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Review on the Evolution of Socio Technological Systems and Their Applications in Energy Systems from a Multilevel Perspective

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Abstract

As a typical social technological system, this article focuses on the historical evolution and basic principles of the multi-level perspective of the social technological system, as well as its application research in the domestic energy field. It attempts to identify the obstacles to China's energy transformation and seek an energy transformation path that conforms to China's characteristics.

Keywords: *social technological system; Multi-level perspective; Energy transformation; Research Review*

Introduction

Nothing is and cannot exist in isolation, and it is in a certain connection with other things, which is either close or sparse, and so is the social technological system. Overall, the socio-technological system is composed of human actors, artifacts, social systems, and technological systems. Since artifacts can be seen as the output of human actors in the social and technological systems, changes in the socio-technological system are the result of human actors (individuals, groups, or organizations) interacting in the evolution of the social and technological systems.

Things are not only universally connected, but also dynamic, meaning that nothing is and cannot be stationary, and they are all in their own motion trajectory or in the trajectory that affects other things. This influence is either strong or mild, and the emergence of new technologies or systems is no exception. Social-technological transition refers to the transition from one social-technological system to another, resulting in a new social-technological system, which in turn promotes social and technological development and even human development. In addition, the three levels of the multi-level perspective analysis framework are also dynamic, and the innovation niche, existing systems, and external environment also interact and influence each other, and this framework is not unified or static.

In view of this, this article takes a connected, dynamic, and developmental perspective to examine the changing process of social technological system transition from three levels of a multi-level analysis framework.

1. The Evolution of multi-level perspective

The theory of social technological transformation was initially proposed by Ren é Kemp in 1994. He acknowledged the importance of shared engineering beliefs and expectations in the direction of technological change, and emphasized the socio-economic dimension in the stability of technological institutions, elucidating the process of transformation from one technological system to another [1]. After this, the theory of social technological transformation has developed into a core conceptual analysis framework, which mainly includes multi-level perspectives (MLP), strategic niche management (SNM), technological system innovation (TIS), and transformation management (TM). These four are interrelated but distinct, with different focuses. However, in terms of MLP, it emphasizes the interaction of innovation niches, social technological systems, and external environment at three levels, And the other three only involve one or two levels [2].

As the main tool for analyzing the transformation of social technological systems, MLP's development process is highly consistent with the development of social technological transformation theory. In 2002, Frank Geels integrated relevant literature on the transformation of social technology systems and proposed the MLP analysis framework to understand the complex dynamics of social technology changes. Subsequently, in 2005, he enriched the theoretical foundation of MLP and proposed six shortcomings of the MLP analysis framework in explaining the process of social and technological transformation, namely: the concept of technological institutions is not broad enough to understand the dynamics in social and technological systems; The analysis of the system is not comprehensive enough; There is no clear process of technological substitution; The diffusion process from innovation niche level to institutional transfer is unclear; The bold arrow in the legend represents a promising new technology or thing, but in reality, system innovation is generated by the interaction between multiple technologies; There are still shortcomings in terms of mode and mechanism. However, in his book "Technical Transitions and System Innovations", Frank Geels supplemented and solved the first three problems, and discussed the latter three problems through examples of sailboats steamships, carriages cars, and piston engine aircraft jet planes [3].

The MLP analysis framework has received many criticisms in explaining social technological transformation, but Frank Geels published "Ontologies, social technological transitions (to sustainability), and the multi-level perspective" in 2010, discussing seven social science ontologies' assumptions about agency and causal mechanisms, as well as their views on social technological transformation, And he believes that MLP is not a fixed or unified theory in explaining social and technological transformation, but a medium-sized theory [4]. Therefore, in describing and analyzing the complex and long-term process of social technological system transformation, MLP is combined with other theories and models to supplement its shortcomings, expand its knowledge level, and enrich the theoretical connotation of social technological transformation. For example, Florian Kern does not use MLP for policy development, but for policy evaluation to pre-evaluate policies that stimulate social-technological transformation [5]. In addition, Wu Xifeng believes that MLP cannot explain many details of the transformation of social technological systems, while Agent-Based Modeling (ABM) can estimate the impact of interaction behavior in complex systems. Therefore, he combines the two and identifies key factors and actors in the phase diagram of ABM simulation as control parameters, which can inspire specific policy recommendations [6]. In a recently published article, Frank Geels, in order to develop his concept of positive detonation, based on the MLP analysis framework, understands social technological transformation as the result of multidimensional interaction between radical niche innovation and existing path-dependent systems, which are stabilized through multiple locking mechanisms and determine the four processes of transformation, He also pointed out that "future research can attempt to develop a broader understanding of critical points based on MLP, which will address endogenous niche innovation, institutional instability, and exogenous shocks" [7].

