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The Low-Carbon Transition of Energy Systems: A Bibliometric Review from an Engineering Management Perspective

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ABSTRACT

As a major solution to climate change, the low-carbon transition of energy systems has received growing attention in the past decade. This paper presents a bibliometric review of the literature on the low-carbon transition of energy systems from an engineering management perspective. First, the definition and boundaries of the energy system transition are clarified, covering transformation of the energy structure, decarbonization of fossil fuel utilization, and improvement in energy efficiency. Second, a systematic search of the related literature and a bibliometric analysis are conducted to reveal the research trends. It is found that the number of related publications has been growing exponentially during the past decade, with researchers from China, the United Kingdom, the United States, Germany, and the Netherlands comprising the majority of authors. Related studies with interdisciplinary characteristics appear in journals focusing on energy engineering, environmental science, and social science related to energy issues. Four major research themes are identified by clustering the existing literature: ① low-carbon transition pathways with different spatiotemporal scales and transition constraints; ② low-carbon technology diffusion with a focus on renewable energy technologies, pollution control technologies, and other technologies facilitating the energy transition; ③ infrastructure network planning for energy systems covering various sectors and regions; and ④ transition-driving mechanisms from the political, economic, social, and natural perspectives. These four topics play distinct but mutually supportive roles in facilitating the low-carbon transition of energy systems, and require more in-depth research on designing resilient low-carbon transition pathways with coordinated goals, promoting low-carbon technologies with cost-effective and reliable infrastructure network deployment, and balancing multi-level risks in various systems. Finally, business models, nongovernment actors, energy justice, deep decarbonization, and zero-energy buildings are recognized as emerging hot topics.

1. Introduction

Humans have harnessed energy to serve their needs for thousands of years, with "economic blood" used as a metaphor for energy in the modern industrial world. Throughout the human history of energy utilization, various scales of energy systems have been set up intentionally or formed automatically, covering different processes, regions, and energy types. In broad terms, an energy system (or sub-system) contains all the elements (e.g., resources, infrastructures, technologies, stakeholders, rules) involved in the whole process (or part) of energy supply and consumption, ranging from energy exploitation, production, storage, and distribution to end usage [1]. On a global scale, the world's energy system has experienced two major transitions and is now going through a third [2]. The first transition took place in the mid-19th century, mainly driven by the first industrial revolution, with the wide-scale utilization of steam engines as a symbol [3]. As the dominant fuel shifted from wood to coal, energy utilization patterns in human society and the underlying infrastructures underwent revolutionary transitions. The second transition occurred in the early 20th century, as oil and gas became the dominant fuel instead of coal. Analogously, the second energy system transition was mainly driven by the second industrial revolution, with the mass utilization of internal combustion engines as a symbol [4]. Unlike the first two transitions of the global energy system, the ongoing third transition is a "proactive" transition rather than a "reactive" one and is intended to adapt to technological progress and transitions in means of production

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and consumption. Since the late 20th century, the issues of global warming and climate change—which are predominantly caused by anthropogenic carbon dioxide emissions—have received growing attention. Realizing that fossil fuel combustion has contributed over 80% of global carbon emissions [5], experts and policymakers began seeking alternative renewable energy sources and low-carbon technologies [6,7]. The third transition of the global energy system thus began with the replacement of fossil fuels with renewables and the upgrading of "dirty" technologies to cleaner ones. There is now a global consensus that energy systems must transition toward a low-carbon and cleaner future.

The low-carbon transition of energy systems is becoming an increasingly important policy agenda in most countries. The Paris Agreement signed in 2015 calls for substantial reductions in anthropogenic carbon dioxide emissions during the 21st century, with ambitious decarbonization targets set up globally [8,9]. More than 190 countries have submitted their Nationally Determined Contributions, and nearly 150 have announced clear emissions reduction commitments [10,11]. Major emitters covering nearly 70% of global carbon dioxide emissions have pledged to meet net-zero emissions by the mid-21st century [12]. With global efforts, energy intensity has decreased by nearly 35% during the past three decades [13]. The electricity generated from renewables has reached 27%, with an annual growth rate of 7% in 2020 [14]. However, the low-carbon transition of energy systems has also encountered challenges, such as economic development and social governance. Industries relying on fossil fuels are heavily hit by emissions constraints [15,16], while oil- and coal-depending countries may face national economic crises [17]. Meanwhile, the development of emerging renewable industries presents obstacles and dilemmas, leading to extra economical and societal burdens [18,19]. In addition, the low-carbon transition may induce social issues such as energy injustice and energy poverty [20]. It is unclear how to achieve net-zero emissions goals through appropriate energy transition paths without drastic risks to social and natural systems [21,22]. Therefore, the energy transition field has attracted growing attention from and efforts by governments, entrepreneurs, and scholars from various disciplines with the aim of developing solutions to emerging problems.

In the literature, there has been growing interest in studying low-carbon transition issues associated with the energy system. Some scholars have attempted to summarize related studies from a general low-carbon transition perspective. For example, Wang et al. [23] conducted a bibliometric review of publications on low-carbon development, which is defined as "a new model of development, from the perspectives of optimizing the economic structure, developing the low carbon energy technology, improving the energy structure and efficiency of energy utilization and so on." Using bibliometric analysis and machine learning techniques, Wang et al. [24] identified research hotspots and trends related to the low-carbon economy. Other scholars have attempted to review related studies from a specific energy system perspective. For example, Zhang et al. [25] reviewed clean-energy-related articles from the Web of Science (WOS) Core Collection database, while Meng et al. [26] summarized the characteristics and trends of publications on low-carbon power systems and Omrany et al. [27] reviewed studies on net-zero-energy building systems. From a more general perspective, Dominković et al. [28] reviewed the research on energy system analysis during the past two decades. Although all these studies provide valuable insights into either the low-carbon transition or energy system analysis, there is still a lack of a middle-range review on the literature addressing issues associated with the low-carbon transition of energy systems from an engineering management perspective. Given its characteristics of integration and coordination, the low-carbon transition of an energy system is indeed a process of system engineering. The ideas and methods of engineering management are effective for managing system engineering projects, as they can be used to scientifically plan, design, implement and control with limited resources to achieve systematic goals [29]. Thus, this paper aims to provide a systematic review of studies on the low-carbon transition of energy systems from an engineering management perspective. The scope of this review is neither so broad that it covers all perspectives on low-carbon development nor so narrow that it focuses on a certain specific energy system. Instead, we focus on a middle-range scope covering all state changes of the general energy system toward lower carbon intensities, with the purpose of providing a full image and comprehensive landscape of existing management studies on the low-carbon transition of energy systems.

