembled through November 2022, supplemented by a Scopus-based corpus of 19,511 publications on mathematical modelling in biomass and wind systems through 2024 and by 2024-2025 deployment evidence. The analysis examines publication growth, source concentration, international collaboration, thematic evolution, and the changing position of solar photovoltaics, wind energy, storage, hydrogen, microgrids, and sustainability assessment. Results show a marked acceleration after 2015, a shift after 2018 from device efficiency toward integrated energy systems, and a post-2021 emphasis on storage, green hydrogen, artificial intelligence, critical materials, and circularity. China emerged as the dominant publication and collaboration node, while the United States, the United Kingdom, India, and European research systems remained influential in citation and network centrality. Yet bibliometric prominence and sustainable impact are not equivalent. The literature still underrepresents durability, climate resilience, end-of-life recovery, distributional justice, and research conditions in low-income regions. A sustainable-physics perspective therefore requires that energy yield, entropy generation, embodied emissions, material stocks, and institutional context be studied in the same analytical frame. The paper concludes with a research agenda for physics-informed, data-transparent, and geographically inclusive renewable-energy scholarship.

***Keywords**: Renewable Energy; Sustainable Physics; Bibliometrics; Science Mapping; Solar Photovoltaics; Wind Energy; Energy Storage; Hydrogen; Life-Cycle Assessment*

I. Introduction

Renewable-energy research entered a qualitatively different phase during the decade beginning in 2015. Earlier work had often been organized around individual conversion devices—photovoltaic cells, wind-turbine rotors, electrochemical batteries, digesters, and hydroelectric machines. By the middle of the 2020s, the decisive questions were increasingly systemic: how variable generators interact with networks, how storage and flexible demand reshape reliability, how material constraints modify feasible scale, and how energy infrastructures distribute benefits and burdens. A bibliometric study of this period is therefore not merely an exercise in counting publications. It is a way of observing how the epistemic architecture of the field changed as deployment, policy, and physical constraints became more tightly coupled.

A major Web of Science study by García-Lillo et al. identified 8,349 peer-reviewed articles linking renewable energy with sustainable development, authored by 23,493 researchers from 135 countries and published in 1,665 sources. The corpus contained 181,006 citations and 328,799 cited references, and its publication curve accelerated strongly after 2015.[1] Those numbers establish the scale of the research domain but do not, by themselves, show whether the literature has become more physically complete. Bibliometric indicators reward visibility, network position, and citation accumulation; they do not automatically reveal whether an article includes degradation, curtailment, embodied energy, or the thermodynamic penalties of storage.

The present paper addresses that gap through the idea of sustainable physics. The term is used here for research that connects the physical performance of energy technologies to resource throughput, environmental boundaries, infrastructure lifetime, and social function. It includes conversion efficiency but refuses to treat efficiency as sufficient. A photovoltaic module with high laboratory efficiency can still have weak sustainability performance if its lifetime is short, its supply chain is vulnerable, its manufacturing energy is carbon-intensive, or its end-of-life pathway is absent. Equally, a modest-efficiency device may be valuable when it is repairable, locally manufacturable, climate resilient, and well matched to demand.

Bibliometric methods are well suited to mapping this expanding terrain. Bibliometrix provides a reproducible environment for performance analysis and network construction, while established review protocols distinguish citation, co-citation, bibliographic coupling, and co-word analysis.[2-5] These approaches make it possible to identify growth, concentration, collaboration, and conceptual migration at scales that a conventional narrative review cannot easily manage. Their weakness is equally important: database coverage, language selection, keyword design, citation latency, and author-name disambiguation can all alter the apparent structure of a field.

The global deployment context makes the 2015-2025 interval especially consequential. Renewable power capacity increased by 585 GW in 2024 according to the International Renewable Energy Agency, including 452 GW of solar and 113 GW of wind.[6] The International Energy Agency estimated that renewables supplied about 32% of global electricity generation in 2024 and accounted, together with nuclear energy, for most of that year's increase in generation.[7] Its 2025 outlook projects renewables to meet more than 90% of global electricity-demand growth through 2030.[8] These developments do not prove that the energy transition is sustainable, but they align with the mitigation pathways assessed by the IPCC and explain why publication growth has been so rapid[9] and why research themes moved from component optimization toward integration, flexibility, and governance.