The multi-level perspective analysis framework has undergone several stages of proposal, supplementation, criticism, improvement, and dynamic development. It contains a large number of theoretical foundations, from the initial evolutionary economics, system theory, innovation theory, longwave theory, and collaborative evolution theory [3] to today's dynamic development. The MLP analysis framework has taken shape, requiring not only dynamic interaction with its own three levels and four stages but also with other theories Model integration to supplement the shortcomings of MLP and expand the knowledge level of MLP. Sun Qigui (2010) summarized a multi-level framework for analyzing social technology systems, emphasizing the interrelationships of three levels, analyzing six interactive mechanisms, and studying the evolution process of technological innovation from niche to social technology domain and then to landscape, highlighting the key role of users in the evolution process [9]. Li Hui (2019) conducted in-depth research on MLP, including its formation background, interdisciplinary origins, macro, meso, and micro level analysis, as well as dynamic nonlinear interactions, enriching the theory of system innovation and sustainable development [10]. Cheng Zhencheng (2020) summarized the changes in the perspective of systems from a single linear to a multi-level complex system in recent years and analyzed the advantages and limitations of its framework [11]. Xue Yixi et al. (2020) sorted out and analyzed the evolution path and key content of MLP, compared their research perspectives and application fields, proposed possible future research directions, and promoted the theoretical development and practical application of these core analytical frameworks [12].

Exploring the transformation of social technological systems based on the MLP analysis framework requires viewing this issue from a connected, dynamic, and developmental perspective. The essence of social technology system transformation is to transform from one social technology system to another, but this does not mean immediately "abandoning" the old social technology system. Only when the process of transformation lasts long enough, the scope is wide enough, the degree is deep enough, and the method is thorough enough, can the newly generated social technology system completely replace the old social technology system. Otherwise, it will be parallel to the old social technology system.

2. Basic Principles

The transformation of the socio-technological system from a multi-level perspective is defined as a complex process of coupling multiple factors such as innovation niches, existing systems, and external environment.

2.1 Innovation niche

When a new technology first appears in the mainstream market, it may be fragile, novel, but unstable, and may not meet expectations in terms of cost-effectiveness, but it is very promising. Therefore, it needs a stable environment to protect its development, replacement, and improvement. This protection mechanism is provided by the niche, which is composed of incubators and some human actors (product advocates), etc. Technology and market niches are two forms of niche development. Technology niches usually precede market niches [8], and the difference between the two is mainly in terms of stability. According to Frank Geels' description, the stability of market niches is higher than that of technology niches [3].

There are two types of development outcomes for new technologies or things at the level of innovation niche:

development and utilization or backward elimination. The first is based on the relevant theories of strategic niche management (SNM) scholars (proposing that there are three processes that play a crucial role in innovation niches: building social support networks, learning processes, and changing and adjusting expectations and visions). Frank Geels believes that in the interaction and strengthening of these three processes, it is beneficial for innovation niches to stabilize and mobilize more resources for the development of new technologies or things, To support the development and utilization of this technology [3]. The second type is also determined by the three processes mentioned above, ultimately leading to the backward elimination of the technology or thing.

2.2 Existing system

In his book "Technical Transitions and System Innovations," Frank Geels divides the existing social and technological system into seven dimensions: technology, user practice and application fields (markets), symbolic significance of technology, infrastructure, industrial structure, policies, and technological scientific knowledge. He believes that these seven dimensions are also collaborative development, with inherent dual driving forces that stabilize the existing social and technological system, There is also a drive to undermine the existing social and technological system. At this level, human actors are not only passively following existing systems and rules but also actively creating new systems and rules, with the driving force of creation coming from various levels.