In this study, we collect a total of 5336 peer-reviewed journal articles from the WOS database through carefully designed searching protocols and screening criteria. A bibliometric analysis tool, VOSviewer, is used to analyze the scientometric features of the literature, including publication trends, regional characteristics, and co-citation networks. Thematic features are also revealed through keywords clustering with the whole sample and deep content analysis of the Essential Science Indicators (ESI) highly cited papers. Finally, we build a comprehensive research landscape of management studies on the low-carbon transition of energy systems and discuss the evolution of hot topics and potential future directions. It is found that the number of related publications has undergone exponential growth during the past decade, with scholars from China, the United Kingdom, the United States, Germany, and the Netherlands making the most contributions. Related studies with interdisciplinary characteristics have appeared in journals addressing energy engineering, environmental science, and energy social science issues. The reviewed studies fall into four major clusters of research themes: low-carbon transition pathways, low-carbon technology diffusion, infrastructure network planning, and transition-driving mechanisms. Interestingly, these four major research themes play distinct yet mutually supportive roles in facilitating the low-carbon transition of energy systems, jointly serving as academic wisdom for the practice. Business models, nongovernment actors, energy justice, deep decarbonization, and zero-energy buildings are recognized as hot topics. In the near future, topics on the coordination of different decarbonization goals, resilience in low-carbon transition pathway designs, the effectiveness of low-carbon technology and infrastructure network deployment, and the control of multi-level transition risks are likely to attract more attention. Generally speaking, this paper contributes to the literature by mapping out a full image and comprehensive landscape of the latest studies on the low-carbon transition of energy systems from an engineering management perspective.

The remainder of this paper is organized as follows. Section 2 describes the data and methodology used in this study, including search protocols, screening criteria, and bibliometric analysis methods. Section 3 displays the scientometric features of the literature sample. Section 4 analyzes the thematic features through keywords clustering and content analysis. Section 5 maps out the research landscape and discusses future directions for research on the low-carbon transition of energy systems. Section 6 concludes the paper.

2. Data and methodology

This study follows the overall process of a systematic literature review, which includes defining the searching protocol, formulating screening criteria, conducting a bibliometric analysis, building research landscapes, and discussing future directions [30,31]. The research procedure of this study is summarized in Fig. 1. Detailed

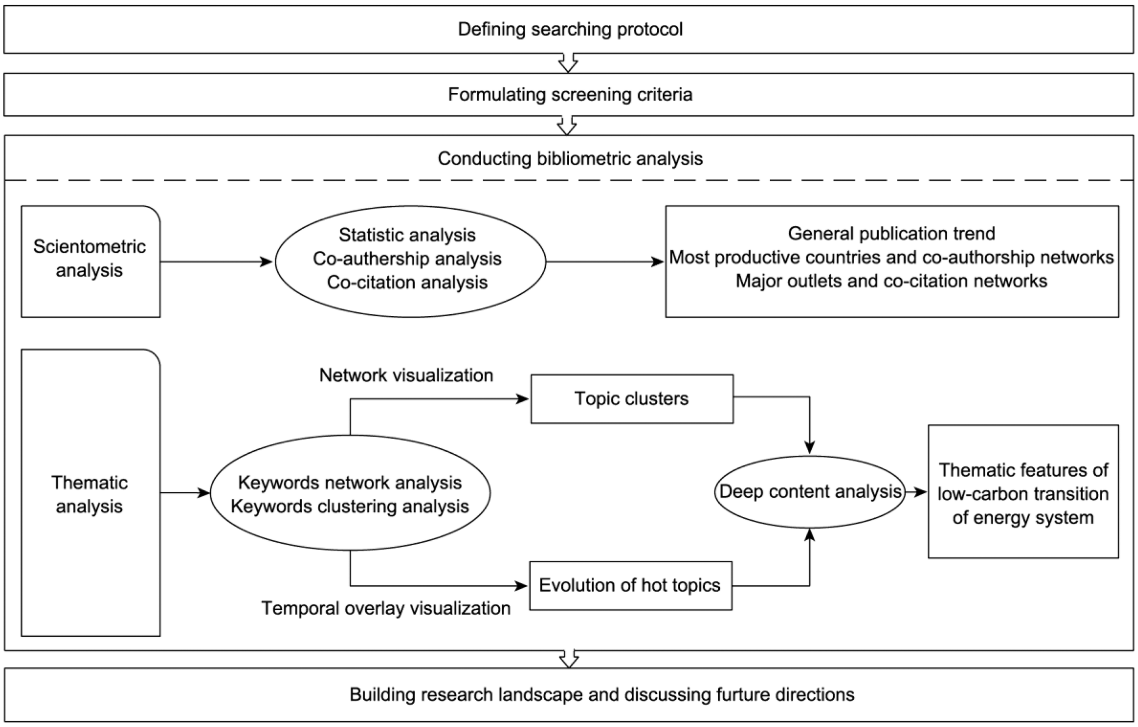

Fig. 1. Research procedure of the systematic review in this study.

descriptions of the sample selection, methodology processes, and underlying reasons for these choices are displayed in Section S1 of the Appendix A.

More specifically, this study uses a general definition of "energy systems" as systems that contain the processes of energy circulation (e.g., exploitation, production, storage, transmission, final usage, and end-of-pipe disposal) for all types of energy (including primary energy such as fossil fuels and renewables, and secondary energy such as electricity and heat) to achieve energy-related functions in human society. In addition, we define the "low-carbon transition of energy systems" as the change in the state of energy systems triggered by carbon emissions reduction targets, which includes transformation of the energy structure (e.g., by replacing fossil fuels with renewables), decarbonization of fossil fuel utilization (e.g., by applying low-carbon technologies such as carbon capture and storage), and improvement of energy efficiency (e.g., by enhancing operational efficiency during the whole process of energy utilization). All published studies relating to this topic from a management perspective serve as potential samples of this review study.

Through carefully designed searching and screening processes, we collected 5336 journal articles published from January 2012 to December 2021 from the Science Citation Index Expanded (SCIE) and Social Science Citation Index (SSCI) Core Collection of the WOS database. Of the collected papers, 166 were ESI highly cited papers. We then used a bibliometric analysis tool, VOSviewer, to analyze the scientometric and thematic features of the literature sample. Based on previous findings and a further deep content analysis, we constructed a comprehensive research landscape of management studies on the low-carbon transition of energy systems with our viewpoints embedded.

3. Scientometric features of the literature

3.1. General publication trend

Based on our sample, the total annual publications of management studies on the low-carbon transition of energy systems are shown in Fig. 2. It can be seen that the number of related publications has undergone exponential growth from 2012 to 2021, with a sharp upward trend since 2017. This phenomenon coincides with our intuition that practical needs drive academic effort in the low-carbon transition of energy systems. After the Paris Agreement came into force in 2016 and the first carbon-neutral act was proposed by Sweden in 2017, an increasing number of countries started to release carbon-neutral plans and ambitious emissions reduction targets. These governmental emphases have given rise to growing attention on the research field of low-carbon transition [32]. The sudden impact of the corona virus disease 2019 (COVID-19) pandemic interrupted past transition trends and introduced more challenges and problems to be solved. The pandemic may also have driven the burst of related studies during 2020 and 2021, by researchers seeking to reconstruct appropriate transition paths toward low-carbon energy systems in the post-pandemic era [33].

