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COMMENTS

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Energy transition management towards a low-carbon world

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1 Introduction

The challenge of climate change has led to the worldwide growing trends in developing a low-carbon, clean, and high-efficiency energy system, which is a significant pathway to safeguard energy security and achieve sustainable development goals (Zhou et al., 2022). To respond to calls for the energy system's transformation, governments have ambitiously implemented various incentive policies by considering the specific circumstances in human energy services and activities (Ding et al., 2020). Despite the world having made notable progress in low-carbon energy transition, it faces numerous challenges, such as the surging energy demand, lack of renewable technology, and imperfect transition management system (Strunz, 2018; Davidson, 2019). Any of these challenges would impede the transformation of energy structure and intervene the government regulation in new market design and global warming mitigation, resulting in slowing down the pace of energy transition (Sachs et al., 2019). Therefore, optimizing the transition management, as well as identifying its critical drivers towards a low-carbon world, has paramount importance (Chofreh et al., 2021). This study aims to review the existing research and put forward the research frontiers on energy transition management to provide a cutting-edge perspective as well as practical guidance on management optimization. Figure 1 shows the general framework of energy transition management.

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2 Energy transition: Concepts and goals

In response to the hit posed by the oil crisis, the German Institute for Applied Ecology initiated the concept of energy transition in the 1980s, aimed at transforming the energy system from fossil fuel-dominated energy resources to renewable-dominated energy resources. Although the goal of energy transition diversifies worldwide with the global society attaching great importance to climate change mitigation, a clean and low-carbon world becomes the common prospect (Zhou et al., 2021). For instance, Carley and Konisky (2020) defined the modern energy transition as a decline in fossil fuel energy, shifting to lower-carbon energy sources, such as wind, solar, and natural gas. Some other scholars suggested that the goal of the energy transition is strongly reliant on clean energy resources, in which traditional energies are entirely replaced by renewable energies (Connolly et al., 2016), whereas phasing out fossil fuels is unlikely. Therefore, the concept of energy transition towards a low-carbon world is prevailing, that is, decarbonizing fossil fuel energy in parallel to the development of clean energy (Sachs et al., 2019). With the energy transition defined as the change in the state of the entire energy system on multidimensions but not a single change in the individual energy sector (Grubler et al., 2016), the concept of a transition to low-carbon energy systems on behalf of the energy transition has emerged. More specifically, the energy transition is more about system decarbonization, including energy production, storage, transportation, and final consumption, showing the transformation of multi-system (e.g., dominant energy sources, technologies, and regimes).

The goals of energy transition are mainly summarized from two perspectives. First, low-carbon energy sources have to reach a certain proportion in the energy structure. For instance, Smil (2010) suggested that the goal of the energy transition is that new fuel takes a 25% share of the

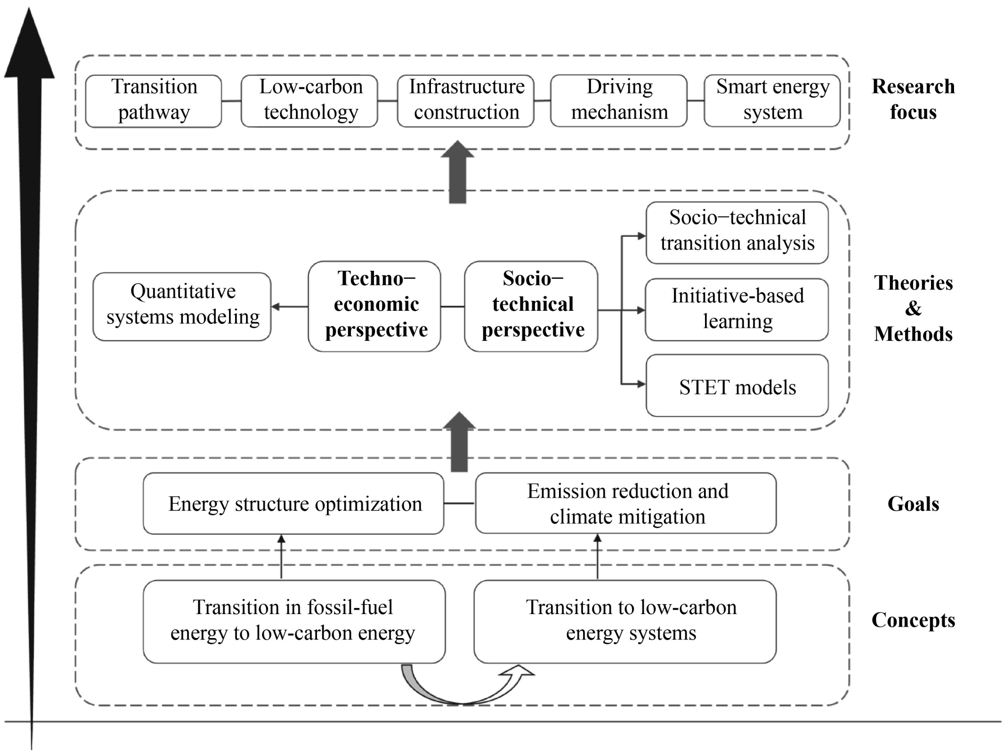

Fig. 1 The framework of energy transition management.