2.3 External environment

The external environment is more extensive and difficult to influence than the socio-technological system. Frank Geels believes that the importance of analyzing the external environment lies in the external structure or background it forms for the interaction of participants. He divides the changes in the external environment into two types: relatively slow changes (culture, population, ideology, etc.) and relatively rapid changes (war, oil prices, economic depression, etc.) [3]. When it comes to the external environment, one has to deal with the concept of externality, and in the MLP analysis framework, the discussion of the external environment often focuses on negative externalities, which are often caused by human actors themselves.

2.4 Three levels of dynamic interaction

The innovation niche, existing system, and external environment are embedded in a nested hierarchical structure. The external environment is embedded in the existing system, while the existing system is embedded in the external environment [3]. Any one of these three is not only influenced by its own internal factors, but also by the other two, and develops in dynamic interaction.

The innovation niche is influenced by existing systems and external environment. Ren é Kemp et al. believe that the success of forming an innovation niche depends on the processes within the innovation niche, as well as the development of existing systems and external environmental levels [8]. However, according to Frank Geels' research, the impact of existing social technology systems on innovation niches is stronger and more direct than the external environment. The pressure of the external environment forces human actors to actively develop new technologies in order to alleviate the pressure and improve the external environment through technological development and innovation. Secondly, institutional or rule-makers also feel the influence of the external environment and begin to develop new or improved corresponding systems, consolidating the new technologies of innovation niches, and passively following corresponding rules by human actors to resolve conflicts in the external environment. For example, Liu Qingquan et al. (2021) proposed that disruptive technology breaks the laws of traditional technology development, giving rise to emerging industries, business models, and innovation cycles [13]. Chi Honggang (2016) revealed the core path from technological innovation to the synergistic evolution of technology and society, ultimately leading to the transformation of the socio-technological system by studying the generation of breakthrough technological innovation and how it gradually promotes industrial upgrading [14]. Chen Zhuochun (2016) proposed four interactive models: niche transfer, niche intervention, niche autonomy, and niche highlighting [15]. Yao Sui et al. (2020) analyzed the obstacles of niche protection in development from six aspects: industrial structure, infrastructure, knowledge base, market and consumer demand structure, public policies and political forces, and social cognition. They proposed to establish and strengthen the spatial function of niche protection through measures such as protection, cultivation, and empowerment, in order to break institutional path dependence [16].

The impact of innovation niche and external environment on the social and technological system. When the existing system cannot keep up with the speed of innovation and development, it will generate destructive power within the system. This destructive power may disappear due to the improvement of the existing system, or it may strengthen under the joint influence of the other two levels, promoting the transformation of the social and technological system. When new technologies that are on the innovation niche and have the potential to solve specific external environmental problems urgently require more resources to replace existing technologies, it will put upward pressure on the existing social and technological system; The external environment, due to a specific prominent problem, will put downward pressure on the existing social and technological system; In addition, when the existing social and technological system cannot solve specific external environmental problems, it will also generate internal pressure; The pressure from these three aspects forces the transformation of the social technology system, and the new social technology system helps to solve external environmental problems in terms of innovation niche and system. For example, Chen Zhuochun proposed a policy analysis method based on system function, emphasizing the importance of innovative system function for the successful development of the system, as well as the interaction between function and structure. He integrated market failure, system failure, and transformation failure into eight failure analysis frameworks: market failure, infrastructure failure, capability failure, interaction failure, institutional failure, directional failure, policy cooperation failure, and reflection failure [17-19].

Innovation niche and the impact of existing systems on the external environment. Undoubtedly, various actions of human actors will affect the external environment, and social and technological systems are no exception. Taking global climate change as an example, the vast majority of human activities cause greenhouse gas emissions, leading to an increase in global CO2 emissions and various adverse weather conditions. Human actors are also aware of this in their actions and have begun to develop new technologies (such as electric cars and clean energy). Institutional makers have also begun to develop new systems and rules to curb CO2 emissions, Expected to alleviate the survival pressure brought about by global climate change.