3.2. Most productive countries and co-authorship networks

According to our sample, a total of 117 countries contributed to research on the low-carbon transition of energy systems. By count-

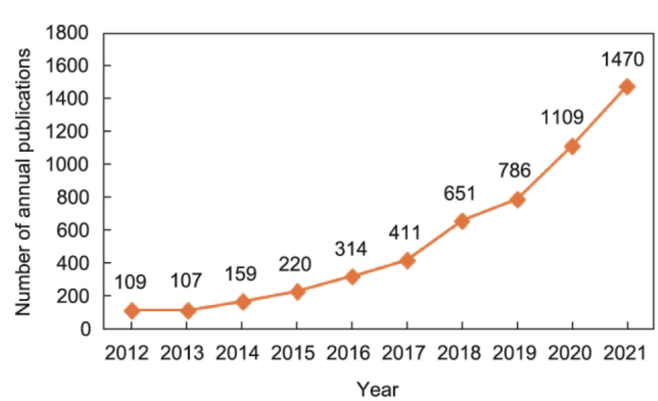

Fig. 2. Annual publication volume from 2012 to 2021.

ing occurrence frequency in the sample publications, the top 10 most productive countries were derived, as shown in Table 1. As illustrated in Section S2.1 in Appendix A, most publications in our sample have multiple authors, suggesting a cooperative trend in this research area. The number of authors per article follows a right-skewed distribution with a mode of 3. We count an article as the contribution of a certain country if it contains at least one author affiliated with this country. China—the most productive country in this field—accounts for 18.46% of the total, while the United Kingdom, the United States, Germany, and the Netherlands represent 15.63%, 15.35%, 12.82%, and 7.29%, respectively. In general, scholars from developed countries tend to pay more attention to the low-carbon transition of energy systems. Almost all countries in the top ten research productive list (as shown in Table 1) are members of the Group of 20 (G20), except Switzerland. This finding indicates that international organizations (e.g., G20 and the European Union (EU)) may help in focusing their members' attention on the global issue of energy decarbonization.

The co-authorship networks among countries were visualized using VOSviewer and are displayed in Fig. 3. As shown in Fig. 3 (a), four countries marked by different colors (i.e., China, the United Kingdom, the United States, and Spain) are recognized as the central nodes of different co-authorship clusters. Each cluster consists of a group of countries with intimate cooperative relationships. It can be seen that countries with close geographic locations tend to have more cooperation in this research area (e.g., the United Kingdom, Germany, and the Netherlands in the green cluster, and Chile, Brazil, and Mexico in the blue cluster). Scholars have also been trying to break spatial barriers to conduct cooperative studies on the low-carbon transition of energy systems (e.g., those in China and Australia). In addition to being the central nodes of clustered small networks, China, the United Kingdom, and the United States are bound to each other with strong links (reflected by the widths of lines between every two nodes). Aside from playing central roles in each of their own sub-networks, these three countries play critical roles in linking sub-networks to form a global cooperative network of studies on the low-carbon transition of energy systems. As shown in Fig. 3(b), the key nodes evolve from the United Kingdom to the United States and then shift to China. In addition, Chinese scholars show a tendency to build cooperative relationships with United Kingdom scholars from emerging new forces such as Pakistan, Vietnam, and Indonesia (as indicated by the yellow links). The changes in the country-level research networks indicate the influence of international relationships between countries.

3.3. Major outlets and co-citation networks

Through a statistical analysis of journals, we compiled the top ten journals with the most publications on the low-carbon transition of energy systems in our sample; these are shown in Table 2, with *Energy Policy*, *Energy Research & Social Science*, and *Applied Energy* taking the top three positions. It can be seen that this topic is popular in various fields, including energy engineering (with representative journals such as *Applied Energy*, *Energy*, and *Renewable Energy*), environmental science (with representative journals such as *Journal of Cleaner Production*, and *Sustainability*), and social science relating to energy issues (with representative journals such as *Energy Policy*, *Energy Research & Social Science*, and *Energy Strategy Review*). Within the 166 ESI highly cited papers in our sample, 27 are published in *Energy Policy*, followed by 16 in *Journal of Cleaner Production* and ten in *Applied Energy*. A list of the top ten highly cited articles is displayed in Table S2 in Appendix A. Overall, the interdisciplinarity of research targeting the low-carbon transition of energy systems provides opportunities for this topic to appear in various journals from different fields and to attract broad inter-

Table 1
Top ten most productive countries in related publications from 2012 to 2021.

Country	Percentage	Country	Percentage
China	18.46%	Italy	5.72%
UK	15.63%	Canada	5.42%
United States	15.35%	Spain	5.13%
Germany	12.82%	Australia	5.10%
Netherlands	7.29%	Switzerland	4.33%

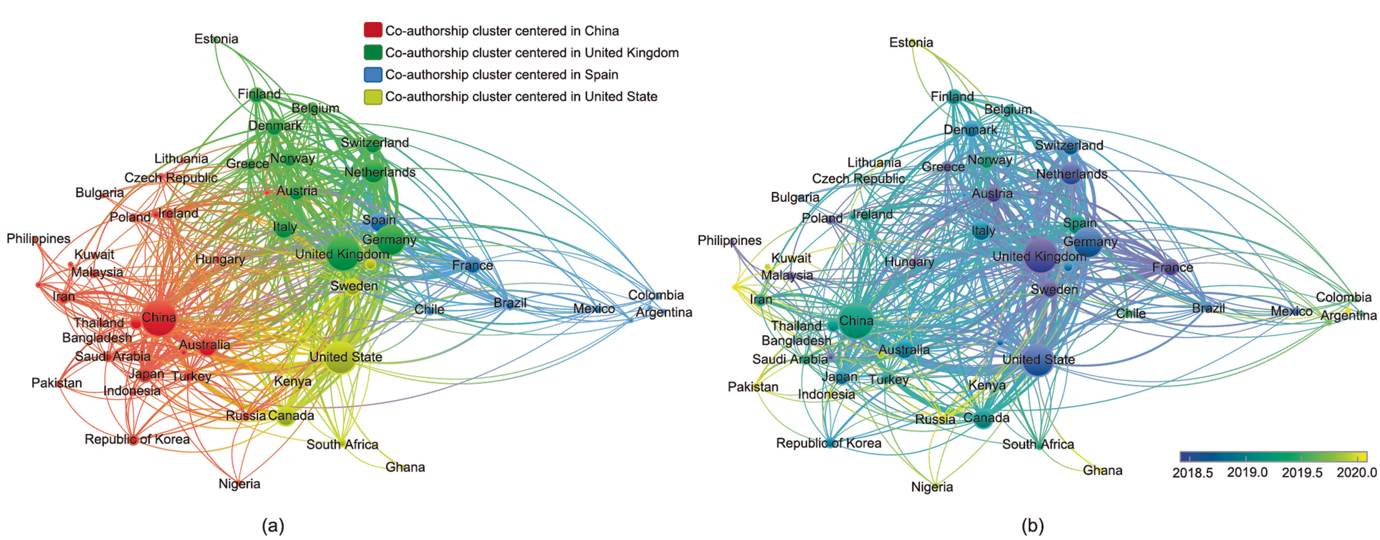

Fig. 3. Country-level co-authorship networks from 2012 to 2021. (a) Clusters of cooperative networks; (b) temporal evolution of the cooperative networks.

