Scientometric Review of the 3D Energy Transition: Decarbonization, Digitalization, and Decentralization in Energy Systems

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***Abstract* — This article presents a scientometric review that quantifies the contribution of the three-dimensional energy transition, that is decarbonization, digitalization, and decentralization, to the research field of energy systems over the period 2001 to 2025. Records were retrieved from Scopus using a two-level query that first captured the general energy systems domain and then stratified it into the three components. Standardized preprocessing, cleaning, and keyword harmonization were applied. Descriptive indicators trace publication growth and portfolio shares, and network mapping with VOSviewer visualizes keyword co-occurrence and topic evolution. Results show substantial expansion of the field and a shift of the research mainstream toward the 3D topics. Decarbonization accounts for approximately half of the corpus, digitalization for about one fifth, and decentralization for a smaller but persistent share. Integration between energy transition components increases over time, with the strongest coupling along the decarbonization and digitalization axes, and a compact but growing 3D core emerges. Topic maps indicate an early policy and renewables nucleus, followed by acceleration in storage, hydrogen, power electronics and control, data-driven operations, cyber security, and market mechanisms for local flexibility.**

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I. Introduction

The transformation of energy systems in the early twenty-first century is increasingly described as the convergence of three interrelated directions: decarbonization, digitalization, and decentralization (hereafter, the 3D paradigm) [1, 2]. Decarbonization entails reducing the carbon intensity of energy supply through the large-scale deployment of renewable energy sources, improvements in efficiency, and the implementation of carbon capture, utilization, and storage (CCUS) technologies. Digitalization establishes a technological layer, spanning sensors, the Internet of Things (IoT), artificial intelligence and machine learning (AI/ML), digital twins, and distributed ledgers, that enables enhanced observability, forecasting, and automated control [3]. Decentralization reconfigures system architecture and governance by expanding distributed energy resources (DER), microgrids, and energy communities, thereby broadening prosumer participation and facilitating local market mechanisms. At the intersection of these three dimensions arises a complex agenda involving the integration of high shares of renewables, the provision of flexibility and cyber-resilience, and the development of new regulatory and market frameworks, rendering a system-level account of the energy transition a subject of intensive scholarly inquiry. In parallel, a broad socio-technical literature on energy transitions has matured, refining conceptual categories and temporal scales of change and emphasizing the roles of institutions, practices, and justice in transition trajectories [4, 5].

The salience of this topic is driven both by the acceleration of climate policy and international Net-Zero targets and by the rapid diffusion of digital technologies for power-system operation alongside the growth of distributed generation. These processes position the 3D paradigm not as a set of isolated trends but as an interdependent framework in which digitalization acts as a horizontal enabler of operational control and integration of renewables/DER, while decentralization imposes new requirements on digital infrastructure, flexibility markets, and data protection [3, 6]. In this configuration, the contribution of the scientific community (its publication scale, thematic clusters, dynamics, and geography) becomes an indicator of the conceptual and technological readiness of the energy transition as well as a source of evidence for policy and industry [7, 8].

At the same time, existing reviews and bibliometric studies tend to focus either on the general field of the energy transition and its associated trajectories, including issues of renewable integration and market design [9], or on specific subsectors. The latter reveals thematic fragmentation: energy storage is examined through the lens of resource management under renewable uncertainty [10]; microgrids and hybrid architectures constitute a rapidly evolving domain with its own clusters and trends [11]; and energy communities are analyzed as an institutional and socio-technical form of decentralization with an emerging conceptual and empirical core [12]. Concurrently, the literature records an acceleration of digital themes in power systems—smart grids, forecasting algorithms, and data-driven optimization—together with a reframing of market and tariff design [13]. Regional studies identify pronounced asymmetries of attention and capability and underscore the need for normalized comparisons and methodologically comparable approaches, for example, for Sub-Saharan Africa [14]. Taken together, this evidence suggests that, despite the breadth of the literature and the rapid development of digitalization and decentralization themes, there remain few integrated studies in which the scientific contribution across all three components of the 3D paradigm is assessed comparatively within a single, reproducible bibliometric framework.

The energy transition within the development of energy systems has been examined using scientometric methods [15, 16]. By constructing publication co-citation networks, these studies visualize the evolution of scientific knowledge in the energy-systems domain and identify the research and technology development front.

In light of the above, the aim of the present study is to assess and compare the scientific contribution to each component of the 3D paradigm - decarbonization, digitalization, and decentralization - based on a bibliometric analysis of the international publication corpus for 2001–2025. The objectives are: (1) to quantify the scale and dynamics of research across the three components; (2) to construct and interpret keyword-based thematic maps and clusters; (3) to identify zones of thematic integration at the interfaces among the 3D components, together with associated research gaps. This design leverages established bibliometric methods while situating the inquiry within the socio-technical theoretical perspective on energy transitions.

