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The Ecosystems Perspective in Energy Research: A New Field is Born?

Dimos Chatzinikolaou[1,2]*, Charis Vlados[1,2,3], Angelika Kokkinaki[2,3]

[1]Department of Economics, Democritus University of Thrace, Komotini, 69100, Greece, [2]Knowledge Management, Innovation and Strategy Center (KISC), University of Nicosia, Nicosia, Cyprus, [3]School of Business, University of Nicosia, Nicosia, Cyprus. *Email: dimchatz@econ.duth.gr

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ABSTRACT

The "ecosystem perspective" seems to be gaining importance in energy research. This paper offers a systematic review of 98 articles to shed light on the burgeoning interest in the "energy ecosystems" perspective. The growth in energy ecosystems research stems from several factors: the integration of approaches that connect energy flows with ecological concepts, the inclusion of emerging technologies and socio-technical nuances, and a significant uptick in academic publications over recent years. Our review identifies four pivotal trends shaping the energy ecosystems discourse: "industrial ecology and sustainable development," "energy transition and socioeconomic evolution," "business and innovation ecosystems in energy," "distributed energy systems, smart grid innovations, and associated policy-regulation dynamics." These trends underscore a pronounced emphasis on energy efficiency in the pertinent literature. Looking ahead, there's a case for adopting a comprehensive macro-meso-micro framework, with a particular spotlight on the intricate roles of individual energy firms within these ecosystems.

Keywords: Energy Ecosystem, Systematic Literature Review, Macro-Meso-Micro Framework, Industrial Ecology, Energy Transition, Distributed Energy Systems
JEL Classifications: O13, P18, Q40

1. INTRODUCTION

In recent years, the application of ecosystemic concepts to understand the intricate interplay within energy systems has gained significant traction. This burgeoning interest is rooted in the influential theoretical framework of business ecosystems introduced by Moore (1993). Today, this framework is being increasingly employed across various industries, with the energy sector emerging as a focal point for many researchers (Viholainen et al., 2021). This is evident in the extensive analysis of Enron's downfall by Iansiti and Levien (2004), attributing the company's collapse to its misaligned strategy with its surrounding business ecosystem.

Recent literature has coined the term "energy ecosystem," reflecting a shift towards a more ecosystemic approach in energy systems. Hellström et al. (2015, p. 235) posit that business models in distributed energy systems are not merely choices made under institutional pressures but are active endeavors to create commercially viable local business ecosystems. Furthermore, Adu-Kankam and Camarinha-Matos (2019, p. 25) define "energy ecosystems" as innovative models in the energy sector, marked by community-centric concepts, decentralization, and collaborative strategies.

Drawing inspiration from Shneider (2009), we recognize that research fields undergo distinct evolutionary phases, each marked by its predominant methodologies. Initially, novel objects and concepts emerge to elucidate observed phenomena. As research matures, a suite of techniques and methodologies is crafted to deepen our understanding. Over time, there's a surge in studies employing these methodologies, eventually reaching a phase where existing knowledge is consolidated without necessarily pioneering new discoveries. Applying Shneider's framework, we hypothesize that the energy ecosystems literature is transitioning between its nascent and developmental stages. Furthermore, the notion of "emerging fields" in academia has captivated many scholars. Kuhn's (1962) groundbreaking work introduced paradigm shifts as pivotal moments when scientific disciplines experience transformative changes, paving the way for fresh research fields. Edge (1995) offers a nuanced perspective, suggesting that emerging fields sometimes represent a reimagining of established concepts. Therefore, Rotolo et al. (2015) provide insights into the characteristics of emerging technologies and fields, identifying markers like a surge in publications and heightened academic interest. From these insights, we can delineate the hallmarks of an emerging field: disruptive changes or paradigm shifts, significant refinement of existing concepts, and a rapid escalation in academic focus and publications.

These criteria seem apt to address the first question this paper seeks to unravel: (A) Why does the ecosystems perspective in the energy sector appears to be emerging as a field of research? Furthermore, the existing discourse suggests another discernible gap in the literature, as it's challenging to pinpoint research trends within energy ecosystems. Consequently, this paper's subsequent question is: (B) What are the predominant trends highlighted in the literature on energy ecosystems, and what is their anticipated trajectory and underlying reasons?

To shed light on these questions, we embarked on a systematic literature review on the subject will employ—the first, to our knowledge. After analyzing 98 articles, four main trends were identified, shaping the emerging "ecosystems perspective in energy" field.

This paper is organized as follows: Section 2 delves into the evolution and fundamentals of energy ecosystems. Section 3 outlines our research methodology. Section 4 presents the outcome of the comprehensive literature review and its insights. Finally, Section 5 offers a critical discussion of the findings.

2. BACKGROUND

2.1. The Evolution of Business Ecosystems

Moore (1996) initially and then Iansiti and Levien (2004) are considered to be the founders of this field, although without explicitly mentioning in their works the influence of the (heterodox) evolutionary approach in economics. Specifically, out of the two fundamental textbooks by Moore (The death of competition, 1996) and Iansiti and Levien (The keystone advantage, 2004), only Moore in an endnote refers to the nodal work in evolutionary economics by Nelson and Winter (1982). In turn, Nelson and Winter (1982) acknowledge in Alfred Marshall the interpretive merit of the biological paradigm and not so much the unquestionable contribution in neoclassical economics (Chatzinikolaou and Vlados, 2019). As Marshall (1890) wrote, the Mecca of economics lies in economic biology (Hodgson, 1993). Moore (1993) offers the seminal work in business ecosystems in the early 1990s, commencing theoretically from the ecological metaphor in business (Moore, 1996, p. 8): "*Biological examples are quite simply the most direct way to explain difficult system concepts. Each time you master a biological example, you learn a systems concept that will be valuable for comprehending the dynamics of business in the new economy.*" Therefore, the business ecosystem is structured according to the biological ecosystem, defined as follows (Moore, 1996, p. 26): "*An economic community supported by a foundation of interacting organizations and individuals—the organisms of the business world.… Those companies holding leadership roles may change over time, but the function of ecosystem leader is valued by the community because it enables members to move toward shared visions to align their investments, and to find mutually supportive roles*." Using business cases and their respective ecosystems, Moore (1996) identifies different phases in the evolution of business ecosystems, which resemble an organism's biological development stages, although acknowledging the potential self-renewal as a unique business ecosystem trait.

The other significant contribution to the commencement of business ecosystem theorizing belongs to Iansiti and Levien (2004). These authors emphasize the need for rethinking networks because, as they suggest: "*When the Internet took off and business networks became ubiquitous, our understanding of management and strategy simply did not keep up*" (Iansiti and Levien, 2004, p. 7). By also building upon the article of Cusumano and Gawer (2002) on the need for readjusted leadership in the Internet platform era (without citing Moore), they pinpoint that (Iansiti and Levien, 2004, p. 8): "*We found that perhaps more than any other type of network, a biological ecosystem provides a powerful analogy for understanding a business network. Like business networks, biological ecosystems are characterized by a large number of loosely interconnected participants who depend on each other for their mutual effectiveness and survival.*" By presenting the cases of different firms, they distinguish between ecosystem strategies and find that various firms in ecosystems take on the metaphorical role of keystone species, setting the development boundaries for the participant organisms. As they explain (Iansiti and Levien, 2004, p. 12): "*Like their biological counterparts, leading firms in business ecosystems, or leading countries in international setting, can play the role either of dominators that reduce productivity and make their partners more vulnerable to external shocks or of keystones that nourish diversity and stabilize their environments even as they vigorously pursue their own ends*."

After this initial conceptualization, various contributions emerged, progressively shaping a fertile field of research. A typical example of the gradually increasing interest is the corresponding systematic literature reviews appearing in the field's influential journals. Specifically, Scaringella and Radziwon (2018) distinguish four primary research directions in the relevant literature: business ecosystems, innovation ecosystems, entrepreneurial ecosystems, and knowledge ecosystems. Similarly, Suominen et al. (2018) conduct a bibliometric review of innovation systems and ecosystems, concluding with four distinct future dimensions concerning the ecosystems of innovation, knowledge, business, and platforms. Specifically, they suggest that innovation ecosystems examine how different actors create value as they cooperate for novelty. For knowledge ecosystems, they propound the investigation of interactions between actors in terms of knowledge in their effort to collaborate and innovate. Concerning business ecosystems, they promote the idea that these systems allow the actors to create and reap value when they are involved in transactions within the innovation process. Finally, for platform ecosystems, they suggest studying how actors are organized and co-evolve around a particular platform (primarily digital).

Gomes et al. (2018) also conduct a similar systematic and bibliometric review of the innovation ecosystems literature. They first present Moore (1993) and Iansiti and Levien (2004) as fundamental to this field. Next, they identify a gradual transition from business ecosystems to innovation ecosystems by citing the works of Adner (2006) and Adner and Kapoor (2010). Gomes et al. (2018) also find that well-founded research is underway in the business, innovation, and platform-based ecosystems. Furthermore, the relevant volume by Harvard Business Review treats ecosystems and platforms as directly linked concepts (Harvard Business Review et al., 2020). Scaringella and Radziwon (2018) also identify a field of ongoing research in service ecosystems, open innovation ecosystems, industrial ecosystems, digital ecosystems, and regional innovation ecosystems.