Table 2
Top ten journals with the most publications from 2012 to 2021.

Journal	Total no. of papers	ESI highly cited papers	Journal	Total no. of papers	ESI highly cited papers
Energy Policy	584	27	*Sustainability*	322	0
Energy Research & Social Science	479	0	*Energy Conversion and Management*	156	6
Applied Energy	453	10	*Renewable Energy*	141	1
Energy	368	9	*Renewable & Sustainable Energy Review*	134	4
Journal of Cleaner Production	334	16	*Energy Strategy Review*	107	2

est from different groups of people, including policymakers, engineering managers, and social scientists.

To better understand the similarity between and correlation of the journals cited in our literature sample, we mapped out the co-citation networks among these journals based on VOSviewer (Fig. S3 in Appendix A). Three clusters with varied research topics were identified, coinciding with our previous analysis of the sample publication outlets. Within the journal co-citation networks, *Energy Policy*, *Applied Energy*, and *Nature Climate Change* are the central nodes of each clustered sub-network. By looking into each cluster shown in Fig. S3, it can be inferred that journals in the red cluster mainly focus on social science topics relating to energy issues (with *Energy Policy*, *Energy Research & Social Science*, and *Resource Policy* being co-cited the most frequently), journals in the blue cluster mainly focus on energy engineering perspectives (with *Applied Energy*, *Energy*, and *Energy Conversion & Management* being co-cited the most frequently), and journals in the green cluster mainly focus on topics relating to environmental science (with *Nature Climate Change*, *Environmental Science & Technology*, and *Ecological Economics* being co-cited frequently).

4. Thematic features of the literature

In this section, the keywords co-occurrence network clustering methodology is applied to identify the major research topics related to the management studies of the low-carbon transition of energy systems. Fig. 4 shows the four thematic categories characterized by keywords in different colors, with red representing keywords related to the topic of the low-carbon transition pathway, blue representing keywords related to the topic of low-carbon technology diffusion, yellow representing keywords related to the topic of low-carbon infrastructure network planning, and green representing keywords related to the topic of transition-driving mechanisms. A subsequent deep content analysis was conducted by manually reviewing and analyzing the 166 ESI highly cited papers in the literature sample based on the thematic catego-

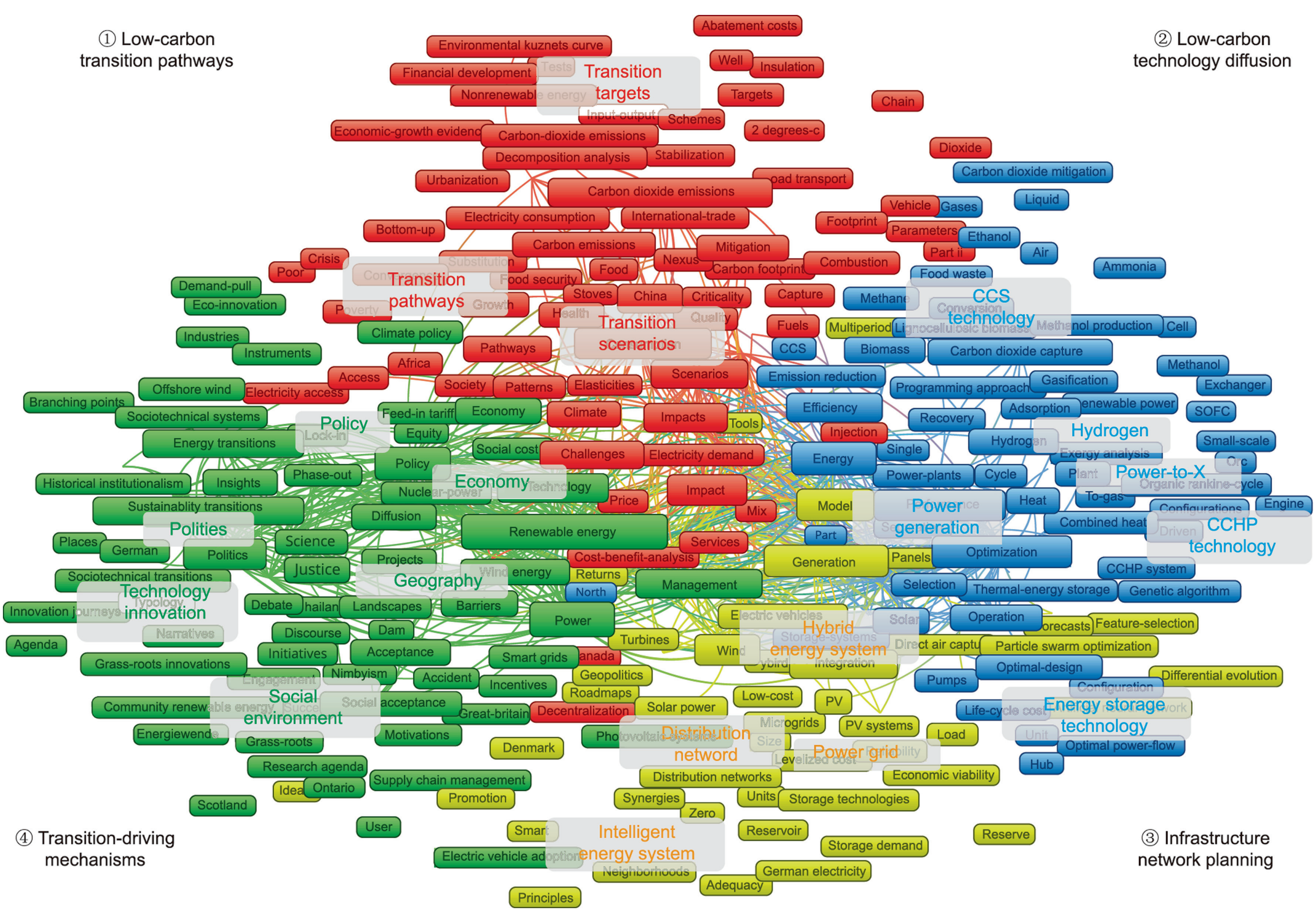

Fig. 4. Thematic networks of studies on the low-carbon transition of energy systems. CCS: carbon capture and storage. CCHP: combined cooling, heating and power. PV: photovoltaic.

rizations of the full sample. The evolution of hot topics in this field was also revealed through a temporal overlay visualization of the keywords network clustering. Detailed analyses are displayed in the following sub-sections.