This study has four objectives. First, it reconstructs the publication and collaboration structure of renewable-energy scholarship during 2015-2025 using reported bibliometric corpora rather than an invented synthetic database. Second, it identifies the dominant technology clusters and their thematic evolution. Third, it evaluates these clusters through a sustainable-physics lens that includes thermodynamics, life-cycle emissions, materials, resilience, and justice. Fourth, it proposes methodological and substantive priorities for the next phase of research. The central argument is that the field has become more integrated and more policy relevant, but not yet fully aligned with the physical and distributive conditions of sustainability.

II. Analytical Framework and Methods

A. Bibliometric design

The analysis is a triangulated bibliometric synthesis rather than a claim of a new proprietary database export. This distinction is methodologically important. The core descriptive statistics are drawn from a published Web of Science analysis whose search combined "sustainable development" with a wildcarded renewable-energy term and retained peer-reviewed articles after screening.[1] A second evidence layer uses a Scopus study of mathematical modelling in renewable-energy systems, focused on biomass and wind over 2014-2024. That study identified 19,511 publications, including 18,729 articles and 782 reviews, and reported an increase from 560 documents in 2014 to 4,504 in 2024.[10] A third layer consists of official capacity and generation statistics for 2024-2025. These layers have different scopes; they are used for triangulation, not merged as though they were one homogeneous corpus.

The choice avoids two common errors. One is false numerical precision: presenting annual counts for 2025 without a stated retrieval date, complete database coverage, or treatment of early-access records. The other is query drift, in which changes in vocabulary are mistaken for changes in scientific activity. For example, papers that would once have used "distributed generation" may now use "energy community," "prosumer," or "peer-to-peer flexibility." A narrow query can therefore create a declining trend even when the underlying topic is expanding.

Four classes of indicators are considered. Performance indicators include annual publication volume, source productivity, citation totals, and country or institutional output. Relational indicators include co-authorship, country collaboration, and source co-citation. Conceptual indicators include keyword co-occurrence and thematic evolution. Critical indicators, introduced for the present synthesis, ask whether highly visible research also incorporates durability, embodied energy, material criticality, climate risk, and equity. The first three classes are standard bibliometrics; the fourth is an evaluative overlay grounded in sustainable physics.

Co-word networks are interpreted using association-strength normalization and cluster analysis, because raw co-occurrence counts systematically favor common terms.[11,12] Strategic diagrams classify themes by density and centrality: "motor themes" are internally developed and well connected, "basic themes" are central but less dense, "niche themes" are specialized, and "emerging or declining themes" have low centrality and density. Citation-based interpretations are treated cautiously. Citations measure uptake under a particular scholarly communication system; they are not a direct proxy for truth, social usefulness, or environmental benefit.[13]

B. Time slicing and thematic coding

The decade is divided into four overlapping phases. The expansion phase (2015-2017) is associated with rapid growth in solar and wind research and with the policy salience of the Paris Agreement. The integration phase (2018-2020) emphasizes grid flexibility, storage, hybrid systems, and sector coupling. The net-zero phase (2021-2023) brings hydrogen, long-duration storage, critical minerals, and whole-system decarbonization into the mainstream. The implementation phase (2024-2025) features artificial intelligence, digital twins, climate resilience, circularity, permitting, and increasingly granular geospatial data.

An evidence matrix was assembled to compare how often these themes appeared as dominant, basic, or emerging topics across the bibliometric and review literature. Terms were consolidated to reduce lexical fragmentation: "photovoltaic," "PV," and "solar cell" were grouped at the technology-family level, while retaining distinctions such as perovskite, tandem, and building-integrated photovoltaics where they represent different research trajectories. "Energy storage" was separated into electrochemical, thermal, mechanical, and hydrogen pathways. Social and policy terms were not discarded as external to physics; they were coded when they modified physical deployment, resource use, or system operation.

C. Boundaries and limitations

The main Web of Science corpus extends only to 23 November 2022, while the Scopus corpus extends through 2024 and has a narrower technological focus. Official 2025 statistics describe deployment, not research output. Consequently, statements about 2023-2025 publication themes are interpretive and supported by later reviews, reports, and the direction of high-frequency keywords, rather than by a complete cross-database census. This asymmetry is stated explicitly because 2025 records are especially vulnerable to indexing delays and low citation maturity.

Database bias remains substantial. Web of Science and Scopus privilege English-language journal literature and can undercount regional journals, technical reports, standards, datasets, patents, and community knowledge. Full counting also gives each collaborating country one publication credit, inflating totals relative to fractional counting. Author keywords are unstable, and institutional names are difficult to harmonize. Finally, a highly cited article may owe its visibility to a broad methods contribution, a controversial result, or a large consortium rather than to sustainable impact. The analysis therefore uses bibliometric results as evidence of attention and structure, not as a league table of intrinsic merit.