Therefore, it is evident that business ecosystems have a clear origin in evolutionary theory. This lineage is also apparent in that it incorporates dimensions of organizational complexity, which it places in the interpretive focus—for foundations, see, for example, Battram (1999) and Kauffman (1993). Complex adaptive systems approaches understand reality at multiple co-evolving levels (Kurtz, 2018). Specifically, Vlados and Chatzinikolaou (2020) argue that business ecosystems are an organic continuation of the analytical perspectives of clusters and national innovation systems (Nelson, 1993). This theoretical viewpoint of socioeconomic aggregations focuses on the increased ecosystemic complexity of the contemporary world and not necessarily on the specialized knowledge and value chain of specific locations (Lundvall, 1992, Porter, 2000).

However, it is the capitalist firm that occupies the central analytical focus within the business ecosystem. Against this background, some related studies perceive this pivotal institution as a "living organization" (Geus, 2002, Vlados, 2019). The inner workings of these living enterprises, characterized by a blend of strategy, technology, and management, play a crucial role in determining the growth potential of the encompassing system (Vlados and Chatzinikolaou, 2019). Numerous scholarly works highlight the importance of viewing the business ecosystem through a "macro-meso-micro" lens, underlining the enhancement of firm competitiveness (Dopfer et al., 2004; Peneder, 2017). The "macro" level encompasses broader economic and societal aspects, "meso" pertains to sectoral structures, and "micro" refers to individual enterprises. Furthermore, the "meso-micro" perspective is vital in the discourse on business ecosystems, as it delves into the relationships among various stakeholders that bolster specific business frameworks in different local or industrial gatherings (Table 1).

Under this multi-layered ecosystemic light, we choose to examine the relative progress achieved in the energy sector. Business development in this field appears to be a defining point in the modern framework of new globalization amid the post-COVID-19 era, Russia's invasion of Ukraine, and the ongoing restructuring of the existing energy security regime (Deniozos et al., 2019; Gaind and Else, 2022; Johnson, 2022; Vlados and Chatzinikolaou, 2021). The dynamics of energy ecosystems seem to be a decisive analytical spectrum to approach socioeconomic development nowadays. The following subsection looks elliptically at the foundations of this academic debate.

2.2. Fundamental Concepts in Energy Ecosystems

According to Bradford (2018), until recently, problems with the electricity grid were addressed either by increasing the energy load of utilities (supply-side) or through modifying or reducing the load profile in the supply chain (demand-side). However, the rapid spread of distributed generation business models and technologies over the last decade has structurally transformed the electricity system of developed economies. In this advanced form of energy production, the customer can participate as the "prosumer"— simultaneously producer and consumer.

As Bradford (2018) acknowledges, even though the traditional paradigm for the grid's operation is undergoing an unprecedented shift, this transformation is not so new. Towards the end of the twentieth century, a vast number of generators were built, allowing massive and efficient energy production. Fast-growing countries even today (such as China and India) base their growth on these generation technologies, such as nuclear energy, coal, and hydroelectric energy (Wang et al., 2019). However, since the beginning of globalization in the 1980s, the slowdown in overall load growth and the increased focus on the better utilization of electricity grid assets in Europe, North America, and Japan has led the market to significant restructuring (Liu, 2016). Smaller-scale generation began to be preferred over the larger one to fill gaps in the electricity system, primarily with the choice of natural gas and increasingly with wind energy and other technologies (Kim, 2019).

The noticeable difference in the new era arises from the gradual emergence of a range of more cost-effective technologies on a smaller scale, targeting to fulfill the consumer's load demand. The well-known solar photovoltaic installations are the most widely used relevant options, although they are not always the most efficient. These solutions are implemented both in residential and industrial areas and facilities. Overall, such production options turn rapidly cheaper due to their support by corresponding energy policies worldwide and in different regions over the past years (Li and Shen, 2019; Pitt and Nolden, 2020). This development encourages even more decentralized energy production and consumption modes, which can be sustainable without government support. However, the existing energy systems do not necessarily adopt these new or restructured generation forms because of capacity and other bottlenecks (Yoo et al., 2021).

A significant problem in the diffusion of these distributed generation technologies is whether the legislation accelerates or decelerates their deployment. The traditional grid regulation and oversight are usually hardly adaptable to these latest technologies. Leading guidelines to facilitate the diffusion of these distributed systems are legal and technical mechanisms for connecting the producers and consumers in the new internet of energy (smart grids) and financing mixes that allow financial capital to identify profit-making corridors using these technologies (Lavrijssen and Parra, 2017).

It remains unknown how much will the distributed generation affect the grid's short- and long-term operation. This form of production is not equally prominent in all economies. Appendix 1 captures the degree of diffusion of energy sources, reaffirming the current transition as the developed world and the BRICS—which consume and produce the most energy—have, in 2020, a renewable mix that rarely exceeds 50%, showing clear divergences. The innovative disruption of incumbent suppliers will depend on the choices made in energy policy—such as grid congestion—and the sustainability of the new business models, which will replace a part or all the energy supply coming from their existing grids (Chen et al., 2014).

In tandem with the evolution of distributed generation methodologies and technologies, there's a burgeoning interest in the concept of energy ecosystems, often referred to as energy business ecosystems. As highlighted in the results section of this study, literature on energy business ecosystems has seen a marked uptick since approximately 2015 onwards. Prior to this surge, most discussions on the topic were found in gray literature, including reports from public institutions and policy forums (President's Council of Advisors on Science and Technology, 2010). However, as the concept of energy business ecosystems has gained traction and recognition as a field, there's been a growing debate about its precise definition. A review of recent literature reveals a convergence of definitions, providing a foundational understanding of the trajectory this research field is taking:

- Hellström et al. (2015) suggest the business model as the fundamental concept to identify how an energy business ecosystem changes. In their words (Hellström et al., 2015, p. 227): "*we believe that the business model is the appropriate unit of analysis for understanding what connects businesses and eventually triggers a system change or the formation of distributed energy (system) business ecosystems*."
- Suryadevara and Biswal (2019, p. 1) investigate the intelligent infrastructure, defining the energy ecosystem as follows: "*The use of smaller localized and distributed energy generation, incorporating renewable sources of energy, help in creating a dynamic energy ecosystem wherein the consumers of electricity can also play a vital role in a distributed generation of power*."
- Rahman et al. (2021, p. 2) also offer a comprehensive enough definition, arguing that: "*In the energy context, platforms are increasingly used to connect consumers to the grid.… while industries, such as retail, real estate, or social media, have a solid foothold of the platform model, platforms as a phenomenon are relatively recent in the energy sector.*"
- Vlados et al. (2021) distinguish different policy objectives for energy business ecosystems. Specifically, they refer to four strategic goals: (a) management of related resources to ensure energy security, (b) sustainable development support to protect the environment, (c) systematic reinforcement of energy production-competitiveness structures and (d) protection from energy-oriented crises through alternative routes for meeting the energy demand.

Drawing from the diverse perspectives presented, energy business ecosystems can be synthesized as a dynamic interplay of localized and distributed energy generation methods, where consumers actively participate not just as passive recipients but as vital contributors to the energy grid. This ecosystem is underpinned by the evolving business models that drive systemic changes and the formation of distributed energy systems. Central to this is the integration of intelligent infrastructure, which not only facilitates the use of renewable energy sources but also fosters a dynamic environment where electricity consumers play a pivotal role in distributed power generation. Furthermore, platforms are emerging as crucial connectors, linking consumers to the grid, especially as the energy sector begins to embrace this model, which has been prevalent in other industries. On a broader scale, policy objectives within these ecosystems aim to ensure energy security, promote sustainable development, reinforce energy production-competitiveness structures, and provide alternative solutions for energy demand, safeguarding against potential crises. In essence, the energy business ecosystem is a multifaceted construct, encompassing micro, meso, and macro levels of analysis, and is characterized by its adaptability, consumer-centric approach, and strategic alignment with broader socioeconomic goals.

3. METHODOLOGY

This research was carried out using a systematic literature review method, analyzing the content of articles identified in specific databases (Snyder, 2019). The systematic literature review method investigates the entire body of knowledge, identifies shortcomings, and suggests potential future research avenues within the predetermined research boundaries. This approach ensues a detailed presentation of the steps followed, aiming to minimize biases and maximize transparency, enabling the research to be reproduced (Tranfield et al., 2003). The recent studies by Lu et al. (2018), Gomes et al. (2018), Scaringella and Radziwon (2018), Jugend et al. (2020), Bhimani et al. (2019), and Ratinho et al. (2020) are examples of systematic literature reviews that follow these methodological orientations, and the approach followed by this paper essentially builds on these reviews.

Concerning the criteria to pick the appropriate articles, Figure 1 depicts the protocol followed. Scopus and Web of Science (WoS) were selected as sources of finding literature because they cover more than 20,000 and 10,000 scientific journals in social sciences. They also allow fully exporting the data required for a bibliometric approach (Harzing and Alakangas, 2016; Mariani and Borghi, 2019; Zupic and Čater, 2015). The date range was irrelevant since the energy business ecosystem concept is new in the literature, and, as expected, all records in the two databases are from 2000 onwards.