II. Data and Methods

The empirical basis for the analysis is a Scopus-derived dataset spanning 2001–2025. The temporal scope captures the early emergence of the transition discourse and its subsequent consolidation. To ensure comparability, the corpus is restricted to English-language publications and standard scholarly document types (journal articles, conference papers, reviews, and book chapters). Records include bibliographic metadata, abstracts, author and index keywords, citation counts, and source information.

The query design follows a two-level logic. At the first level, which is intended to capture the general field, we employ a set of terms that reflect standard disciplinary vocabulary and the principal levels of analysis in energy studies: “energy system,” “power system,” “energy transition,” “power industry” or “power grid,” “energy sector” or “power sector,” “energy policy” or “energy planning,” and “energy transformation.” This umbrella layer is designed to ensure that the search retrieves the core literature on energy systems while remaining neutral with respect to specific technologies or policy instruments.

At the second level, the corpus is structured by the three components of the 3D paradigm. This follows the established interpretation of decarbonization, digitalization, and decentralization as three interrelated drivers of energy system transformation [1]. For the decarbonization block, the keyword set includes “global warming,” “carbon neutral,” “greenhouse gas,” “climate change,” (“carbon dioxide” OR “CO2”) AND emission, “zero carbon,” “low carbon,” hydrogen, renewable, and “clean energy.” These expressions represent canonical markers of the climate mitigation agenda as codified in IPCC assessments and widely applied in bibliometric and policy analysis [17]. The inclusion of both policy-oriented

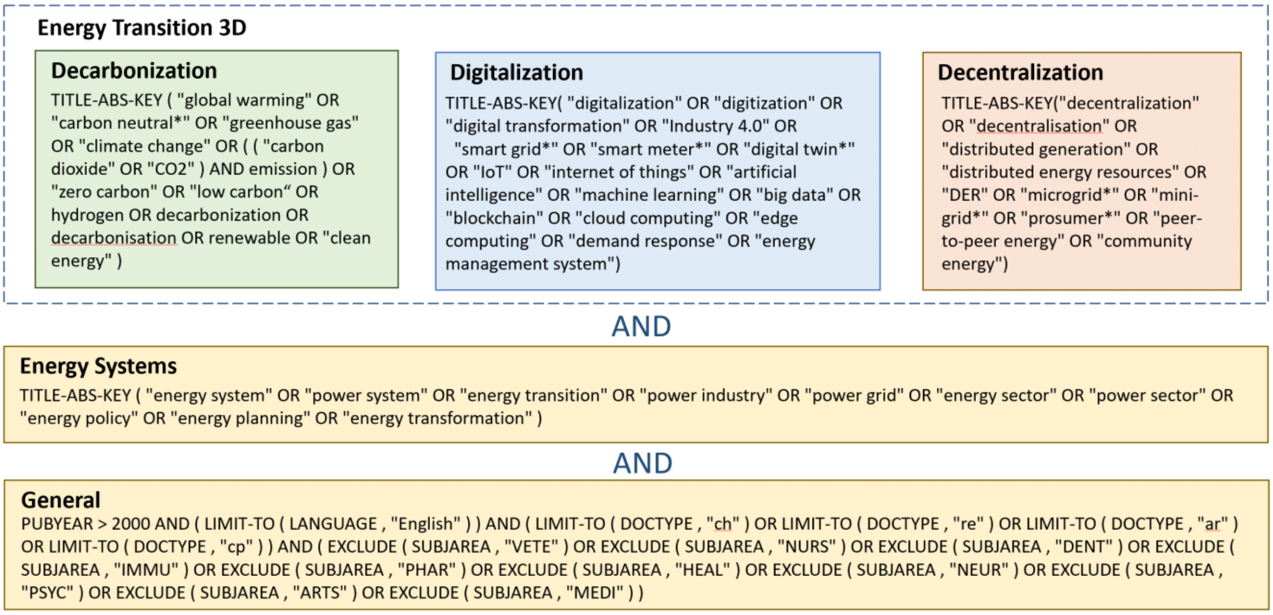

Fig. 1. Structure of search queries in the Scopus international database of peer-reviewed scientific literature.

labels (for example, net zero and low carbon) and technology terms (for example, hydrogen and renewables) increases the likelihood of capturing documents that discuss mitigation pathways, technology deployment, and emissions outcomes within the same analytical frame.

For the digitalization block, the keywords are “digitalization,” “digitization,” “digital transformation,” “Industry 4.0,” “smart grid*,” “smart meter*,” “digital twin*,” “IoT” or “internet of things,” “artificial intelligence” or “machine learning,” “big data,” “blockchain,” “cloud computing,” “edge computing,” “demand response,” and “energy management system.” This set covers both infrastructural layers of digital energy systems and algorithmic or data-centric approaches, aligning with the IEA’s framework and survey literature on smart grids and digital energy [18], [19]. The use of truncation where appropriate (for example, “smart grid*,” “digital twin*”) allows for terminological variants while preserving specificity.