global market. Grubler (2012) proposed that the phase of energy transition refers to the consumption of primary energy sources, such as renewables, nuclear, natural gas, and hydropower, reaching 50% of the global market share. Moreover, Fouquet (2016) presented energy transition's success with renewable consumption taking an 80% share of total energy consumption in particular sectors (e.g., heating, electricity, transportation, and lighting). In addition, some scholars put forward the topic of "100% renewable" on energy transition and power system transition (Connolly et al., 2016). Second, carbon emission reduction and climate mitigation are considered the final goals of the energy transition. With the ambition of limiting global warming to 1.5°C proposed by the IPCC (Intergovernmental Panel on Climate Change), some scholars suggest that the goal of the energy transition is that CO_2 emission in 2030 should be 45% lower than that in 2010 and reaching global net-zero CO_2 emissions around 2050. While under the 2°C scenario, global CO_2 emission should fall by 75% from today's levels in 2030 and global net-zero CO_2 emissions should be achieved around 2070 (Kikstra et al., 2021).

3 Theories and methods for energy transition management

Despite the proliferation of transition theories and analytical methods being well discussed, we briefly review the mainstream theories and related methods from two perspectives: Techno–economic and socio–technical perspectives.

The techno–economic perspective focuses on the transformation of energy flows and distribution (market, services, production, and consumption), which is mainly explained by the relevant economic theories. Representatively, many analyses have been guided by the theories of (neoclassical) environmental economics to explain the changes in the techno–economic system, including but not limited to the market equilibrium, supply–demand balance, and environmental innovation (Smith et al., 2010). In addition, the insights from ecological economics, behavior economics, evolutionary economics, and economic history that go beyond neoclassical economics are discussed to understand the long-term evolution of energy systems, such as cost-optimization. For instance, Grubb et al. (2015) suggested that the Three Domain structure of energy transition, namely, "satisficing", "optimizing", and "transforming", is rooted in three domains of economics: Behavioral, neoclassical, and evolutionary economics, respectively. In addition, economic history has been incorporated into the analysis of a theoretical framework for energy transition, which blends the history macro-economic perspective with the actor-based micro-economic perspective as well as integrates energy transition into a more comprehensive roadmap of economic change (Grubler, 2012).

Quantitative systems modeling, a broad term referring to various quantitative models which root in economic theories, is most commonly used from the techno–economic perspective (Turnheim et al., 2015). Approaches among the quantitative system modeling, such as the Integrated Assessment Model (IAM), scenario analysis, system dynamics, Long-range Energy Alternative Planning (LEAP), Computable General Equilibrium (CGE), and Market Allocation (MARKAL) models (Fishbone and Abilock, 1981; Lofgren et al., 2002; Emodi et al., 2017; Cherp et al., 2018), are used to provide the forward-looking perspective in long-term changes of the energy transition, that is, simulating future transition pathways and optimizing quantitative variables (e.g., economic cost, crop yields, and benefit distribution). In particular, quantitative models can be distinguished as top-down and bottom-up models, in which the former focuses on a more economic-wide perspective and the latter emphasizes a more technical-detail perspective (Böhringer and Rutherford, 2008).

The socio–technical perspective focuses on the transformation of technology innovation and promotion, the studies of which are mainly rooted in sociology and history of technology, science and technology studies (STS), and evolutionary economics (Cherp et al., 2018). Geels (2002) proposed the Multi-level Perspective (MLP), which is the most influential framework among the socio–technical analyses of the low-carbon energy transition. He believes that the energy transition is the nonlinear process of change from one social–technical regime to another, resulting from the interaction of multiple levels: Landscape, regime, and niches. That is, changes at the landscape level create pressure on the regime while bringing opportunities to niches; the growth of niches further destabilizes the regime, as well as promotes niche innovations and regime reformation (Geels and Schot, 2007). Jacobsson and Johnson (2000) introduced the Technological Innovation Systems (TIS) to analyze low-carbon energy transition, which comprises the elements of actor and their competence, networks, and institutions. Results have shown that the TIS theory is appropriate to the research on competition between various ways of energy supply. Another important framework, Strategic Niche Management (SNM), focuses on fostering innovative niches to facilitate technological innovations (Geels and Schot, 2007). Transition Management (TM) is also one of the theoretical frameworks in transition studies; it suggests four different types of governance activities that are policy-oriented for the decision-makers: Strategic activities, tactical activities, operational activities, and reflexive activities (Loorbach and Rotmans, 2010).