Figure 1: The selection protocol

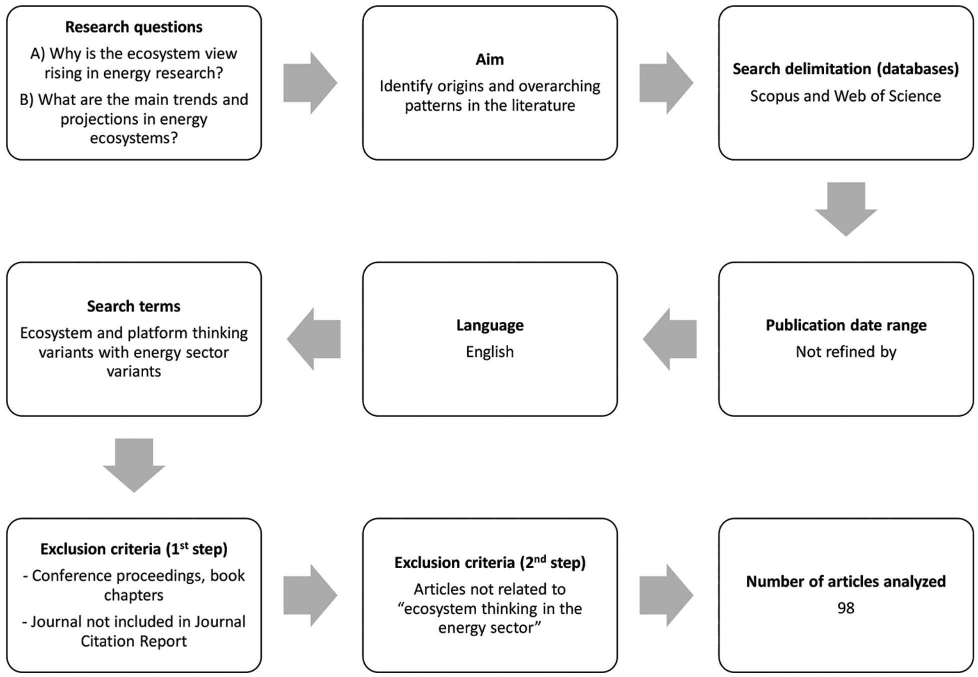


Table 1: The different macro, meso, and micro ecosystemic levels, based on Chatzinikolaou et al. (2021)

Socioeconomic level	What does it involve?
Macro	The overall business and socioeconomic environment—national, international, or supranational.
Meso	Specific sectors, industrial clusters, or business ecosystems.
Micro	Individual firms and other actors in the market.
Macro-Meso	The traditional regional growth perspective.
Macro-Micro	Macroeconomic growth offers and improves the environment for business development.
Meso-Micro	An intermediate environment includes all actors stimulating specific business structures at various localities and industries (local innovation systems).
Macro-Meso-Micro	An integrated understanding of long-term socioeconomic development as the outcome of multilevel interactions.

Concerning the specific search terms, Table 2 offers the strings for the searches carried out in Scopus and WoS on January 22, 2022. As noted in the previous section, the ecosystems perspective concerning the topic under investigation is contained in studies related to business ecosystems, innovation ecosystems, entrepreneurial (or entrepreneurship) ecosystems, platform-based ecosystems, service ecosystems, open innovation ecosystems, industrial ecosystems, digital ecosystems, regional innovation ecosystems, and energy ecosystems. Also, the word "platform" tends to be used as an alternative to the ecosystem. Thus, the corresponding variants for the platforms also were inserted.

The goal was to identify all relevant works in which the authors use "energy" and other variants in keywords. Specifically, the following words were searched[1]: energy, grid, electricity, coal, oil, gas, hydro, nuclear, renewable, wind, solar, biomass, biogas, ocean, thermal, electric, and fuel.

These words were inserted into asterisks to cover all possible variants, such as "microgrid," a term that would not otherwise appear.[2] These keywords came from our knowledge of the industry. They also emerged after reviewing the recent comprehensive textbook by Bradford (2018)—emphasizing its sections. The words about ecosystems and platforms were searched in the "Article Title, Abstract, Keywords" (Scopus) and "Topic" (WoS) fields. Also, asterisks were used again to incorporate neologisms or extensions of words (for instance, the search for the "entrepreneur*" includes both entrepreneurship and entrepreneurial). Furthermore, the phrase "ecosystem of (plus one word) energy" was also searched, enabling the database to find expressions such as the "ecosystem of green energy" or the "ecosystem of clean energy." Finally, the search results were refined by subcategories and topics of the two databases relevant to the research subject (energy, business, social science, economics) and to literature in English only, ending up with 438 and 114 records in Scopus and WoS, respectively.

All entries published in conference proceedings and book chapters were initially discarded (no books appeared in the search). The

1 Not in index keywords since the author's perspective was chosen. According to the distinction made by Scopus, "Author keywords are chosen by the author to best reflect the content of the document." Also, "Indexed keywords are chosen by Scopus and are standardized to vocabularies derived from thesauri that Elsevier owns or licenses. Unlike Author keywords, Indexed keywords take into account synonyms, various spellings, and plurals." (How do Author keywords and Indexed keywords work?, https://service.elsevier.com/app/answers/detail/a_id/21730/supporthub/scopus/)

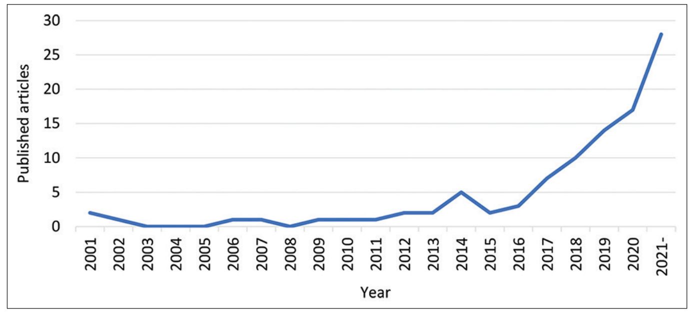
2 Note that WoS does not support this form of search on the left-hand side of the author's keywords, allowing it only in the "Topic," "Title," and "Identifying Code" fields.

Table 2: The search strings and the number of documents (the search was carried out on January 22, 2022)

Scopus	(TITLE-ABS-KEY ("innovat* ecosystem" OR "business* ecosystem" OR "entrepreneur* ecosystem" OR "knowledge* ecosystem" OR "service* ecosystem" OR "industr* ecosystem" OR "digital* ecosystem" OR "energy ecosystem" OR "ecosystem thinking" OR "ecosystem perspective" OR "ecosystem view" OR "platform* ecosystem" OR "innovat* platform" OR "business* platform" OR "entrepreneur* platform" OR "knowledge* platform" OR "service* platform" OR "industr* platform" OR "digital* platform" OR "energy platform" OR "platform thinking" OR "platform perspective" OR "platform view") OR TITLE-ABS-KEY ("ecosystem of" W/1 energy) OR TITLE-ABS-KEY ("platform of" W/1 energy) AND (AUTHKEY (*energy*)) OR AUTHKEY (*grid*) OR AUTHKEY (*electric*) OR AUTHKEY (*coal*) OR AUTHKEY (*oil*) OR AUTHKEY (*gas*) OR AUTHKEY (*hydro*) OR AUTHKEY (*nuclear*) OR AUTHKEY (*renewable*) OR AUTHKEY (*wind*) OR AUTHKEY (*solar*) OR AUTHKEY (*biomass*) OR AUTHKEY (*biogas*) OR AUTHKEY (*ocean*) OR AUTHKEY (*thermal*) OR AUTHKEY (*fuel*)) AND (LIMIT-TO (LANGUAGE,"English")) AND (LIMIT-TO (SUBJAREA,"ENER") OR LIMIT-TO (SUBJAREA,"BUSI") OR LIMIT-TO (SUBJAREA,"SOCI") OR LIMIT-TO (SUBJAREA,"ECON"))	438
WoS	((TS=("innovat* ecosystem" OR "business* ecosystem" OR "entrepreneur* ecosystem" OR "knowledge* ecosystem" "service* ecosystem" OR "industr* ecosystem" OR "digital* ecosystem" OR "energy ecosystem" OR "ecosystem thinking" OR "ecosystem perspective" OR "ecosystem view" OR "platform* ecosystem" OR "innovat* platform" OR "business* platform" OR "entrepreneur* platform" OR "knowledge* platform" "service* platform" OR "industr* platform" OR "digital* platform" OR "energy platform" OR "platform thinking" OR "platform perspective" OR "platform view" OR "ecosystem of" NEAR/1 energy OR "platform of" NEAR/1 energy)) AND ((AK=(energy*) OR AK=(grid*) OR AK=(electric*) OR AK=(coal*) OR AK=(oil*) OR AK=(gas*) OR AK=(hydro*) OR AK=(nuclear*) OR AK=(renewable*) OR AK=(wind*) OR AK=(solar*) OR AK=(biomass*) OR AK=(biogas*) OR AK=(ocean*) OR AK=(thermal*) OR AK=(fuel*))))[3]	114

articles published in journals with no impact factor listed in the Journal Citation Report also were removed. This practice is also followed by the systematic literature review of Jugend et al. (2020), which concerns an enhanced understanding of public support for innovation. Following this methodological choice, the number of documents in Scopus was reduced to 183. The titles and abstracts were read then, and all articles not belonging to the "ecosystems perspective" and energy were discarded. Primarily, social science publications were retained, emphasizing that socioeconomic actors co-evolve within their energy systems, as highlighted by Viholainen et al. (2021).

Figure 2: Evolution of the total number of publications



After this stage, there were 98 articles left in the list created in Scopus. A review of all 114 WoS search results was performed in this phase to identify potential non-indexed Scopus articles, resulting in no change. From this point on, the final 98 articles were analyzed.