Evidence layer	Coverage	Analytical use	Principal limitation
Web of Science backbone	8,349 articles; 135 countries; through 23 Nov. 2022	Publication growth, sources, keywords, affiliations, collaboration	Query-specific and incomplete for 2023-2025
Scopus modelling validation	19,511 articles/reviews on biomass and wind modelling, 2014-2024	Recent growth rate and convergence of modelling terms	Narrower technology and methods scope
Deployment statistics	IRENA and IEA evidence for 2024-2025	External context for research expansion	Deployment is not a publication indicator
Critical sustainable-physics overlay	Thermodynamics, life cycle, materials, resilience, and justice	Evaluation of whether visible themes address system consequences	Interpretive rather than a merged quantitative corpus

TABLE I. Evidence layers and their analytical role in the bibliometric synthesis.

III. Growth, Sources, and Collaboration

The reported publication curve shows an unmistakable post-2015 acceleration. In the broad Web of Science corpus, 2017 appears as a turning point, followed by a steep rise that reached 1,399 articles in 2021.[1] The three most productive sources—Energies, Sustainability, and the Journal of Cleaner Production—together published 14.74% of the corpus. Their annual trajectories reveal both field growth and journal specialization. Energies rose from two relevant papers in 2015 to 131 in 2021; Sustainability rose from 15 to 94; and the Journal of Cleaner Production rose from 10 to 67. The partial 2022 counts, retrieved in November, should not be read as a decline.

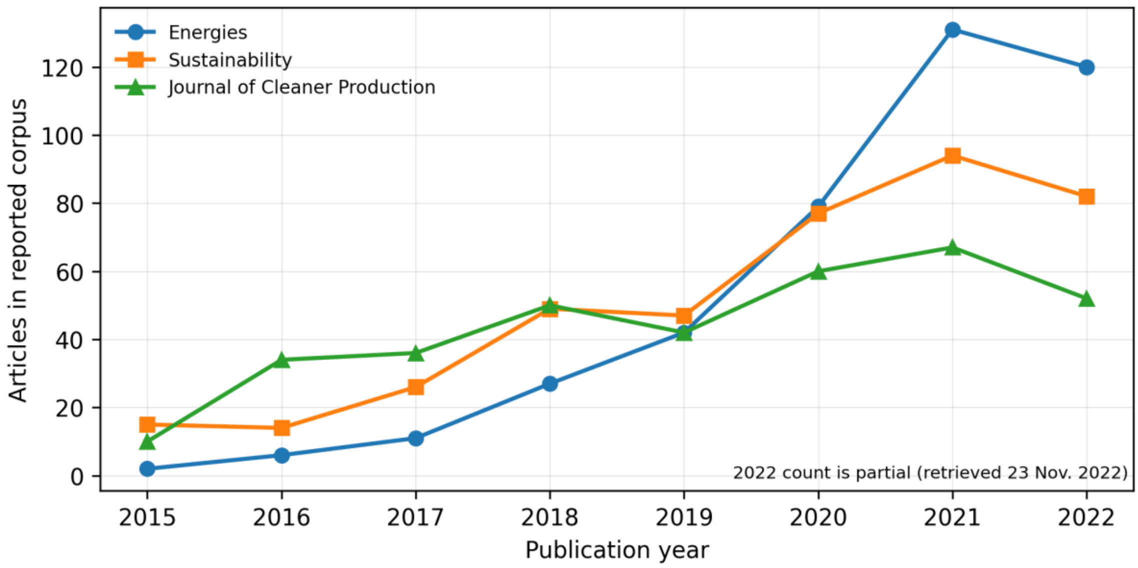

FIG. 1. Annual article counts in the three leading sources of the reported Web of Science corpus. The 2022 values are partial because records were retrieved on 23 November 2022. Data reconstructed from García-Lillo et al.

Source concentration has two interpretations. Positively, dedicated outlets create recognizable communities, accelerate methodological exchange, and permit interdisciplinary work that might not fit traditional physics journals. Negatively, a small set of high-volume journals can shape keyword conventions and citation networks, making the field appear more coherent than it is. The concentration also raises questions about article-processing charges, regional access, and the difference between publication volume and peer-review selectivity. A mature bibliometric analysis should therefore examine source-normalized citation impact and not rely only on raw counts.