4.1. Research on the low-carbon transition pathway

The low-carbon transition pathway plays an essential role in shaping future energy systems [34]. Through a deep content analysis of the ESI highly cited papers on low-carbon transition pathways in our literature sample, we find that scholars have focused on designing transition pathways that are contingent on various spatiotemporal scales and transition constraints. Fig. 5 shows a categorization of the prevailing factors considered in the studies of low-carbon transition pathways. In terms of spatial and temporal scales, transition pathways toward low-carbon energy systems have been studied at the city level [35], country level [36], regional union level [37], and global level [38], with short-term (e.g., 2030), mid-term (e.g., 2050), and long-term (e.g., 2100) projections. Regarding transition constraints considered in pathway designs, scholars have studied both internal and external constraints of energy systems. Internal constraints include energy categories [37], carbon emissions [39], and energy demands [40] within the energy system in focus, while external constraints include economic growth, governmental policy, and grassroots participation [41,42].

Target selection is an essential issue in transition pathway designs. In our literature sample, the targets of "100% renewable energy system," "net-zero carbon emissions," and "limiting global warming to 2 or 1.5 °C" were frequently used. However, different transition pathway designs may lead to distinct consequences, such as the efforts made and outcomes revealed, some of which may deviate from the original goals or even contradict each other [38]. To maintain a balance between different decarbonization goals, more comprehensive design studies will be needed for the low-carbon transition pathways of energy systems. Moreover, some of the transition scenarios used in simulation models (e.g., 100% renewable energy) are difficult to achieve in the near future, and thus contradict reality [37]. Scholars should pay more attention to the validity of models when designing low-carbon transition pathways of energy systems [38]. In addition, scholars have demonstrated that the uncertainties associated with low-carbon transition pathways are likely to trigger economic and environmental risks [39], as well as social problems such as energy injustice [43] and energy poverty [44]. Some scholars have proposed solutions to control transition risks, such as developing energy laws and policies, highlighting stakeholder responsibilities, and promoting sector coordination [45,46]. More research efforts will be needed to construct resilient transition pathways.

4.2. Research on low-carbon technology diffusion

Low-carbon technology utilization and diffusion are critical for driving the low-carbon transition of energy systems [47]. Upon reviewing the ESI highly cited papers associated with low-carbon technology diffusion in our literature sample, we find that scholars have mainly focused on renewable energy technologies, pollution control technologies, and other technologies facilitating the energy transition. Fig. 6 illustrates some specific technologies frequently studied in our sample literature. In regard to renewable energy utilization, scholars have focused on generation technologies and storage technologies. Solar and wind energies are the most common renewable energies studied in the literature and have also been recognized as the most promising renewable technologies to achieve mass utilization in the near future [48,49]. Effective storage technologies (e.g., hydrogen storage and battery storage) have been recognized as essential support for the massive utilization of renewables [50,51]. As for pollution control technologies, various types of carbon capture and storage (CCS) [52] and green production technologies (e.g., combined heat and power technology [53] and green desalination technology [54]) have been studied. Regarding other technologies facilitating the energy transition, scholars have shown that developing critical metal technologies [55] and information and communication technology [56] can significantly support the diffusion of low-carbon technologies.

On the other hand, it has been found that some previously popular technologies (e.g., biogas technologies [57] and nuclear technologies [58]) might not match the growing requirements for the low-carbon transition of energy systems, which requires careful evaluation studies of the underlying technologies. Furthermore,

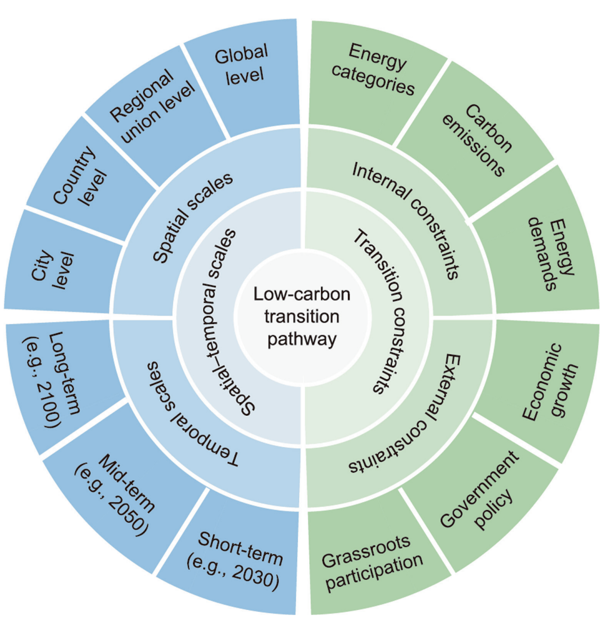

Fig. 5. Factors considered in studies on the low-carbon transition pathway.

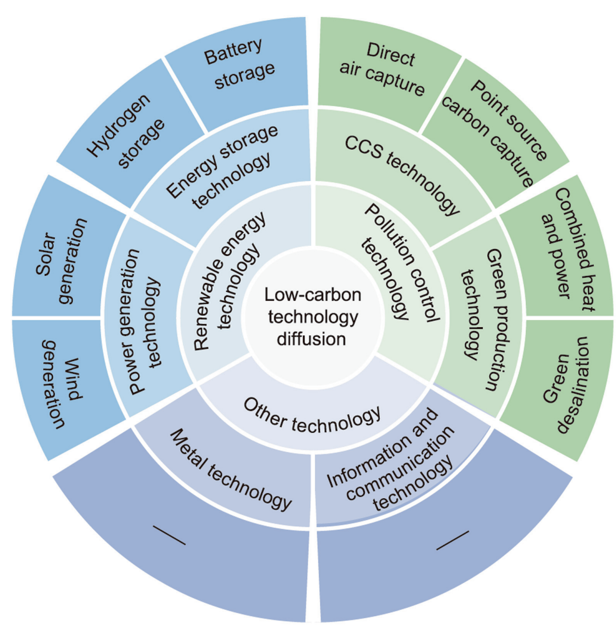

Fig. 6. Prevailing low-carbon technologies studied in the literature. CCS: carbon capture and storage.

the increasing installation of renewable power plants is characterized by unstable production and intermittency [59], which may cause severe damage to the power grid's reliability and stability [48,49]. Thus, it is essential to put more effort into researching multi-energy complement systems with the incorporation of energy storage technologies. In addition, scholars have demonstrated that renewable energies cannot entirely replace fossil fuels in the short term [59]. Thus, co-existing models of emerging renewables and traditional fossil fuels are desperately needed for the low-carbon transition process of energy systems. Moreover, it is challenging to promote low-carbon transition in carbon-intensive sectors due to high costs [47]. Additional research should be put into low-carbon technologies in the carbon-intensified transportation and manufacturing sectors that have not been well studied at the current stage.

4.3. Research on low-carbon infrastructure network planning

The low-carbon infrastructure network is fundamental for supporting the diffusion of low-carbon technology and the transition of energy systems. Reviewing relevant ESI highly cited papers showed that scholars mainly focus on the network planning of electricity and integrated energy systems. Fig. 7 illustrates the research focuses of the studies on low-carbon infrastructure network planning in our literature sample. In terms of the electricity network, both power generation infrastructure and power distribution network have been studied, with particular interest in photovoltaic generation infrastructure and the power grid. Environmental conditions and generation potential are frequently considered factors in the location and capacity decision models of power plant deployment [60], while efficiency [61], reliability [62], and flexibility [63] are major principles for designing the power grid. In terms of the integrated energy system (which is often a connected system with mixed energies), the forms of combined electricity, heat, and cooling systems are frequently studied [64,65]. Scholars have also studied both on-grid and off-grid integrated energy systems. The former refers to energy systems that are connected to external energy systems; such systems have been studied on different scales, such as buildings [66], communities [67], and regions [64]. The latter refers to stand-alone energy systems without access to external energy systems, which have gained attention for remote areas such as deserts [65] and islands [68].