The 98 articles were initially analyzed with a bibliometric approach to identify the chronological succession of these publications. Second, a network analysis was performed using VOSviewer (van Eck and Waltman, 2017), aiming to find the co-occurrence of keywords and identify the trends within which the publications are distinguished. In the last stage, the qualitative study was implemented to recognize the theoretical foundations of ecosystems in the energy sector. Then, it could be possible to clarify the generic trends of this research theme. Finally, spreadsheets were used for all other graph illustrations.

4. RESULTS

4.1. Bibliometric Analysis

4.1.1. Evolution of the number of articles

Figure 2 shows the evolution and distribution of articles per year. A steep increase is evident from 2017 onwards, as only 22 of the 98 articles (22%) are published between 2001 and 2016. The remaining 78% is published after 2017.

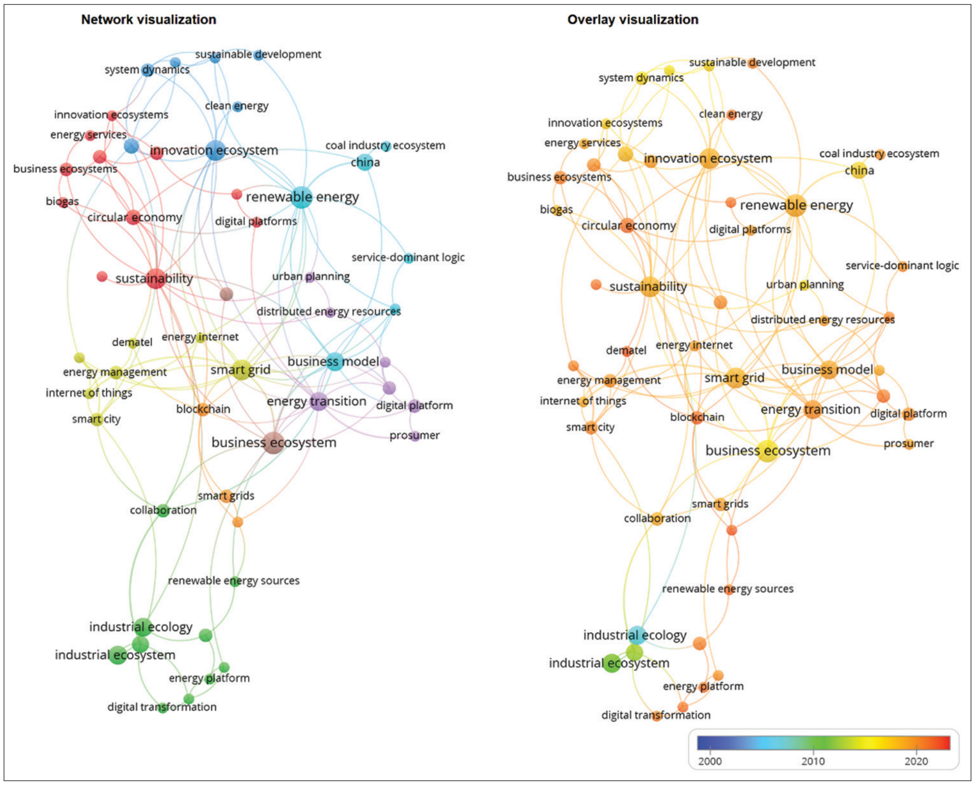
4.1.2. Keyword co-occurrence

The.csv file created in Scopus using all the available fields was first imported into the VOSviewer software. The keyword co-occurrence visualization was then selected to build a network that shows their relatedness.[4] According to the software, the relatedness of the items is determined by the number in which they appear together. The software inserts the occurrences by default to visualize the network in different clusters of words, based on "the number of documents in which a keyword occurs" and the "total link strength," meaning the strength derived by the number of links of an item with other items. Figure 3 shows the network and overlay visualizations created by the co-occurrences for author keywords, taking two co-occurrences as the minimum value.

3 Refined by Web of Science Categories: Energy Fuels or Green Sustainable Science Technology or Management or Business or Economics or Regional Urban Planning or Development Studies. Also refined by Language: English.

4 In all visualizations, the default for "full counting" instead of "fractional counting" was kept because no further processing was needed on the exact results derived from the "full counting" method.

Figure 3: The "author keyword" network is visualized in strength-linked clusters (left-hand side) and year-linked clusters (right-hand side)



The stronger links derive from the keywords smart grid, energy transition, renewable energy, sustainability, innovation ecosystem, business ecosystem, and business model—two links are the minimum strength value for a line to connect two nodes. The rest keywords have less than four occurrences. On the left-hand side (network visualization), the following patterns can be observed: industrial ecology and industrial ecosystem (with green color), sustainability (red), smart grid (yellow), which is closely related to the blockchain sphere (orange), energy transition (purple), renewable energy (light blue), innovation ecosystem (dark blue), and business ecosystems (brown), which overarches all the rest. On the right-hand side (overlay visualization), the central role of the "business ecosystem" occurrence is evident, resulting from a relatively weak link from studies on industrial ecology.

The analysis of index keywords provided in Scopus by the content providers can also show different research clusters within the topic. Figure 4 presents the network and overlay visualization for the author and index keywords, taking three co-occurrences as the minimum value.

This visualization shows the following strong keywords: ecosystems, innovation, energy policy, decision making, alternative energy, sustainability, smart grid, sustainable development, energy, and business ecosystems. As with the visualization in Figure 3, a line will connect two nodes only if it has a minimum strength value of two links. The rest keywords have less than ten occurrences. On the left-hand side (network visualization), similar patterns to the "author keywords" can be observed. A notable difference is the overlap of various clusters, which can concern different themes. All the significant groups lie centrally in the network: ecosystems (with red color), innovation (with dark blue), sustainable development and energy policy (purple), alternative energy (light blue), and sustainability (green). This result indicates that the authors of this field might approach the matter from an interdisciplinary perspective and from multiple angles. From the overlay visualization (right-hand side), it is again confirmed that the field initiates from the environmental study of industrial ecology, which subsequently declines due to the rise of more business- and socioeconomic-development-oriented approaches.

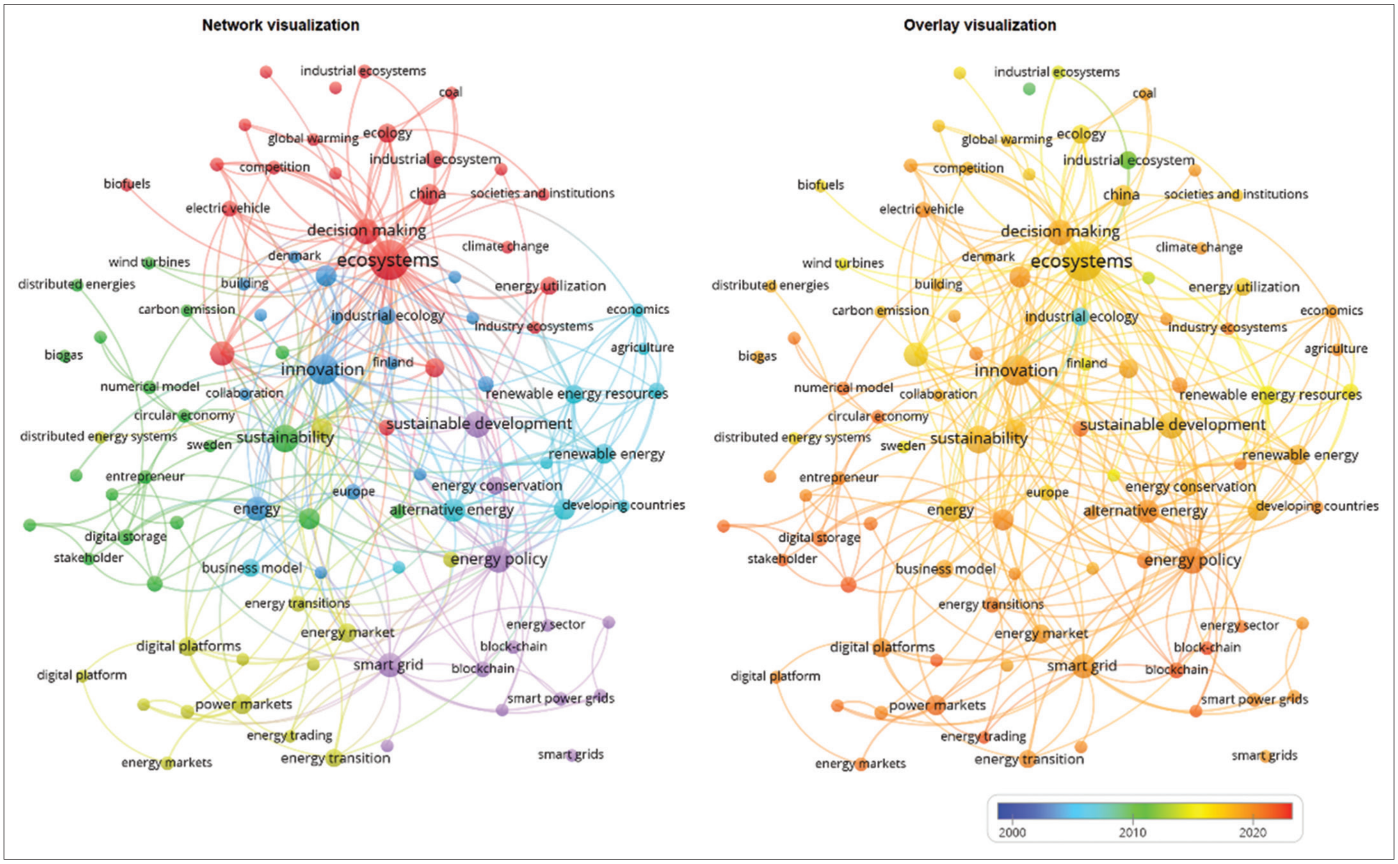
4.1.3. Journal, occurrence frequency, and citation analysis

The "Journal of cleaner production," the "Energies," and the "Sustainability" have published most of the papers, with 16, 16, and 13 records, respectively, covering 46% of the entire sample. Figure 5 presents the total number of articles per journal and period.