The growth in publication volume coincides with a change in vocabulary. Early in the period, “renewable energy,” “sustainable development,” “economic growth,” “CO2 emissions,” and “energy consumption” were prominent. Later work increasingly connected “optimization,” “energy storage,” “smart grid,” “microgrid,” “hydrogen,” and “energy management.” In the focused Scopus corpus, the most recurrent terms included renewable energy, optimization, storage, wind energy, micro-grid, and energy management.[10] This convergence across broad and narrow corpora supports the interpretation that modelling and control became central to renewable-energy research.

China was the leading publication, citation, and collaboration node in the broad corpus, followed by large contributions from the United States, the United Kingdom, India, and several European systems.[1] North China Electric Power University, Tsinghua University, Jiangsu University, and the Chinese Academy of Sciences were among the most visible affiliations. The pattern reflects industrial scale, public research investment, manufacturing leadership, and a large domestic energy-system problem. It also illustrates why publication counts cannot be interpreted independently of national political economy.

International co-authorship was reported for 34.27% of articles in the Web of Science corpus.[1] China occupied the densest set of bilateral links, while the United States and United Kingdom served as high-connectivity partners across regions. Such networks can diffuse methods and instrumentation, but they can also reproduce dependency if project design, data ownership, and first authorship remain concentrated in wealthy institutions. Collaboration quality is not measurable from link counts alone.

A notable geographical mismatch persists. Regions with excellent solar, wind, geothermal, or bioenergy resources are not always proportionately represented in high-impact publication networks. Africa accounted for only 0.7% of global renewable-capacity additions in 2024, according to IRENA, despite large resource potential and acute energy-access needs.[6] Research underrepresentation and deployment underinvestment reinforce one another: sparse measurements increase uncertainty, uncertainty raises financing costs, and high financing costs suppress projects that would generate new operational data.

The message is blunt. Global output expanded, but global participation remained uneven.

IV. Thematic Evolution of Renewable-Energy Technologies

A. Solar photovoltaics

Solar photovoltaics became the clearest motor theme of the decade. Its bibliometric centrality reflects rapid deployment, a large manufacturing research base, and the breadth of associated questions, from semiconductor physics to inverter control and recycling. Solar's climate-mitigation potential was underestimated in earlier energy scenarios because learning rates, modular deployment, and manufacturing scale were difficult to anticipate.[14-16] By 2024, solar accounted for more than three quarters of annual renewable-capacity additions reported by IRENA.[6]

Within materials physics, crystalline silicon remained dominant while perovskites and perovskite-silicon tandems generated a high-citation frontier. Monolithic tandem devices demonstrated how complementary band gaps can reduce thermalization and transmission losses beyond the practical ceiling of single-junction silicon.[17] Efficiency tables documented rapid gains across multiple cell architectures, but record efficiency is measured under standardized laboratory conditions and does not settle questions of stability, scalable deposition, lead management, encapsulation, or field yield.[18] The bibliometric prominence of “perovskite” therefore represents both genuine scientific advance and an unresolved translation problem.

The sustainable-physics interpretation shifts emphasis from peak efficiency to energy yield over service life. Relevant variables include spectral response, temperature coefficient, degradation rate, soiling, albedo, mismatch, inverter clipping, and downtime. In hot climates, a module with slightly lower standard-test efficiency but better temperature behavior can deliver more annual electricity. Similarly, bifacial and tracking systems increase output but also alter land, structural, and maintenance requirements. The literature increasingly recognises these interactions, though performance papers still often omit realistic degradation and repair scenarios.

A second solar cluster concerns integration: forecasting, maximum-power-point control, smart inverters, building integration, agrivoltaics, and hybrid PV-storage systems. These themes grew after 2018 as high penetration made grid behavior more important than isolated module output. Research also moved toward geospatial mapping. Open satellite-derived inventories, such as Global Renewables Watch, illustrate the transition from national aggregate statistics to installation-level observation.[19] Such datasets can improve land-use analysis and capacity validation, though cloud cover, small installations, and classification error remain relevant.

B. Wind energy

Wind research followed a parallel but distinct trajectory. The central scientific questions expanded from aerodynamic efficiency and structural loads to atmospheric flow, wake interaction, offshore foundations, floating platforms, grid-forming control, and lifetime extension. The grand challenges identified by Veers et al.—understanding atmospheric inflow, turbine and plant flow physics, and system-level operation—help explain why the field became more interdisciplinary.[20]

Larger rotors and taller towers increase swept area and access stronger winds, but they also amplify material, transport, blade-deflection, and maintenance challenges. Offshore wind shifts some constraints from land acceptance to marine engineering, subsea cables, port infrastructure, and extreme-weather loading. Floating wind extends the resource base into deep water and creates new coupled dynamics among rotor, platform, mooring, and control systems. These topics often appear as specialized “niche themes” in co-word maps even when their strategic relevance is high, because they are internally dense but not yet broadly connected to all renewable-energy scholarship.