In addition to the basic principles (e.g., efficiency, reliability, and flexibility) and conditions (e.g., local resource potential) considered in the existing literature, scholars have been calling for attention to many other vital issues, such as energy poverty and injustices associated with energy network planning [69]. Furthermore, scholars have noticed the heavy financial burdens placed on governments by energy infrastructure deployment [70]—an issue that calls for more research on encouraging nongovernmental investments into low-carbon energy network construction and improving cost efficiency for infrastructure deployment. Effective policy designs and coordination among various stakeholders will be essential to achieve such goals. From a methodology perspective, the accuracy of past network planning models for electricity systems has been challenged by the uncertainties caused by intermittent renewable energies connecting to the power grid on a growing scale [70]. More adaptive algorithms for predicting and optimizing power grids are necessary. Moreover, constructive novel designs remain to be developed for integrated energy systems that combine multiple energy sources with higher efficiency, stronger robustness, and lower cost [68].

4.4. Research on low-carbon transition driving mechanisms

The mechanisms driving the low-carbon transition of energy systems comprise a cutting-edge field in the literature. The related ESI highly cited papers discuss various political, economic, social, and natural factors, along with their synthetical mechanisms (Fig. 8). Scholars taking a political perspective have studied the influences of national policies and international politics on the decarbonization of energy systems. The former includes energy innovation policies [71] and energy democratic policies [72], while the latter includes the factors of geopolitics [73], regional unions [74], and rising powers [75]. Related research from an economic perspective has demonstrated that investment and financing [76,77], market mechanisms (e.g., peer-to-peer energy trading

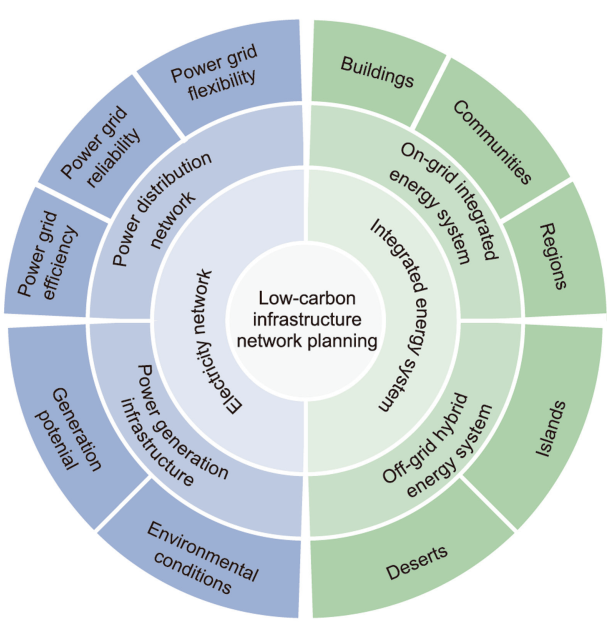

Fig. 7. The research focuses of studies on low-carbon infrastructure network planning.

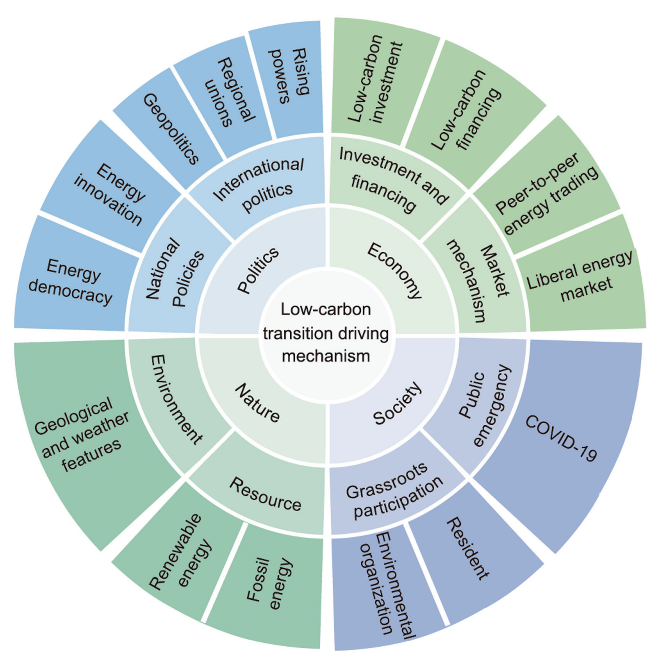

Fig. 8. Factors mentioned in studies of low-carbon transition driving mechanisms.

[78] and a liberal energy market [79]), and the circular economy model [80] could have great impacts on energy transitions. From a social perspective, grassroots participation and public emergency have been recognized as key influential factors for accomplishing energy transition goals. For example, public engagement [81] and environmental organizations [82] have played significant roles in promoting the decarbonization of energy systems, while the impact of the COVID-19 pandemic slowed down such transitions [83]. From a natural environment perspective, spatiotemporal energy resource endowments (both fossil fuels and renewable energy resources) and environmental factors (e.g., geological and weather features) are crucial prerequisites for building low-carbon energy systems [84,85].

Although the topics investigated by the studies reviewed here have been broadly and comprehensively investigated, some of the assumptions made by these studies may deviate from practice and fall short of reflecting the complexity and dynamics of reality [77,86]. Therefore, scholars should attempt to capture the characteristics of practical energy systems and to better evaluate the role of each driving factor in the transition toward low-carbon energy systems. Diversification of supporting policies should be well studied and implemented in order to control risks and protect vulnerable entities such as indigenous environmental defenders [87,88]. When designing a policy mix (which has been claimed to be more efficient than a single policy [86]), scholars must consider the consistency, coherence, and credibility of the underlying policy tools. The uncertainties of public behaviors and their potential impacts on the low-carbon transition of energy systems must also be considered [81]. In addition, the synthetical mechanisms of various factors require more in-depth studies, which may cover the interactive effects of different factors [89] and the synthetics of multiple systems, including technological, economic, societal, political, and environmental systems [90]. It is notable that the COVID-19 pandemic has brought short-run interruptions to energy systems and has significantly influenced the energy transition process [33]. The long-term impacts of the COVID-19 pandemic on the low-carbon transition of energy systems remain to be revealed in the post-pandemic era.