12 articles are between 2011 and 2015, 4 in 2006-2010, and 3 in 2001-2005. It is noteworthy that the "Journal of cleaner production" keeps publishing relevant articles. After the first era, the "Ecological economics" and the "International journal of sustainable development and world ecology" have not revisited the topic. A similar trend also appears in the "Environment, development and sustainability" and the "Business strategy and the environment," which have not published relevant papers again, perhaps because their scope fits the framework of environmental studies and ecology and not so much the issues around energy. Furthermore, articles also appear on topics not purely in the energy sector but in the scopes of evolutionary economics, the transport sector, anthropology, industrial innovation, development, marketing, and spatial planning.

This bibliometric method and analysis of journals enabled tracing the origins and understanding the generic future trends. Figure 6

Figure 4: The "author" and "index" keyword network is visualized in strength-linked clusters (left-hand side) and year-linked clusters (right-hand side)



shows the frequency of occurrence of specific words. This frequency was traced after merging all the.pdf files.

Specifically, four plus one searches were performed. In the first case, the frequency of specific words related to the broader topic was examined. It was proved that the vast majority concerns the concepts of innovation ecosystems, business ecosystems, industrial ecosystems, and energy platforms. The frequency of specific variants related to the author keywords was investigated in a second step, identifying "energy" and "electric" as the most frequent occurrences. Other forms of energy and renewable energy occur with similar frequency. In the third case, the frequency of occurrence of fundamental concepts was examined. It turns out that innovation, technology, and policy occur more often than the rest. Words from the field of engineering are used less frequently. The fourth search was for general terms related to the method used: the qualitative approach is overwhelming. Concerning the last case, this was implemented after the qualitative analysis of the following section: specific terms that seemed to lead to the emergence of different trends in the field were searched. Specifically, in this search, energy efficiency is nodal as it exceeds in absolute numbers all other researched concepts related to the trends distinguished after the qualitative analysis. In addition, the prosumer dimension is more frequent than the spheres of sustainable development, energy transition, industrial ecology, and distributed energy.

Finally, the citation network analysis can offer complementary data that enhance the understanding of how this field is clustered. Figure 7 presents the results of the citation analysis.

A citation link shows the connection between two articles when one article cites another. The VOSviewer software does not distinguish between the two articles since it simply displays both records when one is linked to another. The execution of this command results in a relatively remote relationship between the articles. Only 32 of the 98 papers are connected, separated into 11 groups. This weak relationship shows that this area of research is still in its infancy as the authors do not recognize common ground in its inception. These groups, in their chronological order, can be named as follows:

i. Industrial ecology (Korhonen, 2001; Korhonen et al., 2001; Snäkin and Korhonen, 2002; Wolf et al., 2007)
ii. Industrial ecology revisited (Liwarska-Bizukojc et al., 2009; Leduc and Van Kann, 2013)
iii. Business ecosystems and innovation ecosystems in the energy sector (Chen et al., 2014; Surie, 2017; Kolloch and Dellermann, 2018; Wu et al., 2018; Yao et al., 2021; Blasi and Sedita, 2020)
iv. Different business ecosystems of the energy sector (Rong et al., 2017; Aaldering et al., 2019)
v. Prosumer innovations (Lavrijssen and Parra, 2017: Ahl et al., 2020)
vi. Coal ecosystem resilience (Wang et al., 2017, 2019, 2020)
vii. Improving energy efficiency (Goldbach et al., 2018; Kangas et al., 2018; Kim and Ha, 2021)
viii. Energy transition (Kloppenburg and Boekelo, 2019; Nwaiwu, 2021; Singh et al., 2021)
ix. Sustainable development (Wurster et al., 2020; Arribas-Ibar et al., 2021)

Figure 5: Articles per journal and period

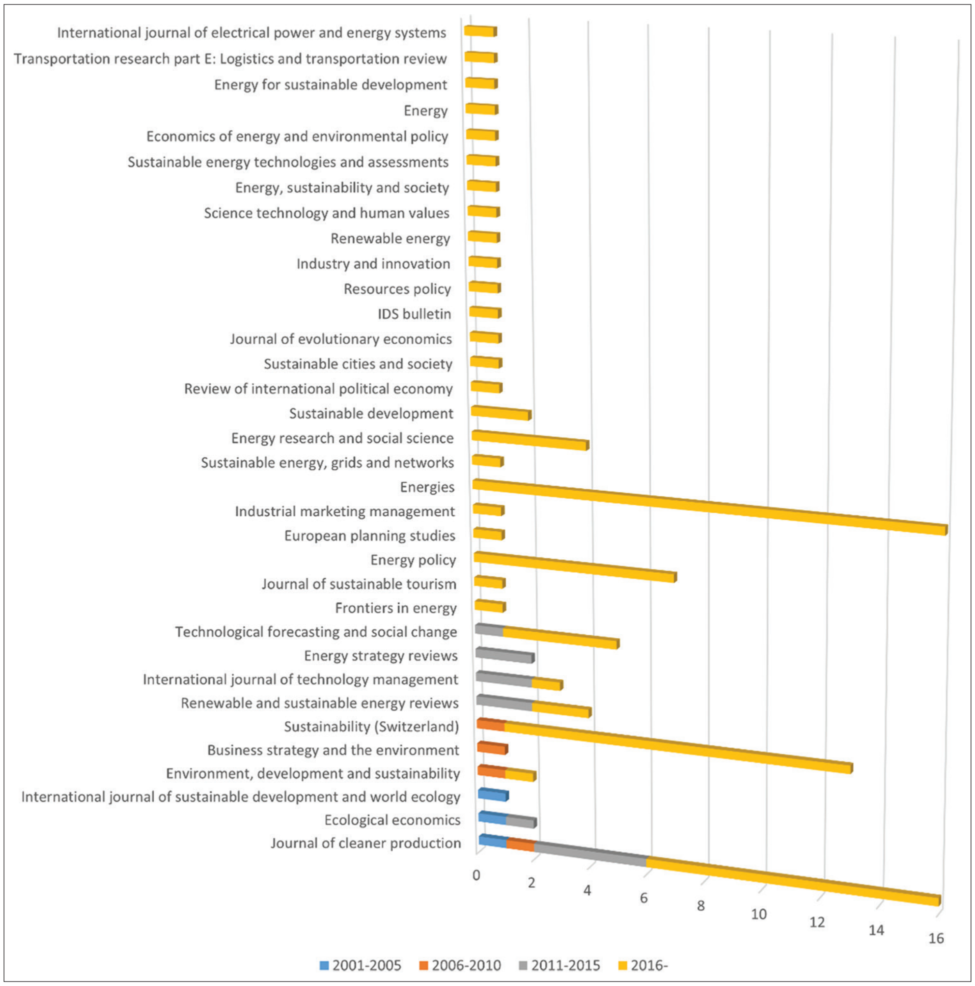


Figure 6: The frequency of specific words in the 98 articles, based on the absolute number of occurrences