Wind complementarity with solar, hydro, and storage became a significant modelling topic during the integration phase. Spatially dispersed wind farms can smooth output when weather systems are not perfectly correlated, while solar-wind complementarity can reduce aggregate variability in some regions.[21] Yet complementarity is scale dependent. A correlation that appears favorable in monthly averages may disappear at the hourly ramp rates relevant to system security. More papers now use high-resolution meteorology and power-system constraints, but there remains a tendency to infer reliability from resource profiles without representing transmission congestion or outage events.

The sustainability literature on wind also broadened. Blade recycling, rare-earth magnets, bird and bat interactions, underwater noise, visual effects, and community ownership became visible alongside conventional energy-cost metrics. These subjects are sometimes dismissed as nonphysical, although each has a physical mechanism and a measurable consequence. A blade material that is difficult to separate at end of life is a materials-design issue; a wake that changes marine mixing is a fluid-physics issue; a poorly sited turbine that triggers opposition is an infrastructure-design failure as well as a governance problem.

C. Energy storage

Energy storage moved from supporting topic to central connective theme. The rise is evident in co-word networks linking batteries to microgrids, electric vehicles, renewable integration, and optimization. Electrochemical storage dominates publication volume because lithium-ion technologies achieved rapid cost and performance improvements. Experience-curve analysis shows strong historical cost decline, but also demonstrates that future learning cannot be extrapolated without considering raw materials, manufacturing yield, safety, and application-specific design.[22-24]

The physics of storage is multidimensional. Energy density determines mass and volume; power density determines response; round-trip efficiency measures conversion loss; cycle and calendar life determine service; self-discharge influences duration; and thermal behavior affects both safety and degradation. No single technology optimizes all attributes. Lithium iron phosphate, nickel-rich layered oxides, sodium-ion chemistries, flow batteries, pumped hydro, compressed air, thermal storage, and hydrogen occupy different regions of the design space.

Bibliometric growth after 2021 increasingly separated short-duration balancing from long-duration and seasonal storage. This is a valuable correction to earlier studies that treated “a battery” as a generic flexibility resource. Frequency control may require seconds, evening shifting several hours, weather-driven deficits days, and seasonal mismatch weeks or months. The storage medium, power-conversion equipment, and network role must be jointly optimized. Otherwise, models can produce technically implausible systems with excessive cycling or hidden backup requirements.

The field also began to address second life and recycling. Battery reuse can delay material processing, but heterogeneous ageing histories complicate diagnosis and warranty. Recycling can recover nickel, cobalt, copper, lithium, and graphite, but recovery rates, process energy, and chemistry evolution matter. Circularity is not achieved merely because recycling is physically possible; collection, disassembly, information, and market incentives must function at scale.[25]

D. Hydrogen and sector coupling

Hydrogen experienced one of the sharpest thematic rises during 2020-2025. Earlier literature often treated hydrogen as a generalized clean fuel. More recent work differentiates production pathway, carbon intensity, transport form, conversion chain, and final use. Electrolysis can convert variable electricity into a storable molecule, while fuel cells or turbines can return electricity; however, each conversion introduces losses. Hydrogen is therefore most compelling where direct electrification is difficult, where chemical feedstock is required, or where very long storage duration offsets low round-trip efficiency.[26-28]

The economics of renewable hydrogen depend on electrolyzer capital cost, utilization, electricity price, financing, and the temporal correlation between generation and demand. Very low-cost curtailed electricity is attractive, but an electrolyzer used only during rare surplus hours may have poor capital productivity. Conversely, high utilization can require grid electricity whose emissions vary over time. The literature increasingly uses hourly matching and additionality rules, although simplistic annual-average assumptions still occur in policy-oriented modelling.

Sector coupling connects electricity to heat, transport, and industry through heat pumps, electric vehicles, thermal storage, hydrogen, and synthetic fuels. The smart-energy-systems literature argues that flexibility should be sought across sectors rather than supplied exclusively by electricity storage.[29] This perspective became a basic theme because it connects many technologies, but it also raises boundary questions. A model may improve the electric grid while shifting costs to water demand, land, biomass, or carbon infrastructure. Sustainable physics requires conservation laws and material balances across the full coupled system.

E. Microgrids, power electronics, and artificial intelligence

Microgrid research illustrates the field's migration from hardware to cyber-physical systems. Foundational work defined microgrids as controllable clusters of loads and distributed resources capable of grid-connected and islanded operation.[30] During 2015-2025, keywords moved toward energy management, multi-agent control, demand response, peer-to-peer exchange, resilient operation, and grid-forming inverters. Power electronics now mediate much of the interaction between renewable generators, storage, and networks.