For the decentralization block, the terms are “decentralization” or “decentralisation,” “distributed generation,” “distributed energy resources,” “DER,” “microgrid*,” “mini-grid*,” “prosumer*,” “peer-to-peer energy,” and “community energy*.” This vocabulary captures the architectural and organizational shift toward distributed resources, local markets, and energy communities, and it is grounded in foundational microgrid literature together with recent reviews of community-based energy models [20 - 22]. The combination of technical descriptors (for example, microgrids and DER) with socio-institutional concepts (for example, prosumers and energy communities) enables the retrieval of both engineering-centric and governance-oriented strands of the decentralization discourse.

Taken together, this two-level dictionary balances recall and precision. The first level secures comprehensive coverage of the energy systems domain, while the second level supports a reproducible stratification of the corpus into thematic clusters aligned with the 3D paradigm of the energy transition. The explicit linkage to established reports and reviews provides conceptual legitimacy and facilitates comparability with prior bibliometric studies.

All terms are searched in TITLE-ABS-KEY fields. Global filters harmonize the selection across blocks: publication year greater than 2000, English language, and exclusion of non-energy biomedical areas not germane to the present inquiry. The detailed query structure in the international database of peer reviewed scientific literature Scopus is shown in Figure 1.

Retrieved records are exported in standardized formats and subjected to a consistent preprocessing pipeline. Normalization includes lowercasing and harmonization of British and American spellings (e.g., decarbonization / decarbonisation) followed by lemmatization. Abbreviations such as RES or DER are unified and connected to the related terms (e.g. RES = renewable energy resources). Document duplicates are removed primarily via DOI matching; in the absence of

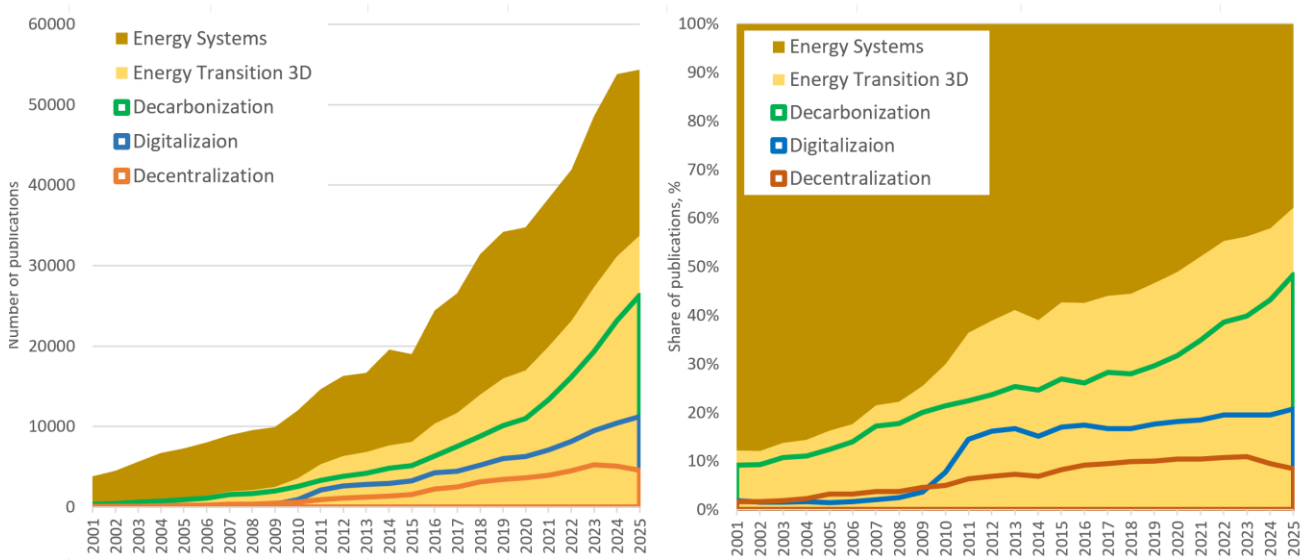

Fig. 2. Annual publication counts and relative shares on energy-transition research in energy systems together with 3D components (decarbonization, digitalization, and decentralization) over 2001–2025.

DOIs, fuzzy title matching with year and source tie-breakers is applied. Subject-area filters are verified to reduce contamination from adjacent but out-of-scope fields.

The descriptive component comprises annual publication counts and citations, which collectively trace phases of emergence, consolidation, and accelerated growth. To compare the three components, records are tagged by block after de-duplication, allowing computation of portfolio shares within the transition-themed corpus. Headline proportions from the working dataset indicate that decarbonization accounts for approximately half of the output, digitalization for roughly one fifth, and decentralization for a smaller, though steadily expanding, share. Country-level contributions are summarized through publication counts and a simple impact proxy (citations per publication), acknowledging that more refined field-normalized indicators would strengthen cross-national comparisons.

III. Results and Discussion

Using the query structure outlined in the previous section, bibliographic records were retrieved from the Scopus database for the period 2001 to 2025. The corpus reflects the state of indexing as of 10 December 2025; consequently, data for 2025 remain slightly incomplete. Figure 2 shows quantitative publication growth and relative shares on energy-transition research in energy systems together with 3D components (decarbonization, digitalization, and decentralization).