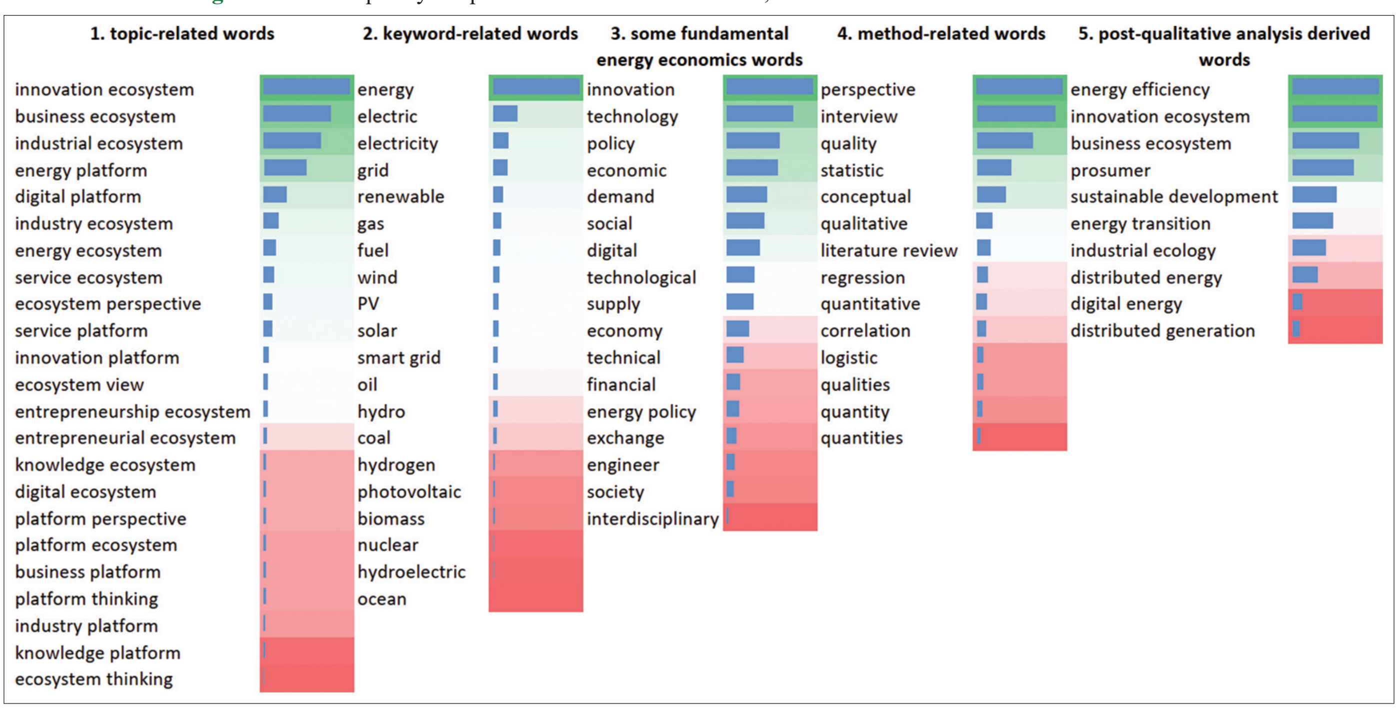
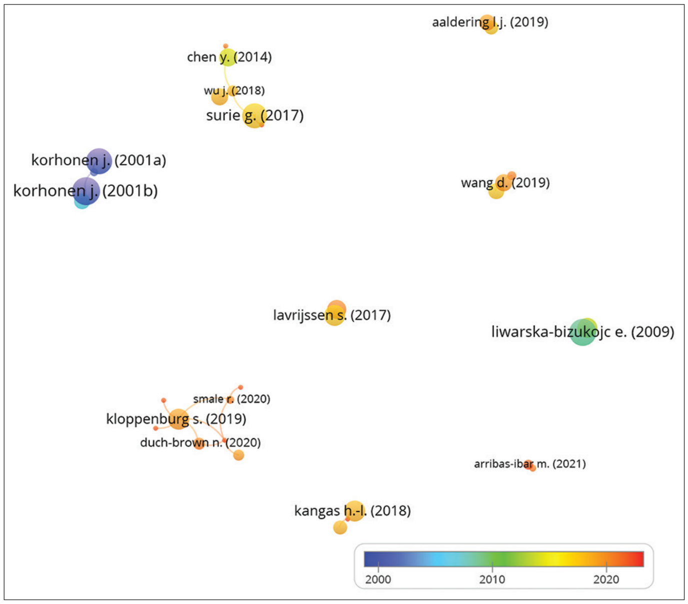


Figure 7: Clusters out of citation links



x. Digital energy platforms and associated policies (Xu et al., 2019; Duch-Brown and Rossetti, 2020; Niet et al., 2021)
xi. New electricity exchange platforms (Smale and Kloppenburg, 2020; Montakhabi et al., 2021)

Assessing the bibliometric data, it can be argued that the field is rather nascent, with a fragmented citation network suggesting a lack of consensus or foundational literature. The diverse clusters identified, ranging from industrial ecology to new electricity exchange platforms, underscore the multifaceted nature of the topic. While the citation analysis provides a macroscopic view of the field's development, it also hints at the need for more integrated research to establish common ground. As we transition to the qualitative analysis next, we will delve deeper into the nuances of these emerging trends, aiming to provide a more comprehensive understanding of the field's trajectory and its overarching themes.

4.2. Qualitative Analysis

Upon analyzing the articles, these works were grouped into four dominant research trends. These trends suggest that articles form groups or "families" based on shared research priorities, methodologies, and conclusions (Figure 8)[5]:

1. Industrial ecology explores the flows of energy and materials within industrial chains, drawing analogies with biological ecosystems, while sustainable development aims to meet current needs without compromising future reserves.
2. The term energy transition denotes the shift from exhaustible to inexhaustible energy sources, while socioeconomic development refers to ongoing developments in the socioeconomic environment, often influenced by elements such as energy transformations.
3. In the energy space, business ecosystems include interconnected firms, institutions and stakeholders that shape and reap benefits from their collaboration, while innovation ecosystems emphasize shared arrangements that foster breakthrough advances and corrective measures.
4. Distributed energy systems are about local energy production or conservation near places of consumption—smart grids combine digital exchanges with energy systems to enhance efficiency and reliability, with concurrent policies and decisions shaping the guidance and oversight for these innovations and systems.

Therefore, the origin is traced in meso-oriented studies on industrial ecology. More recently, this field appears to extend toward different macro-focused sustainable development aspects from an environmental and ecological perspective. Also, more recent studies refocus on sustainable development issues in the evolving context of contemporary energy transition (arrow A, Figure 8). In turn, this trend examines, from the early 2010s onwards, different cases concerning the energy business ecosystems, primarily on issues of overarching socioeconomic development. A node is also identified in various meso-level studies that suggest solutions for specific energy aspects and problems (arrow B). The last pillar is the trend of distributed energy systems, smart grid innovations, and related policy-regulation dynamics. This trend is being researched with increasing intensity, originating from meso-micro implications and shared influences with the field of energy business ecosystems, exploring specific aspects of reinforcing the diffusion of distributed energy solutions (arrow C).

We identify the progressive emergence of another intriguing micro-origin strand (arrow D). As the field evolves, we anticipate this aspect to gain momentum. Such a shift could harness insights from contemporary evolutionary economic theories, integrate "biological models" in modern organizational theory, and, most importantly, enrich discussions around symbiotic strategies framed in terms of co-opetition and organic innovation (Brandenburger and Nalebuff, 1996; Välikangas and Merlyn, 2002). Specifically, the operational practices of energy firms appear underexplored in this debate, particularly the micro-level approach in energy research. In our subsequent discussion and interpretation of findings (Section 5), we will elucidate why this relatively recent shift (Ahokangas et al., 2018; Ma et al., 2019; Parisot, 2013) is increasingly likely to happen. Finally, the energy efficiency dimension can be argued that traverses inherently all these trends as it does not form a node on its own but is included in most related analyses.

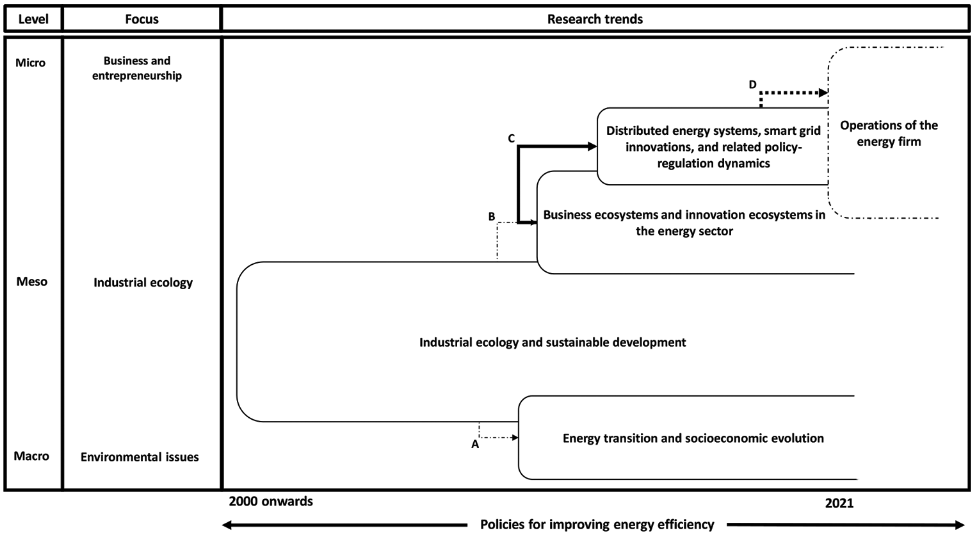
4.3. The Emergence of Energy Ecosystems Research

The growing interest in energy ecosystems research indicates its potential as an emerging field. Based on our introductory framework, the emergence of a new field of research can be identified by (I) indications of new paradigms, (II) adjustments or enhancements of existing ideas, and (III) an increase in academic publications and attention. These criteria are examined further based on our previous analysis.

I. Emergence of new approaches: The works of Korhonen (2001), Korhonen et al. (2001), and Snäkin and Korhonen (2002) introduced a shift in the energy ecosystems discourse. These contributions propose a deviation from traditional industrial ecology, moving towards an ecosystem perspective

5 Appendices 2-5 visualize the keyword networks of these four trends.

Figure 8: Focus and trends of the energy ecosystems' literature



that relates industrial metabolism to the flow of materials and energy, similar to metabolic processes.