Socio–technical transition analysis and initiative-based learning are the two mainstream approaches adopted in the socio–technical perspective, in which the former focuses on monitoring the changes and interplays of multidimensions in a socio–technical system, and the latter focuses on understanding the motives and expectations of actors (Turnheim et al., 2015). In particular, descriptive methods are mainly used, including but not limited to qualitative case studies. Moreover, despite the quantitative system modeling approach restricting their application range in techno–economic studies, scholars argue that quantitative models should incorporate the socio–technical insights beyond the techno–economic factors, such as socio–technical energy transition (STET) models (Li et al., 2015). Specifically, the STET models are combined by three domains: Techno–economic detail, explicit actor heterogeneity, and transition pathway dynamics, which have been applied to the fields of energy supply, transportation, and buildings, such as the Behavior Lifestyles and Uncertainty Energy model with Multi-level Perspective on transitions (BLUE-MLP) (Trutnevyte et al., 2014), Chappin's Power Sector Agent-based Model (ABM) (Chappin and Dijkema, 2009), and Complex Adaptive Systems, Cognitive Agents, and Distributed Energy (CASCADE) model (Li et al., 2015).

4 Research focus and trends

In general, the recent research on energy transition management is dominated by four fields: Transition pathways towards the low-carbon energy system at different levels, low-carbon technology adoption and promotion, supporting infrastructure and pipeline construction, and driving mechanism towards the energy transition. Our review and outlook of the said research focus are as follows.

(1) Transition pathway towards the low-carbon energy system

Existing research has focused on the energy efficiency improvement, structure optimization, and end-of-pipe treatment, studying the changes in specific indicators (e.g., energy intensity, renewables share, and carbon intensity) at multilevel perspectives (e.g., countries, regions, and industries). Subsequently, particular attention has been gradually provided to analyzing the selection of specific technical pathways; the research methods include the integrated assessment model, decomposition method, optimization model, scenario analysis, and system simulation (Liu and Mancarella, 2016; Cherp et al., 2018). Therefore, considering the heterogeneity of different regions and industries (e.g., resource endowment, energy demand, and socioeconomic factors) parallel to designing an appropriate pathway for low-carbon energy transition should be further investigated.

(2) Low-carbon technology adoption and promotion

The success of low-carbon energy transition mainly depends on the widespread adoption of low-carbon technologies, such as clean energy technologies (e.g., wind, solar, hydrogen, and nuclear), carbon capture and storage

(CCS) technology, energy efficiency improvement technology, and new vehicles. Scholars have paid great attention to those technologies worldwide, particularly hydrogen technology, by analyzing their application mode, business model, diffusion pattern, barriers, incentives, and promotion policies. In addition, the research is performed at the country and the city levels (Che et al., 2022), which may yield more insightful policy or management implications for the energy transition. Several new technical industries have emerged with the promotion of innovative energy technologies (e.g., electric vehicles, energy storage systems, and smart grids). Therefore, the interaction between industrial development and low-carbon technologies can be regarded as a research hotspot with further investigation.

(3) Supporting infrastructure and pipeline construction

Supporting infrastructures, such as transmission and distribution networks, oil and gas pipelines, energy storage devices, and charging stations, are inevitable for an effective energy system. The energy transition requires not only the improvement of infrastructure and pipeline deployment (e.g., the integrated grids of "electricity–heat–gas" and reliability improvements of renewable grid connection), but also the construction of support infrastructure in new energy industries (e.g., electric vehicles charging stations and hydrogen fueling stations). Therefore, constructing an integrated network planning model and finding a practical solution by accurately evaluating the parameter range become the research frontiers in this field.

(4) Driving mechanism towards the energy transition

It is of great significance to study the driving mechanism of such a transition since the actual energy transition process can be affected by different drivers (e.g., policies, markets, society, and resources). In recent years, scholars have employed not only the empirical analysis to evaluate the impact of the specific driver on the energy transition with observational data, but also the modeling analysis to study the potential effects of different drivers with theoretical research. Therefore, recognizing the different effects of different drivers and their multi-interactions would be a breakthrough in this field.

5 Conclusions

Energy transition is an inevitable process to achieve the ambitious goal of global sustainable development, so that the research on energy transition management and its driving mechanism play crucial roles (Chofreh et al., 2021). This paper presents some enlightening thoughts on the research of energy transition management, which help people understand the research frontiers and challenges. Looking into the future, prospective studies should be carried out to assess the potential interaction between energy and other sectors (e.g., technology, economics, society, and nature), considering the heterogeneity of regions and industries. Meanwhile, designing the practical pathway of the energy transition is also a long-term challenge faced by energy transition management. Lastly, synergizing the energy transition with the revolution of information technology to build a reliable and smart energy system is also worth investigating.

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