The analysis indicates a pronounced expansion of publication activity in energy research overall and a sharp intensification of the Energy Transition 3D strand within that corpus. Total publications in the energy systems domain increased from 3,849 to 54,330, while the Energy Transition 3D subset grew from 469 to 33,761. The share of 3D in the overall corpus rose steadily: from 12% in 2001 to 30% in 2010, approximately 43 to 49% in 2016 to 2020, surpassing one half in 2021 (52%), and reaching 62% by 2025. These figures point not only to quantitative growth but also to a qualitative shift in the center of gravity of research agendas toward decarbonization, digitalization, and decentralization within energy systems.

The internal structure of energy transition research shows asymmetric yet coordinated growth across all three components. Publications on decarbonization increased from 354 to 26,280, and its share within Energy Systems rose from 9% to 48% by 2025, with a sustained acceleration after 2018. Digitalization is the fastest growing component in relative terms: from 72 to 11,245 publications and from 2% in 2001 to 21% in 2025. A key inflection occurred around 2010 to 2012, when the share rose from 8% to 15 to 16%, followed by stabilization at 18 to 21% during 2019 to 2025. This inflection marks the point at which the digitalization concept entered broad circulation in the research literature. Decentralization rose from 63 to 4,601 publications, with its share increasing from 2% to a peak of 10 to 11% in 2018 to 2023, then moderating to 9% in 2024 and 8% in 2025. This pattern may reflect both a reorientation of research effort toward decarbonization and digitalization and potential lags in the indexing of 2024 to 2025 work on distributed energy and community models.

A phase-based representation is also observed on Fig. 2. Phase 1 (2001 - 2009) shows a gradual rise in the 3D share from 12% to 25% at modest absolute volumes. Phase 2 (2010 - 2016) exhibits a structural break: the 3D share increases to about 43%, digitalization moves rapidly from the periphery toward the quasi-core (from 8% to 17%), and decarbonization consolidates its dominance (21 to 26%). Phase 3 (2017 - 2021) is characterized by consolidation, with Energy Transition 3D occupying 44 to 52% of the total corpus and all three components growing in tandem. Phase 4 (2022 - 2025) features a deepening of decarbonization's dominance (share rising from 39% to 48%), a persistently high contribution from digitalization (19 to 21%), and a plateau in decentralization, including a modest decline from 11% to 8%. Taken together, these results indicate that by the mid-2020s the energy transition had shifted from a discrete thematic niche to the principal research mainstream within energy systems, with decarbonization setting the overall scale, digitalization providing speed and controllability, and decentralization driving architectural transformation and institutional innovation.

Dividing the Energy Transition 3D corpus into mutually exclusive subsets: single-component publications (decarbonization only, digitalization only, decentralization only), pairwise intersections (decarbonization–digitalization, decarbonization–decentralization, digitalization–decentralization), and the three-way core itself we quantify the extent of thematic integration by year. The results indicate a marked rise in integrative work. Aggregating by periods, the share of publications that engage at least two components grows from 6.5% in 2001–2009 to 17.8% in 2010–2016 and 20.8% in 2017–2025; within this, the three-way core increases in absolute terms from 44 to 1,279 to 5,996 records and reaches about 3.1% of the 3D corpus in the latest period. Pairwise overlaps are led by decarbonization–digitalization (rising to 8.9% in 2017–2025), followed by decarbonization–decentralization (6.1%) and digitalization–decentralization (2.7%). Despite this consolidation, single-component contributions remain the majority: decarbonization-only accounts for roughly 52.0% of the 2017–2025 3D corpus, digitalization-only for 20.6%, and decentralization-only for 6.7%. Taken together, the evidence points to a progressive coupling of research agendas across the 3D paradigm, with the strongest integration occurring along the decarbonization–digitalization axis and a smaller, but