II. Adjusting established notions: Several works, such as those by Hellström et al. (2015), Tsvetkova et al. (2015), and Kanda et al. (2021), have gained attention and frequent citations, reflecting their potential impact across different trends. These papers offer new perspectives or modifications on established concepts. For instance:
- Macro-level policy strategy and green infrastructure: Section 2 discussed the tendency of rapidly developing nations, such as China and India, to rely on larger generation technologies. Notably, there's a recognition of the emerging cost-effectiveness of smaller-scale technologies, as highlighted by Wang et al. (2019). Building on this, Kim (2019), provides insights into the development of hybrid industrial ecosystems in East Asia, emphasizing the significant role of policy decisions in promoting green infrastructure in the region, thereby enriching the broader global perspective.
- Refining the meso-level ecosystem with emerging technologies: Plewnia (2019) highlights the adaptability of sharing economy models, positing that they could reshape the energy sector in light of decentralized renewable technologies. This perspective, often associated with the "prosumer" label in energy system literature, represents a nuanced shift (Bradford, 2018). Instead of viewing energy solely as a commodity, it's perceived as a shared resource, prompting a move towards collaborative consumption and generation. Concurrently, studies by Erol et al. (2021) and Hou et al. (2021) emphasize blockchain's potential to revolutionize the energy sector. As discussed in Section 2, there exists a legislative challenge in disseminating distributed generation technologies, underscoring the necessity for mechanisms to bridge producers and consumers (Lavrijssen and Parra, 2017). The insights from Erol et al. (2021) and Hou et al. (2021) provide potential technological solutions to these challenges, illustrating how blockchain might streamline connections and promote cleaner energy methodologies.
- Micro-level symbiotic relationships and sustainable development: Hellström et al. (2015), Tsvetkova et al. (2015), and Kanda et al. (2021) integrate industrial ecology concepts with business ecosystem principles. Instead of viewing energy ecosystems merely as technical entities, they conceptualize them as socio-technical systems rooted in collaboration. Such interactions enable stakeholders within the ecosystem to leverage distributed energy systems and innovative business models for sustainable value creation. Hellström et al. pinpoint the business model as a catalyst for systemic change in these ecosystems. This perspective resonates with the overarching theme that collaborative ecosystems can foster sustainability, an idea also noted in previous literature like Bradford's (2018). However, such literature often lacks specific micro-level guidelines.

III. Trends in academic publications: Figure 2 displays a trend in the field's academic publications. Approximately 22% of articles were published between 2001 and 2016, while 78% appeared after 2017, indicating the growing interest in this field.

4.4. A Critique and Forecast of Future Developments

In the realm of energy ecosystem literature, the energy efficiency dimension consistently stands out, revealing its central role either explicitly or implicitly. This trend underscores the enduring emphasis on economic imperatives grounded in benefit-to-cost ratios. Yet, this economic-centric view, described as the homo economicus approach (Urbina and Ruiz-Villaverde, 2019) can sometimes overshadow a more evolutionary perspective on socioeconomic ecosystems.

As discussed in Section 2, when dissecting business ecosystems, it is vital to employ an integrated macro-meso-micro viewpoint. This holistic perspective encompasses the broader societal dynamics, specific sectoral structures, and individual enterprises. At the heart of this multilayered framework is the capitalist firm, seen as a "living organization." Recognizing its central role is crucial for a thorough comprehension of ecosystem interactions and their subsequent influence on socioeconomic progress. The reviewed literature illustrated a progression from meso-level investigations of industrial ecology to wider environmental considerations, and then onto specific micro-level issues. Notably absent was an acknowledgment of the macro-meso-micro perspective, even though modern evolutionary economics increasingly perceives socioeconomic systems as integrative entities spanning macro, meso, and micro levels (Dopfer et al., 2004).

In addition, despite the extensive research in business and entrepreneurship, there seems to be a limited exploration of the intricate operations of energy firms within these ecosystems, hinting at a potential avenue for future research. While a few micro-oriented studies were identified in our literature review, no prevailing trend was evident. It is, however, notable that the works of Shuen et al. (2014) and Planko et al. (2017) may signify the onset of a new direction. The former delves into dynamic capabilities in the upstream oil and gas industry, while the latter suggests that smart-grid participants collaborate extensively in system-building networks to navigate challenges and forge new ecosystems.

Looking ahead, recent literature, including foundational works by Moore (1993) and Iansiti and Levien (2004), as well as more recent contributions (Chatzinikolaou and Vlados, 2019; Coad et al., 2018), delves deeper into the ecosystemic roles of firms. These perspectives, which are somewhat overlooked in the burgeoning energy ecosystems field, might witness a resurgence. Such viewpoints draw analogies between firms' trajectories in socioeconomic systems and evolutionary patterns seen in biology. Within this evolutionary paradigm, all socioeconomic structures, when perceived through an ecosystem lens, can be equated to biological organisms. Here, innovation emerges as the key catalyst for adaptation and survival. Thus, as the energy ecosystems field evolves, a micro-focused approach may likely ascend, spotlighting the nuanced interactions of energy firms and their indispensable positions within the energy ecosystem.

5. DISCUSSION AND CONCLUSION

5.1. Rethinking the Concept of Energy Ecosystems

This paper provided a systematic review of the field of energy ecosystems. By critically delving into this academic landscape, it highlighted significant works and concepts and evolving trends that define its progression. Through bibliometric and qualitative scrutiny of 98 articles, it was found that the ascendancy of the energy ecosystem perspective is reflected in several ways. Firstly, by the advent of new approaches that transition from the conventional industrial ecology approach to one that analogizes industrial operations with metabolic functions. Secondly, by tweaks to prevalent concepts encompassing policy directives, the inclusion of emerging technologies like the sharing economy and blockchain, and a more holistic view of energy ecosystems as socio-technical systems emphasizing collaboration for sustainable value generation. Additionally, an impressive surge in scholarly publications has been noted, with a substantial 78% published post-2017, underscoring the escalating interest in this field.

The following points succinctly answer the questions:

- Key Takeaway A: Why does the ecosystems perspective in the energy sector appears to be emerging as a field of research? The surge in energy ecosystems research can be attributed to the adoption of new approaches linking energy flows to ecological concepts, refinements incorporating emerging technologies and socio-technical considerations, and a marked increase in related academic publications in recent years. Furthermore, four overarching trends in energy ecosystems were identified: "industrial ecology and sustainable development," "energy transition and socioeconomic evolution," "business and innovation ecosystems in energy," "distributed energy systems, smart grid innovations, and associated policy-regulation dynamics."
- Key Takeaway B: What are the predominant trends highlighted in the literature on energy ecosystems, and what is their anticipated trajectory and underlying reasons? The energy ecosystem literature highlights four key trends, emphasizing energy efficiency and benefit-to-cost relationships. However, the way forward suggests a need for a holistic macro-meso-micro perspective and an enhanced focus on the nuanced roles of individual energy firms within these ecosystems.

Based on the above, a renewed definition for energy ecosystems can also be considered. In particular, the term "ecosystem" in various analyses seems often to deviate from its biological origins, being used instead as a shorthand for "economic system." This adaptation can sometimes lead to confusion, especially when the intricate dynamics of biological analogies in social sciences are overlooked. A subset of articles within our review sample appeared constrained due to this ambiguity. To address this, it's essential to revisit and redefine the concept of the energy ecosystem, drawing inspiration from its biological roots. We propose the following definition: "*Energy ecosystems are dynamic networks of interdependent socioeconomic entities that co-evolve. These entities interact with their wider socioeconomic and natural environments across multiple interconnected spatial scales, with a persistent focus on optimizing energy efficiency.*"

5.2. On an Integrative Energy Ecosystems Policy

The emergence of the energy ecosystems field, as identified in this research, underscores the need for a comprehensive policy framework that addresses the macro, meso, and micro scales of the energy sector in order for sustainable energy ecosystems to emerge. The overarching trends identified in our study could provide a preliminary vision roadmap for shaping an integrative macro-meso-micro "energy ecosystems policy."

- Sustainable development and industrial symbiosis (macro-level): The "industrial ecology and sustainable development" trend emphasizes the interconnectedness of material and energy flows. A holistic policy should prioritize industrial metabolism, where industries collaborate to optimize resource use, reduce waste, and contribute to sustainable development objectives.
- Energy transition and business ecosystems (meso-level): The trends of "energy transition and socioeconomic evolution" and "business ecosystems and innovation ecosystems in the energy sector" highlight the need for a policy that perceives mutuality among all ecosystem stakeholders. Therefore, an

integrative energy ecosystems policy should not only address the evolving forms of energy demand and supply but also recognize and support the interconnectedness of co-evolving actors within the energy sector.

- Empowering local energy ecosystems and business innovation (micro-level): The emergence of "distributed energy systems, smart grid innovations, and related policy-regulation dynamics" and the forecasted "operations of the energy firm" trends underscore the importance of local energy ecosystems and business innovation. An integrative energy ecosystems policy should empower local energy ecosystems, emphasizing "glocal" strategies over global ones, and strengthen the competitiveness of firms at the heart of the energy ecosystem (Dameri et al., 2019; Swyngedouw, 2004).

5.3. Limitations and Future Research Avenues

This study is accompanied by certain limitations. A primary methodological constraint pertained to the exclusion of articles that incorporated the term "business ecosystem" and its derivations in the body of the paper. Such an exclusion may have omitted some relevant records. Future research could explore alternative databases, particularly given the constraints in searching the main body of texts in platforms like Scopus and WoS. Also, the present search focused primarily on the author's keywords. Broadening the search parameters to encompass "index words" might furnish a more comprehensive literature base.