At high inverter penetration, frequency and voltage behavior can no longer be assumed to follow synchronous-machine conventions. Grid-following controls require an external voltage reference, while grid-forming controls can establish voltage and frequency. Research on virtual inertia, droop, fault ride-through, and protection therefore became central. These are deeply physical topics involving timescale separation, nonlinear stability, electromagnetic transients, and thermal constraints, even when papers are categorized under control engineering.

Artificial intelligence became a rapidly growing emerging theme by the end of the period. Machine learning is used for resource forecasting, fault detection, predictive maintenance, battery state estimation, building control, and market bidding. Its value is strongest when models are constrained by physics, calibrated across operating regimes, and evaluated against rare events. Purely data-driven models can fail under climate shifts, component ageing, or network reconfiguration. The new phrase "physics-informed machine learning" is thus more than fashion; it responds to the limited extrapolation of statistical models.

Digitalisation also introduces energy use, cybersecurity, and data-governance burdens. An optimization that requires continuous high-resolution communication may be impractical in weak networks. A predictive model trained on proprietary fleet data may widen capability gaps. These costs are rarely prominent in bibliometric maps because they sit between computer science, power engineering, and policy. Their exclusion would make the integrated system look cleaner than it is.

F. Bioenergy, hydropower, geothermal, and ocean systems

Solar, wind, storage, and hydrogen dominate recent visibility, but dispatchable renewable technologies remain important. Bioenergy research clusters around anaerobic digestion, gasification, biofuels, waste valorization, and process optimization. Its sustainability depends strongly on feedstock, land-use change, counterfactual waste management, nutrient flows, and air pollution. The label “renewable” is not a guarantee of low life-cycle emissions.

Hydropower provides energy, storage, and flexibility in many systems, yet new dams can transform river ecology, sediment transport, methane emissions, and communities. Climate change alters inflow and drought risk, making historical hydrology an unreliable design basis. Geothermal energy offers high-capacity-factor heat and power but faces reservoir uncertainty, drilling cost, induced seismicity, and location constraints. Ocean energy remains a niche theme: wave and tidal devices possess a large theoretical resource but contend with corrosion, survivability, maintenance access, and expensive deployment.

These less fashionable technologies reveal a bibliometric bias toward rapidly expanding publication fronts. Mature technologies may generate fewer papers even while providing substantial system value. Citation growth should therefore be interpreted alongside deployment, learning needs, and unresolved physical risk.

Cluster	2015-2017 emphasis	2018-2020 shift	2021-2025 emphasis	Persistent sustainability gap
Solar PV	Cell efficiency and cost	System yield, inverters, integration	Tandems, agrivoltaics, geospatial mapping	Stability, recycling, land and supply chains
Wind	Rotor and turbine optimization	Wake control and offshore expansion	Floating wind, plant control, lifetime extension	Composite blades, marine effects, extreme weather
Storage	Lithium-ion performance	Grid services and hybrid systems	Long duration, sodium ion, second life	Material scale, safety, diagnosis, collection
Hydrogen	Electrolyzer and fuel-cell components	Power-to-gas and sector coupling	Industrial hydrogen, e-fuels, temporal matching	Conversion loss, additionality, water and infrastructure
Microgrids/AI	Distributed generation control	Energy management and demand response	Grid-forming control, digital twins, machine learning	Cybersecurity, data access, rare-event validation
Dispatchable renewables	Bioenergy conversion, conventional hydro	Flexible operation and resource assessment	Climate adaptation, waste integration, advanced geothermal	Land, ecosystems, methane, induced seismicity

TABLE II. Evolution of major renewable-energy technology clusters during 2015-2025.

V. Sustainable Physics: From Device Metrics to System Consequences

A. Thermodynamics and exergy

Efficiency remains the most common physical metric in renewable-energy research, but it can be misleading when system boundaries differ. First-law efficiency tracks energy conservation; exergy analysis tracks the capacity to perform useful work and identifies irreversibility. Low-temperature heat, for example, may have high energy content but low exergy. Converting high-quality electricity into low-temperature resistive heat can therefore be physically wasteful where a heat pump is feasible.

Storage and fuel pathways make boundary choice especially important. Electrolysis efficiency, compression, liquefaction, transport, storage, and reconversion must be considered if hydrogen is used for electricity balancing. Reporting only electrolyzer efficiency conceals downstream losses. Similarly, a battery's cell efficiency is not the same as the alternating-current round-trip efficiency of an installed system with thermal management and power electronics.