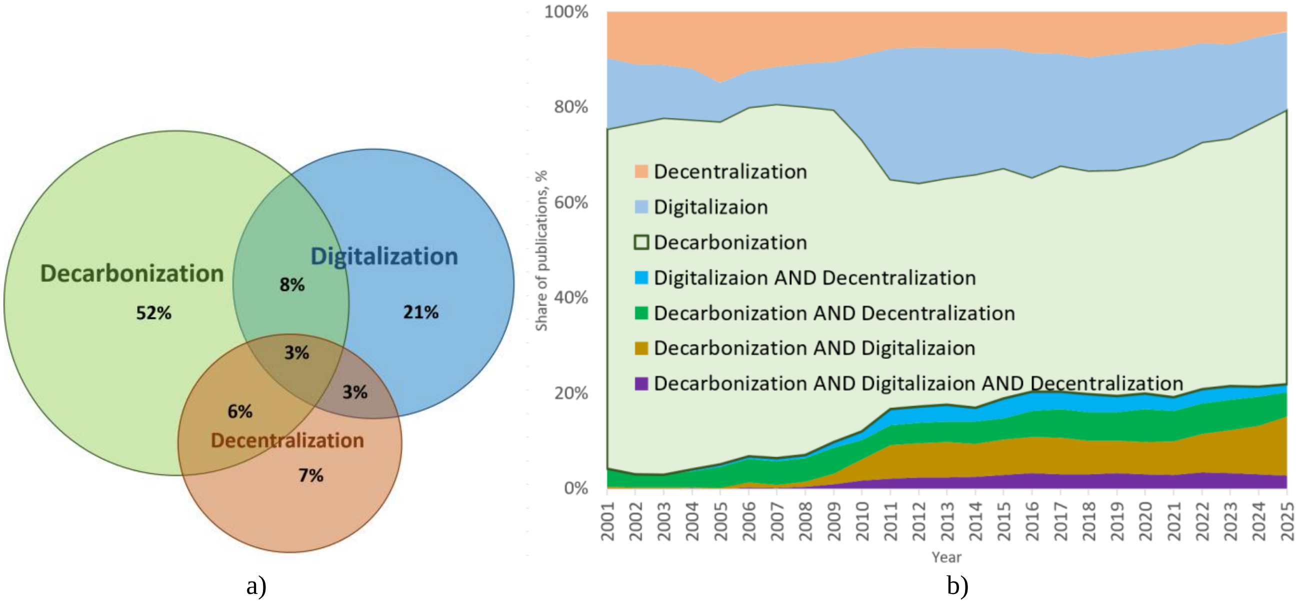

***Fig. 3.** Overlaps among the 3D components in the Energy Transition 3D corpus in energy systems, 2001–2025: (a) Venn diagram showing total publication shares; (b) yearly share distribution.*

growing, three-way core.

Figure 3 (a) illustrates that decarbonization remains the system-forming strand, accounting for just over half of the 3D corpus in singleton form. Integration occurs primarily along the decarbonization–digitalization axis (8%), with smaller but nontrivial overlaps for decarbonization–decentralization (6%) and digitalization–decentralization (3%). The three-way core is compact (3%), suggesting that genuinely triadic studies are still a minority relative to single-component contributions. Taken together, the composition points to a field where decarbonization sets the dominant research baseline, digitalization acts as the principal transversal enabler, and decentralization contributes a focused but more specialized body of work interfacing with the other two components.

Using VOSviewer [23], thematic maps for each component of the 3D energy transition (decarbonization, digitalization, and decentralization) were generated from the top 1,000 keywords drawn from the component-specific article subsets, applying a publication citation threshold greater than 20 (see Fig. 4–6). The color scale encodes the average publication year over 2001–2025, where blue indicates earlier years and yellow indicates later years, which allows the temporal evolution of macrotopics to be assessed. Node size reflects keyword frequency rather than importance, and the average-year metric is sensitive to recent surges; both factors should be considered when interpreting the maps.

The decarbonization map in Figure 4 exhibits a core–periphery structure with a pronounced temporal gradient. At the center lies an earlier cluster around renewable energy source, energy policy, climate change, carbon dioxide, fossil fuel, and alternative energy. The blue and turquoise hues indicate that during the 2000s and early 2010s the discourse shifted from a climate policy frame toward the scaling of renewables and their system integration.

By the mid-2010s the core becomes more technology oriented. Adjacent, relatively larger nodes include solar energy, photovoltaics, solar power generation, energy storage, electric battery, smart grid, demand response, and microgrid. Their green coloration signals continued growth through the 2010s, while the size of the PV and storage nodes confirms sustained high frequency across the entire 2001–2025 period.

A later wave is visible in yellow clusters along two fronts. First, electrochemistry and hydrogen: hydrogen production, electrolysis, fuel cell, electrocatalyst, and