An intriguing observation in this study is the apparent limited citation interconnectivity amongst the papers in this field, as illustrated in Figure 7. Such a pattern could imply a fragmented or lack of cohesive understanding in the field. Alternatively, it might highlight that the subject is in its formative stage, with researchers operating within isolated frameworks or grounded on divergent foundational principles. Given the interdisciplinarity in energy research (Schmidt and Weigt, 2015), a burgeoning field may witness varied themes, theories, and methodologies, reflecting its depth and breadth, even if these elements currently seem disjointed. Future research could provide valuable insights by mapping energy ecosystems trajectories through backward-citation linkages, aiming to uncover the field's deeper roots in social and other scientific disciplines—a method employed effectively by Lazzeretti et al. (2014).

In conclusion, it became apparent that certain studies within the energy ecosystems field have re-contextualized earlier energy concepts and intertwined them with ecosystem-based economic perspectives. This underscores the potential birth of a distinct research arena. Yet, the real-world applicability of these energy ecosystem metaphors in economic settings, and their actual incorporation into routine practices and policymaking, warrants further investigation. Delving deeper into the intricacies of the macro-meso-micro energy ecosystems policy framework seems crucial.

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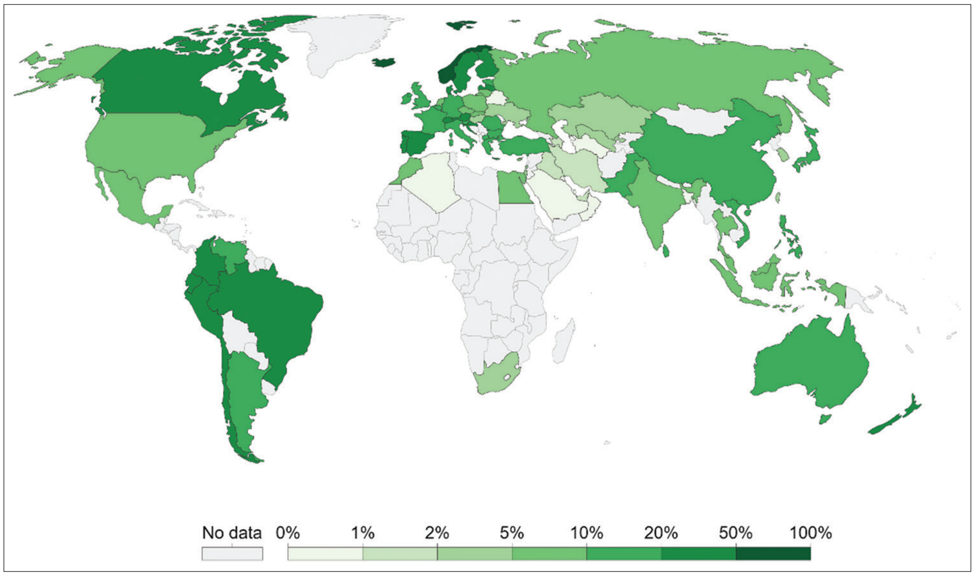
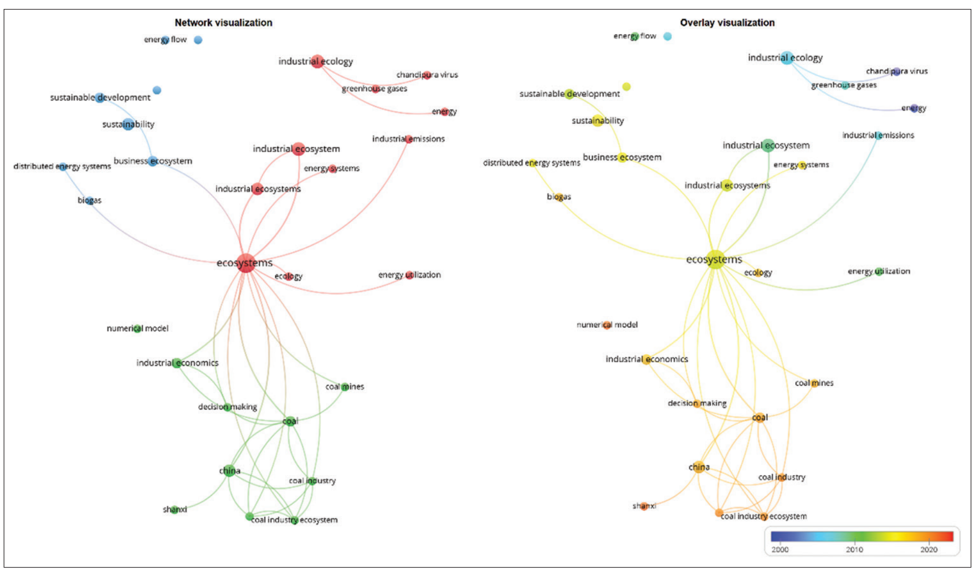
APPENDIX

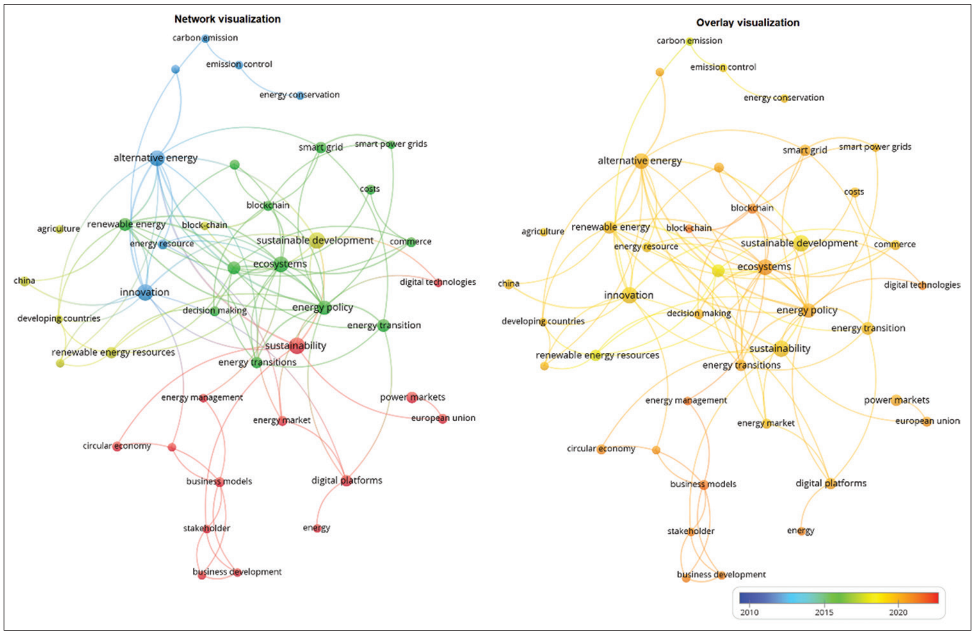
Appendix 1: Share of renewables as a primary energy source, 2020 (The renewables include hydroelectric, solar, wind, geothermal, bioenergy, and ocean. Source: https://ourworldindata.org/renewable-energy#how-much-of-our-primary-energy-comes-from-renewables)



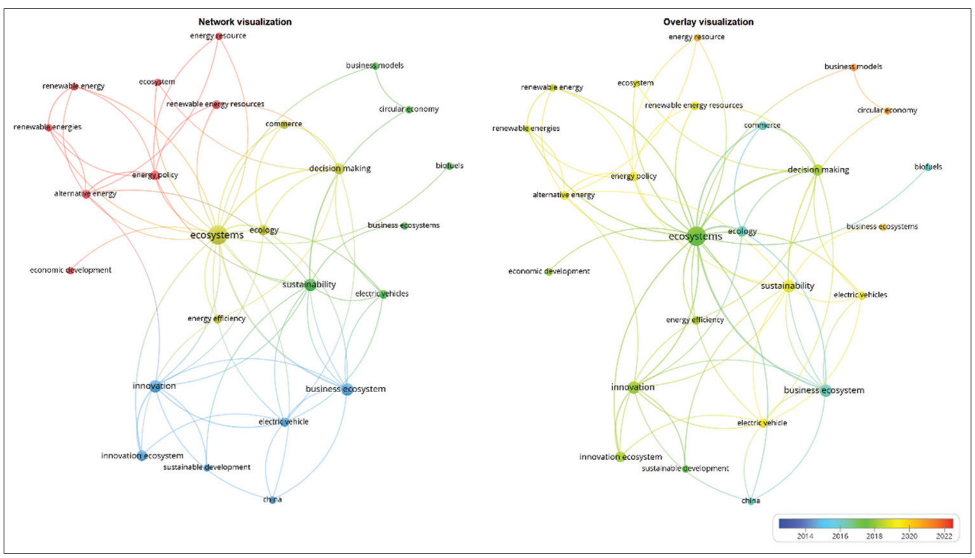
Appendix 2: "Author" and "index" keyword network for the trend "industrial ecology and sustainable development" (Min. 2 occurrences; 2 links also is the min. strength for a line to connect two nodes)



Appendix 3: "Author" and "index" keyword network for the trend "energy transition and socioeconomic evolution" (Min. 3 occurrences; 2 links also is the min. strength for a line to connect two nodes)



Appendix 4: "Author" and "index" keyword network for the trend "business ecosystems and innovation ecosystems in the energy sector" (Min. 3 occurrences; 2 links also is the min. strength for a line to connect two nodes)



Appendix 5: "Author" and "index" keyword network for the trend "distributed energy systems, smart grid innovations, and related policy-regulation dynamics" (Min. 3 occurrences; 2 links also is the min. strength for a line to connect two nodes)