4.5. Evolution of hot topics

To reveal the evolution of hot topics related to the low-carbon transition of energy systems during the last decade, we displayed a temporal overlay visualization of keywords based on the VOSviewer software, which is shown in Fig. 9. The time horizon is divided into three stages, as reflected by colors that gradually change from dark blue to yellow. In stage one, as shown in the upper-right dark blue circle of Fig. 9, keywords such as "reduction," "conservation," "CCS," "scenarios," and "targets" were frequently mentioned. This indicates that scholars mainly focused on emissions reduction, energy conservation, and low-carbon transition pathway studies during this period. In stage two, keywords including "renewable energy," "power," "solar," "wind," "hydrogen," "policy," and "management" became the prevailing terms—most of which are positioned at the center of the visualization and support the main body of the keywords network. During this period, the electrification of energy systems was in the spotlight [91], with solar energy [48], wind energy [49], and hydrogen energy [50] gaining increasing attention. Scholars began to pay more attention

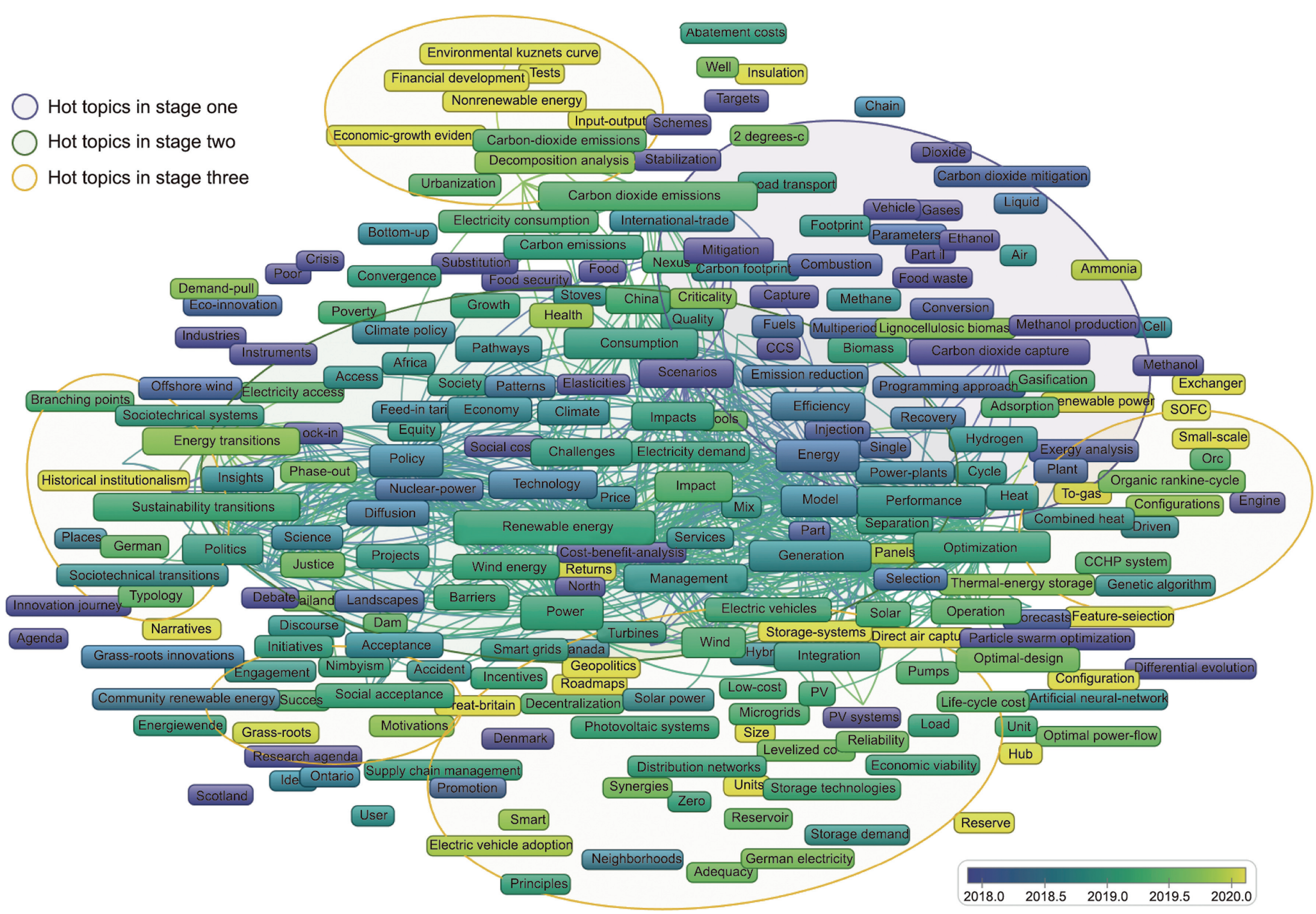

Fig. 9. The evolution of hot topics relating to the low-carbon transition of energy systems.

to the driving mechanisms of low-carbon transitions (e.g., low-carbon investment behaviors [77]), which are recognized as critical in facilitating efficient, reliable, sustainable, and appropriate energy transitions. In stage three, keywords such as "storage systems," "small-scale," "smart," "geopolitics," and "grassroots" frequently appeared, as shown at the edge of Fig. 9, expanding the research framework formed in stage two. The research stream tends to focus on studying energy storage systems [51], innovative applications of smart technologies in energy systems [92], and new business models such as distributed renewable energy with small scales. More stakeholders (e.g., grassroots), potential conflicts, and risks associated with the energy transition are gaining increased attention from academics.

5. Discussions

5.1. The research landscape for the low-carbon transition of energy systems

According to our analysis of the existing literature, research on the low-carbon transition of energy systems has been increasing rapidly in the last decade, with China, the UK, and the United States playing leading roles in this field. The interdisciplinarity of studies on the low-carbon transition of energy systems has brought together scholars from various fields, including energy engineering, environmental science, and social sciences, creating publications in academic journals within different domains. With the increasing practical need to foster the low-carbon transition of energy systems, it is plausible that a continually increasing number of scholars from various regions and academic disciplines will be drawn into studying the low-carbon transition of energy systems. Effective and efficient cooperation will be key in creating valuable and practical knowledge in this field. Building cooperative relationships between scholars from developed and developing countries can be mutually beneficial, enabling scholars from developing countries to learn from the experience of developed countries and scholars from developed countries to test theories in broader contexts. In particular, it would be beneficial for researchers to cooperate with scholars from China, the UK, and the United States on studying the low-carbon transition of energy systems, as these three countries have been playing central and leading roles in this field.

By means of keywords clustering of the literature sample and a deep content analysis of the ESI highly cited papers, we identified four major research topics in the reviewed studies: the low-carbon transition pathways, low-carbon technology diffusion, low-carbon infrastructure network planning, and low-carbon transition driving mechanisms. These four clusters of studies play distinct but mutually supportive roles, as illustrated in Fig. 10. More specifically, studying low-carbon transition pathways with different spatiotemporal scales and transition constraints provides plans to achieve transition goals toward low-carbon energy systems. Such plans can guide the deployment of low-carbon technologies and infrastructure networks by formulating targets, guidelines, and actions. Conversely, low-carbon technology diffusion and infrastructure network planning are two decisive aspects that support the accomplishment of low-carbon transition pathway designs. Low-carbon infrastructure networks also play a fundamental role in promoting the diffusion of low-carbon technologies. Finally, the catalytic or obstructive effects of various factors from political, economic, societal, and natural systems—as well as their individual and synthetic driving mechanisms for the low-carbon transition of energy systems—should be well studied and considered in the studies within the other three thematic clusters. Taken together, these four clusters of studies form a full image of the research landscape for the low-carbon transition of energy systems. Scholars with different skills supporting the studies of these four topics are encouraged to work together to co-produce systematic research facilitating low-carbon transition goals.