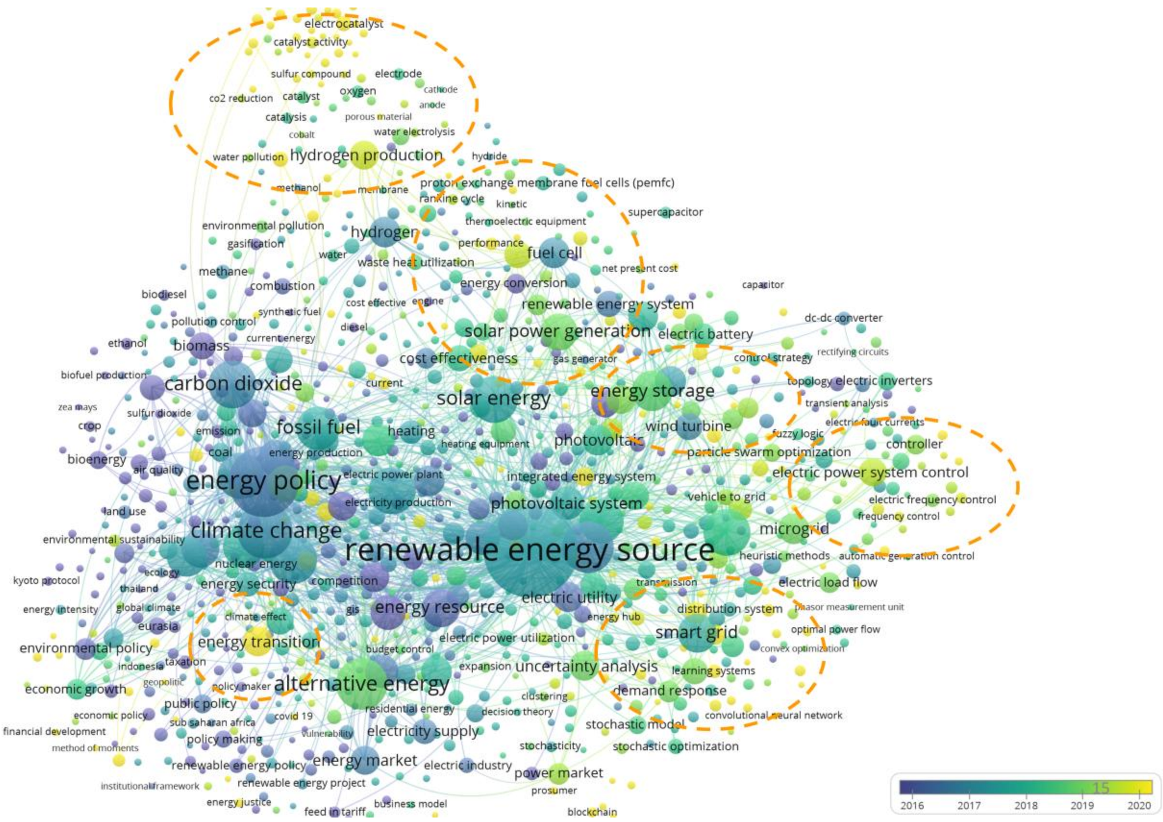

Fig. 4. Decarbonization: keyword co-occurrence map within energy-systems research, 2001-2025.