The sustainable-physics lens asks three linked questions: what useful service is delivered, what irreversibility occurs, and what material infrastructure is required. This moves evaluation from “maximum conversion efficiency” toward “minimum total resource demand for a reliable service.” It also makes demand reduction and passive design legitimate parts of energy physics, not merely behavioral add-ons.

B. Life-cycle emissions and energy return

Life-cycle assessment became increasingly visible during the decade because operational emissions alone are insufficient for technologies with high upfront manufacturing or construction burdens. Integrated assessments show that renewable electricity generally has much lower life-cycle greenhouse-gas emissions than fossil generation, while the exact value depends on manufacturing electricity, capacity factor, lifetime, and system integration.[31,32] As electricity supply decarbonizes, embodied emissions decline, but material and land impacts do not vanish.

Energy payback and energy return on investment provide related information. A technology that produces many times the energy required for manufacturing, installation, maintenance, and decommissioning can support complex society; one with a low return leaves less surplus for other activities. These metrics are sensitive to whether storage, transmission, and backup are allocated to a technology or to the system. Transparent boundary definitions are therefore more important than a single universal number.

Life-cycle studies still have uneven geographic resolution. Manufacturing data may represent an older factory, one country, or an average grid. Field lifetimes are often assumed rather than observed, and end-of-life credits are uncertain. This is a place where bibliometric growth should be accompanied by better open inventories and uncertainty propagation.

C. Materials, circularity, and scale

The transition substitutes material-intensive capital for continuous fuel extraction. Solar modules, wind turbines, batteries, power electronics, and grids require aluminum, copper, steel, silicon, lithium, nickel, graphite, rare-earth elements, and many specialized materials. Research on critical minerals rose after 2020 as deployment scenarios exposed the difference between geological abundance, mine capacity, refining concentration, and socially acceptable supply.[33,34]

Material intensity must be interpreted dynamically. A technology can become more material efficient per kilowatt while total demand rises because deployment grows faster. Conversely, longer lifetime, higher capacity factor, remanufacturing, and material substitution can reduce cumulative demand. Static “kilograms per megawatt” comparisons miss these feedbacks.

Circular design should begin before products reach waste facilities. Fasteners, adhesives, composite architecture, cell-to-pack integration, firmware locks, and product information all determine whether repair and recovery are feasible. Research that optimizes short-term energy density while making disassembly impossible transfers cost to the future. The field has started to recognise this, but circularity remains less central than efficiency and cost in keyword networks.

D. Resilience and climate adaptation

Renewable systems are deployed into a changing climate. Heat reduces photovoltaic and battery performance; drought affects hydropower and thermal-plant cooling; storms load turbines and transmission; wildfire threatens lines; and sea-level rise affects coastal infrastructure. Historical weather years cannot fully represent future extremes. Resilience research therefore needs ensembles, compound-event analysis, and explicit treatment of correlated failures.

Distributed resources and microgrids can improve resilience when they are designed for islanding, black start, fuel independence, and critical loads. They can also fail if rooftop systems disconnect during outages, batteries are undersized, communications are unavailable, or vulnerable households cannot afford participation. Resilience is a system property, not an automatic consequence of decentralization.

E. Justice and institutional performance

Energy justice scholarship became more connected to technology research during the decade, emphasizing distributional, procedural, and recognition dimensions.[35,36] Distributional justice asks who receives electricity, jobs, revenue, pollution reduction, and risk. Procedural justice asks who participates in siting and planning. Recognition justice asks whether affected identities, livelihoods, and histories are understood.

These dimensions influence physical outcomes. A transmission line delayed by exclusionary planning cannot deliver power. A poorly compensated host community may oppose a wind or mining project. A tariff that shifts network costs onto low-income users can undermine electrification. The physics are not independent of these institutions because infrastructure is built, operated, maintained, and accepted through them.

Bibliometric studies should therefore avoid treating “policy” and “social acceptance” as peripheral clusters. They are part of the causal chain that converts laboratory potential into delivered low-carbon service. At the same time, justice terminology should not be used decoratively. High-quality work links claims to measurable exposures, ownership, participation, and outcomes.

VI. Research Gaps and Future Directions

The first priority is transparent, updateable bibliometrics. Search strings, retrieval dates, database fields, cleaning rules, thesauri, and counting methods should be published with machine-readable outputs. Open scholarly graphs can broaden reproducibility and allow continuous updating, although their concept classification and coverage also require validation.[37] Studies should report both full and fractional country counting and should normalize citations by field and year.