5.2. Potential research topics in the future

Based on our analysis of the thematic evolution of studies on the low-carbon transition of energy systems, several keywords were recognized as emerging hotspots, including "business model," "nongovernment actor," "energy justice," "deep decarbonization," and "zero-energy building." These recognized hotspots reflect the challenges presented by current low-carbon transition practices in energy systems. First, as the low-carbon transition of energy systems often builds on new technologies and emerging industries, it may bring challenges to traditional business models. Therefore, innovation in business models is essential for facilitating the low-carbon transition—a topic that is becoming attractive to researchers. Second, the low-carbon transition of energy systems is a complex form of system engineering, which cannot be accomplished by a single force such as a government alone. Studies on nongovernment actors and interactions among various stakeholders are gaining increased attention in this field, particularly regarding grassroots participation and the public's energy consumption

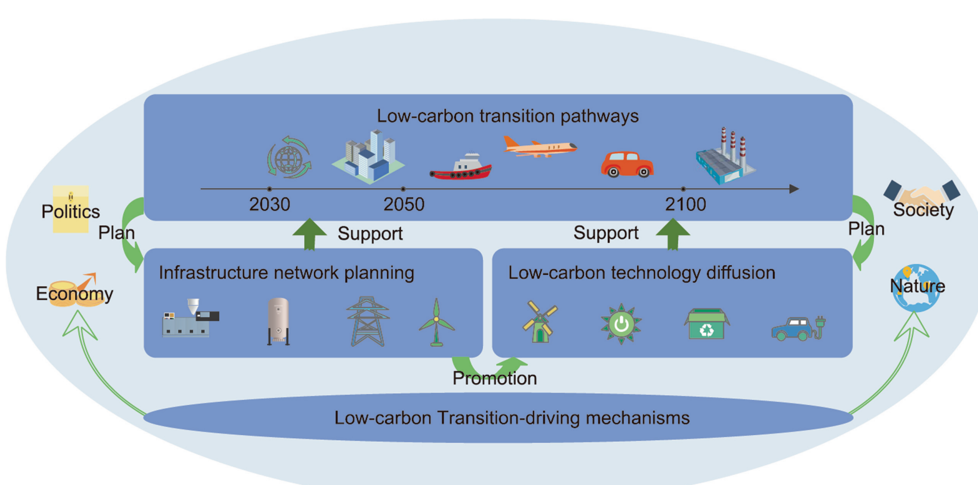

Fig. 10. The research landscape for the low-carbon transition of energy systems.

behaviors. Third, the social impacts of the energy transition have received a great deal of attention in recent years, driving scholars to focus on associated social issues such as energy injustice and energy poverty. It can be foreseen that more efforts will be put into this research direction, as the transition of energy systems is likely to trigger multiple changes in human society. Finally, with the growing severity of climate change and the increasing need to control carbon emissions, more ambitious low-carbon transition targets and technologies are entering the spotlight, such as deep decarbonization and zero-energy building.

In addition, we propose several in-depth research directions for future studies on the low-carbon transition of energy systems based on our previous thematic and deep content analysis. In terms of low-carbon transition pathway designs, more comprehensive studies should be developed on balancing different decarbonization goals. Moreover, low-carbon transition risks should be well controlled, and more resilient transition paths should be designed. In terms of low-carbon technology diffusion, the deployment of several low-carbon technologies should be further promoted, especially regarding multi-energy complementary systems that integrate advanced energy storage technologies and smart energy systems. In terms of low-carbon infrastructure network planning, more advanced methodologies should be developed to incorporate more essential factors for achieving broad goals, including efficiency, reliability, and flexibility. Cost and benefit analyses play important roles in such planning, as infrastructure construction usually requires huge setup investment and has long-term impacts. In terms of low-carbon transition driving mechanisms, future research should put more effort into capturing the practical characteristics of various influential factors and analyzing their interactive effects and synthetic mechanisms.

In regard to studies in a Chinese context, several related research topics are at the forefront. First, due to the increasing uncertainties driven by the COVID-19 pandemic and international relationships, the Chinese government and scholars have been emphasizing the importance of risk management. It has become a central task among Chinese scholars to study how to cope with the risks associated with the energy transition and how to design more resilient transition pathways toward low-carbon energy systems. Second, Chinese scholars have been consistently developing policy tools to promote the low-carbon transition of energy systems. At the current stage, scholars are particularly interested in the emissions trading scheme (ETS), as the national ETS has been established and implemented since 2021. Topics such as the industries covered by the ETS, emissions quota allocation rules, and carbon pricing mechanisms are of great interest. Third, China's resource endowment and historical energy structure present significant challenges in replacing fossil fuels, especially in regard to coal. Chinese scholars will need to come up with solutions to support the smooth exiting of fossil fuels and to cope with potential economic and social turbulence [93].

6. Conclusion

This paper presents a bibliometric review of studies on the low-carbon transition of energy systems from an engineering management perspective. The scientometric features of the 5336 selected publications were analyzed with the assistance of VOSviewer, including the general publication trend, regional characteristics of authorships, and co-citation networks of journals. The thematic features of the sample studies were revealed by means of a keywords clustering analysis of the whole sample and a deep content analysis of the 166 ESI highly cited papers. Through this study, a research landscape of the field under focus was constructed, and the evolution of hot topics and potential future directions within this field were discussed.

Our review study finds that the number of related publications has undergone rapid growth during the past decade, with most authors coming from China, the United Kingdom, the United States, Germany, and the Netherlands. These studies were published in diverse journals covering energy engineering, environmental science, and energy social science issues. Four major research themes were identified: the low-carbon transition pathway, low-carbon technology diffusion, infrastructure network planning, and transition-driving mechanisms. All four topics play distinct yet mutually supportive roles in facilitating the low-carbon transition of energy systems. Furthermore, business models, nongovernment actors, energy justice, deep decarbonization, and zero-energy buildings were observed to be hot topics. Energy security, economic burden, and social risks during the low-carbon transition process are gaining increasing attention. In addition, the coordination of various decarbonization goals, resilience in low-carbon transition pathways, efficiency in low-carbon technology and infrastructure network deployments, and the control of multi-level transition risks require more in-depth studies in the near future. Driven by practical needs, the research field of energy transition management has been undergoing continuous expansion. More timely reviews from different angles would be essential for recognizing frontier topics and building systematic knowledge that can guide both research and practice.

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Compliance with ethics guidelines

Peng Zhou, Yue Lv, and Wen Wen declare that they have no conflict of interest or financial conflicts to disclose.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2022.11.010.

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