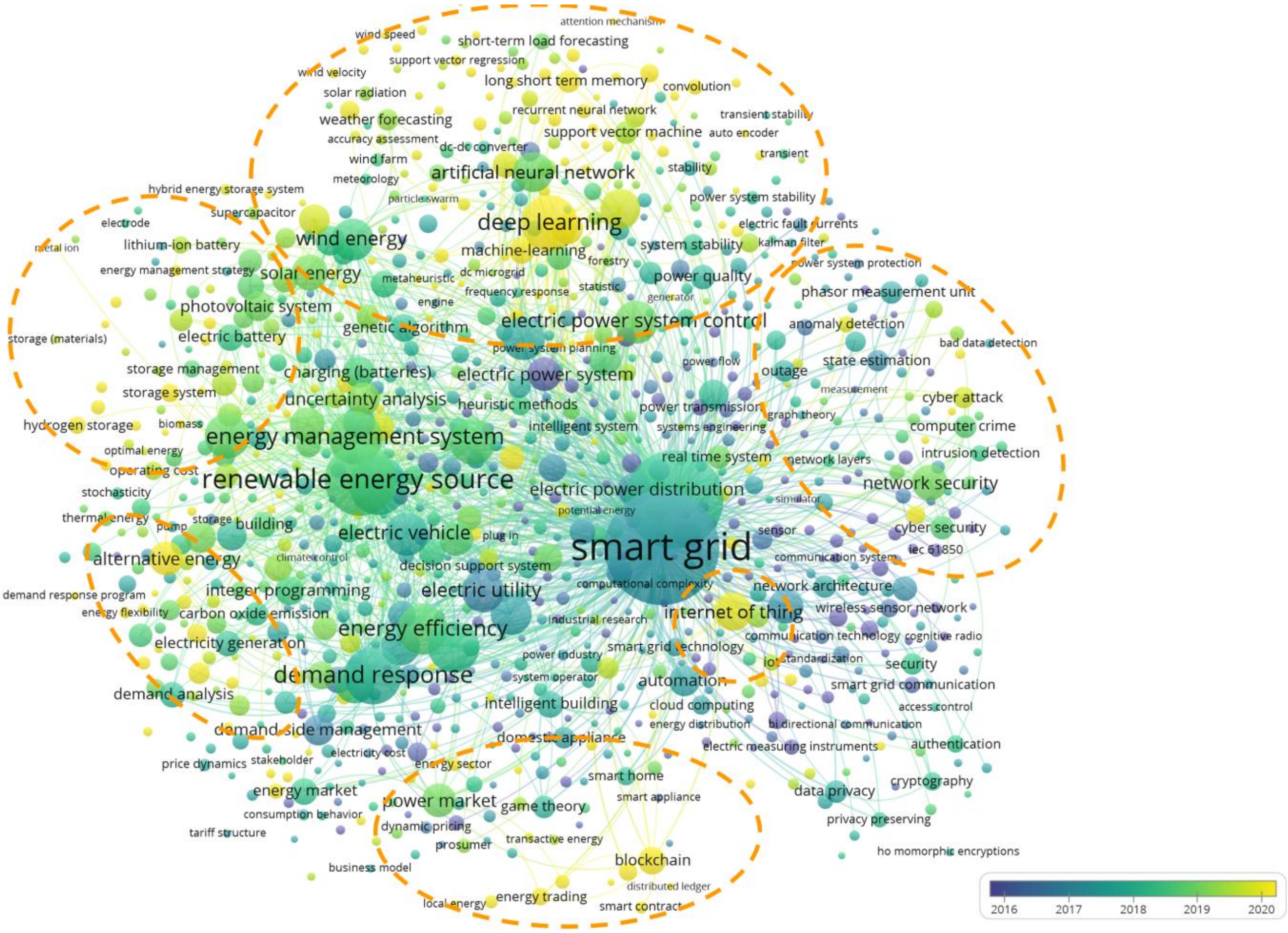

Fig. 5. Digitalization: keyword co-occurrence map within energy-systems research, 2001-2025.

related materials represent comparatively recent and fast-growing subfields. Second, power electronics and system control: electric power system control, inverters, dc-dc converter, controller, frequency control, together with algorithmic methods such as particle swarm optimization, stochastic models, and neural networks. These areas reflect a transition from simply adding renewables to actively managing flexibility and power quality at high variable renewable shares.

Bridging topics include integrated energy system, vehicle-to-grid, uncertainty analysis, and cost effectiveness. Their relatively late average year suggests strengthening attention after 2018 at the interface of engineering and economics.

Figure 5 shows the "Digitalization" thematic map, which exhibits a clear core-periphery structure and a pronounced temporal gradient. At the center are early, high-frequency nodes such as smart grid, demand response, energy management system, renewable energy source, energy efficiency, internet of things, and links to electric power distribution and electric utility.

From the mid-2010s onward the core becomes increasingly technology and algorithm oriented. Larger, later clusters appear around deep learning, artificial neural network, internet of thing, support vector machine, and forecasting, including short-term load, wind, and solar, together with uncertainty analysis and optimization. This pattern reflects a shift toward data-driven methods for prediction and operational planning. In parallel, a cyber-resilience contour strengthens, centered on network security, cyber-attack, intrusion detection, anomaly detection, state estimation, and phasor measurement unit, with yellowish hues signaling acceleration in 2018–2025. At the interface of markets and ICT, clusters on blockchain, smart contract, energy trading, transactive energy, and demand-side management trend later, indicating the institutionalization of digital transactions and local flexibility markets. Connections to electric vehicle, charging, electric battery, and storage management point to the integration of DER within the