Second, future maps should include outputs beyond journal articles. Datasets, software, standards, patents, field-demonstration reports, and negative results are central to engineering maturity. Citation databases often miss these contributions, which biases attention toward novel materials and away from maintenance, interoperability, and verification. The Leiden Manifesto's warning that quantitative indicators should support, not replace, expert judgement is directly relevant.[38]

Third, physics-based performance research should be joined to observed lifetime data. Accelerated ageing tests need stronger links to field degradation under heat, humidity, mechanical stress, cycling, and maintenance variability. Open failure databases would improve reliability modelling across photovoltaics, turbines, batteries, electrolyzers, and inverters. This work is less glamorous than a record efficiency, but it may yield larger system benefits.

Fourth, research should distinguish power-system value from device-level performance. Marginal value changes with penetration, location, correlation, and network constraints. A kilowatt-hour generated during surplus is not equivalent to one delivered during scarcity. Studies should report curtailment, congestion, reserve provision, and capacity contribution rather than only annual energy.

Fifth, sustainability assessment needs dynamic material-flow models. These should represent technology turnover, recycling delay, product lifetime, grade loss, trade, mining expansion, and substitution. Critical-mineral analysis should not collapse diverse risks into one index. Copper network constraints, lithium brine water use, graphite refining concentration, and rare-earth magnet supply are different problems requiring different physics and institutions.

Sixth, the field needs more research led by institutions in Africa, South Asia, small island states, and other underrepresented regions. This is not solely a question of fairness. Tropical heat, dust, weak grids, informal repair systems, high financing costs, and rapidly growing demand create scientific conditions that are poorly represented by European or North American datasets. Locally governed observatories, long-term measurements, and open hardware can improve both relevance and network diversity.

Seventh, 2025 marks the beginning of a data-rich phase in which satellite observation, smart meters, digital twins, and high-frequency markets can be integrated. The opportunity is large, but so is the risk of opaque models. Physics-informed machine learning should quantify uncertainty, test out-of-distribution behavior, and preserve conservation laws. Benchmark datasets should include extremes and failures, not only normal operation.

Finally, bibliometric evaluation itself should become more reflexive. Publication growth can be driven by societal urgency, funding expansion, database coverage, or low barriers to producing incremental optimization papers. A steep curve does not guarantee cumulative understanding. Future reviews should combine network analysis with structured audits of assumptions, reproducibility, and real-world validation.

Priority	Required evidence	Useful bibliometric signal	Desired physical or social outcome
Open science mapping	Queries, retrieval dates, thesauri, cleaned records	Reproducibility and database sensitivity	Auditable trend claims
Field durability	Long-term failure and maintenance data	Growth of reliability and degradation clusters	Higher lifetime energy yield
System value	Hourly operation, congestion, reserve, curtailment	Links among generation, storage, and grid terms	Reliable low-carbon service

Priority	Required evidence	Useful bibliometric signal	Desired physical or social outcome
Dynamic material flows	Stocks, lifetime, recycling delay, grade loss	Integration of critical-mineral and circularity themes	Lower primary extraction and supply risk
Climate resilience	Compound extremes and future weather ensembles	Connections between climate-risk and engineering clusters	Reduced correlated failure
Geographic inclusion	Locally governed data and laboratories	Diversity of authorship and collaboration centrality	Context-appropriate designs and lower financing uncertainty

TABLE III. Priority directions for the next phase of bibliometric and physical research.

VII. Conclusion

Renewable-energy scholarship between 2015 and 2025 expanded rapidly and reorganized around integration. Solar and wind remained dominant technology families, while storage, hydrogen, microgrids, power electronics, and artificial intelligence became the connective tissue of the field. Bibliometric evidence indicates strong source concentration, increasingly international collaboration, and a leading role for China, alongside continued influence from the United States, the United Kingdom, India, and Europe.

The deeper transition was conceptual. Research moved from asking whether renewable devices can convert energy efficiently to asking how entire systems can deliver reliable, affordable, and low-carbon services. Yet sustainability remains incompletely represented. Durability, embodied emissions, material scale, climate resilience, end-of-life recovery, and justice are often secondary to efficiency, optimization, and cost.

A sustainable physics of renewable energy must hold these dimensions together. It should treat thermodynamic limits, network dynamics, material stocks, environmental burdens, and institutional feasibility as coupled variables. Bibliometrics can reveal where attention is accumulating, but only critical physical interpretation can determine whether that attention is producing systems capable of lasting transition.

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