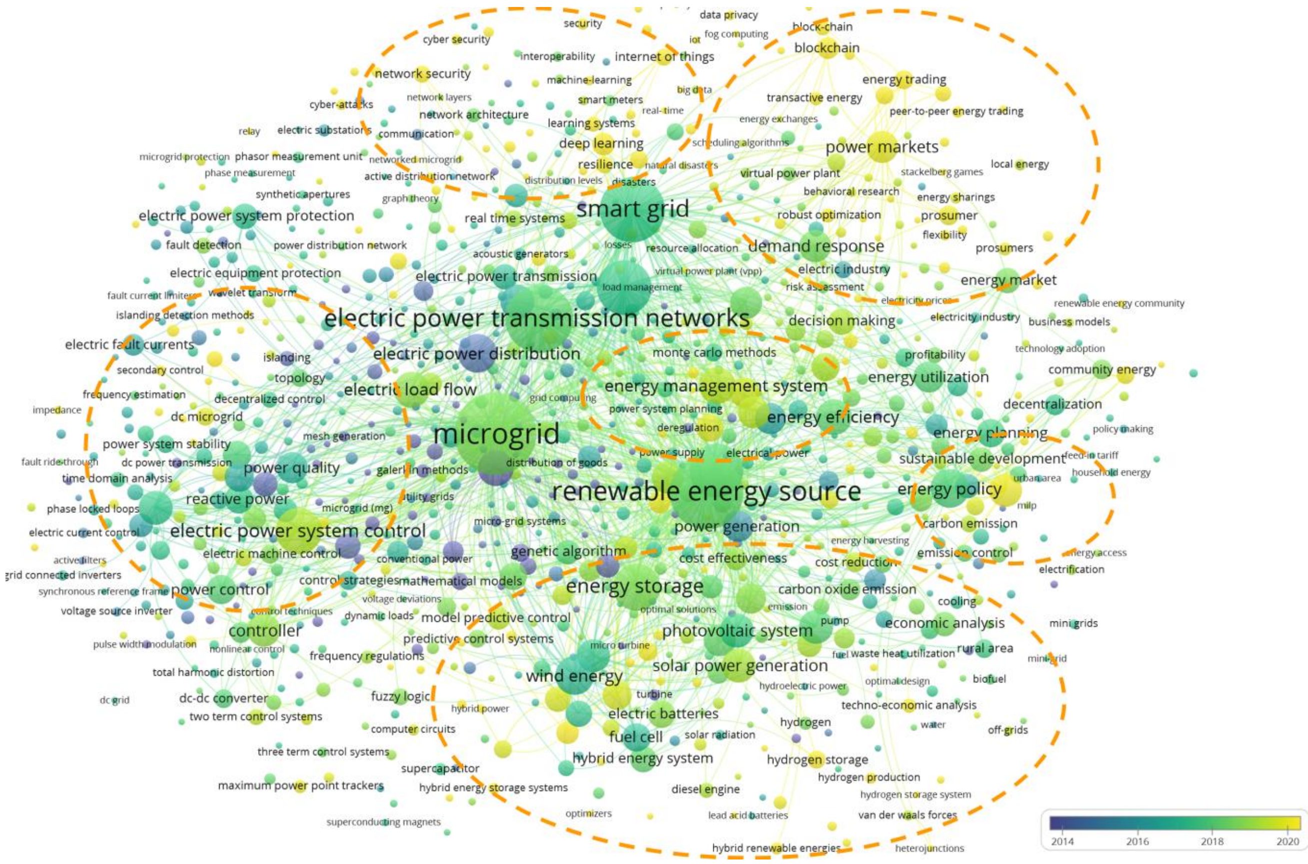

Fig. 6. Decentralization: keyword co-occurrence map within energy-systems research, 2001-2025.

digital control layer. Overall, the evolution proceeds from the classical smart-grid and demand-response paradigm to a mature digital ecosystem in which machine-learning methods, cybersecurity, platform solutions, and transaction mechanisms are central.

Figure 6 represents the decentralization topic map as a compact technical core with a clear temporal gradient from engineering-focused foundations toward market and community themes. Early, high-frequency nodes cluster around microgrid, renewable energy source, energy storage, photovoltaic system, wind energy, and electric power transmission networks, together with control and protection topics such as electric power system control, controller, reactive power, fault detection, stability, dc microgrid, and dc-dc converter. This pattern reflects the initial emphasis on distributed architectures, power electronics, and operational reliability for integrating variable renewables. From the mid-2010s the map broadens toward system operation and planning, with energy management system, demand response, decision making, uncertainty analysis, and techno-economic analysis gaining prominence. Later-year clusters concentrate on power markets, transactive energy, energy trading, blockchain, prosumers, and community energy, indicating a shift toward market design, participation models, and institutional arrangements for local energy systems. A parallel strand in the upper left highlights network security and cyber-attack detection, signaling growing attention to cyber-resilience of distributed infrastructures. Taken together, the evolution moves from hardware and control of microgrids to socio-technical integration through markets, communities, and cybersecurity.

To aid interpretation, the decentralization map can be read in conjunction with the decarbonization and digitalization maps (cf. Fig. 4–5). Several high-frequency constructs recur across figures and anchor the triad: energy storage, photovoltaic system and wind energy link decarbonization to decentralization; smart grid, demand response, and energy management system connect decentralization with digitalization; microgrid appears in all three as the canonical distributed architecture. The temporal gradients are also coherent: the 2016–2020 window marks a shared inflection where data-driven forecasting and control (Fig. 5) intersect with large-scale VRE deployment and storage build-out (Fig. 4) and with the maturation of microgrid operation and protection (Fig. 6). At the same time, each map retains distinctive late-emerging contours: hydrogen and electrocatalysis in decarbonization; machine-learning methods and cybersecurity in digitalization; and market and community constructs such as transactive energy, energy trading, and community energy in decentralization. Together these correspondences and divergences indicate progressive coupling of the three components around a common operational stack, while preserving domain-specific frontiers.

IV. Conclusion

This scientometric assessment shows that research on energy system transformation has moved from a peripheral niche to the principal mainstream, with the three-dimensional framework now structuring the field. Decarbonization functions as the system forming axis, digitalization has matured into a transversal enabler of forecasting, control, and market participation, and decentralization advances through distributed energy resources, microgrids, and energy community architectures. The internal composition of the literature displays increasing pairwise integration and a small but expanding triadic core, which indicates convergence of technological, digital, and institutional trajectories. Thematic maps show a temporal shift from policy and resource framing to technology intensive fronts, including storage and hydrogen, power electronics and system control, machine learning methods, cyber security, and transactive energy, consistent with the operational challenges of high shares of variable renewables. Given the secular growth of global publishing and uneven country contributions, future work should incorporate field normalized impact indicators, country level baselines, and analyses of collaboration networks, and should triangulate bibliometric evidence with patent and demonstration datasets. The study has limitations related to a single database, an English language focus, and indexing latency for 2025, and it outlines a reproducible path for future comparative analyses.

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