3. The Application of MLP Framework in Energy Systems

3.1 Energy subsystem

In the field of power systems, Chen Zhuochun et al. (2012) divided the transformation of China's power system into three-time dimensions based on the MLP framework: short-term, medium-term, and long-term. This time analysis provides important support for understanding the long-term evolution of the power system and proposes three possible development paths: short-term transformation, medium-term reconstruction, and long-term reset, highlighting the multi-level nature of power system transformation [20]. Subsequently, Nie Yan (2017) conducted an in-depth analysis of the evolution process and key elements of China's power grid towards a smart grid based on the theory of social technological transformation. He proposed four stages for the transformation of the power grid: strengthening macro pressure, emerging multiple niches, growing advantageous niches, and establishing a new system. He highlighted the obstacles and breakthrough paths of the transformation and provided detailed analysis and policy recommendations for the intelligence and greening of the power industry [21]. In addition, Chen Zhuochun et al. (2018) conducted an in-depth analysis of how German offshore wind power technology promotes sustainable transformation of energy systems through the MLP framework, highlighting the key role of the government in technological innovation and system transformation [22]. In addition, in the fields of new energy vehicles, shale gas, fossil energy, etc., Xue Yixi et al. (2013) used MLP theory to analyze the dynamic connections and collaborative evolution of various elements in the field of new energy vehicles, providing important insights for understanding the development trend of new energy vehicles. He designed transformation scenarios and provided insights and suggestions for the upgrading of the automotive industry [23]. Li Juan (2021) analyzed the relationship and evolution between different levels of elements in shale gas development based on the theory of social-technological transformation. She proposed development models at different stages, highlighting the effectiveness of government leadership in the initial stage, and providing a reference model for the development stage of shale gas development [24]. Huang Xingting et al. (2022) analyzed the composition and inherent correlation of fossil energy from the perspective of socio socio-technological paradigm and proposed a policy tool combination framework to unlock the lock-in of high carbon fossil energy from three perspectives: technological economy, social cognition, and rights rules [25].

The above studies collectively emphasize the close interaction between social and technological factors, as well as the importance of multi-level perspective analysis. This comprehensive research method provides solid theoretical support and practical guidance for energy transformation in different fields, helping to promote social and technological transformation to achieve sustainable development goals.

3.2 Energy Transformation System

For the entire energy transformation system, different scholars analyze it from their respective perspectives. Regarding the mechanism, Lv Tao (2015) used a multi-level model to analyze the transformation of Dutch electricity and proposed that China should strengthen the design of energy transformation strategies, support energy technology innovation and new energy infrastructure construction, and establish a legal system and institutional mechanism that meets the needs of energy transformation [26]; Yao Sui (2020) explored five themes: the depth of transformation mechanisms, action subjects, geographic space, politics and power, and policy research. He analyzed the current situation of sustainable development and emphasized that existing research not only helps to understand the urgency and importance of China's socio-technological system transformation but also helps to understand the essence and internal mechanism of system transformation, so as to more accurately determine short-term and medium-term action goals and directions [27]. Starting from the MLP framework research, Wang Jun'an (2017) first reviewed the process of China's energy development and transformation using the MLP analysis framework, then pointed out the practical difficulties of China's energy transformation, and finally listed the multi-level breakthroughs in China's energy internet energy transformation difficulties [28]; Guo Pibin et al. (2019) combined MLP research with energy transformation and proposed a research framework of "influencing factors driving mechanisms governance policies", emphasizing the need to identify transformation driving factors and clarify participants at all levels to formulate targeted governance policies for China's energy transformation [29]; Fan Ying et al. (2021) proposed key areas and key areas for sustained energy transformation in China from multiple dimensions such as market, policy, innovation, and behavior by analyzing existing institutional and external pricing barriers [30]. In studying the path of energy transformation, Li Hui (2023) took China's energy system as an example, explored the internal mechanism of promoting low-carbon transformation of the energy system based on the MLP framework from the external environment, and proposed three different energy transformation paths using grounded theory and fsQCA: industrial structure adjustment type, resident environmental demand-type, and transitional type [31]. Huang Tianhang (2021) used a multi-level perspective method to analyze the transformation case of the traditional industrial zone in Ruhr, Germany and attempted to explore the path of China's energy transformation driven by innovative development, providing strong support for China to solve sustainable development problems [32].

The above research provides diverse perspectives and methods for understanding China's energy transformation issues, emphasizing the interaction of policy, technology, and social factors, and providing important references for formulating comprehensive energy transformation strategies; It also highlights the urgency of energy transformation, providing strong support for addressing climate change and sustainable development.

4. Conclusion

From the above literature review, it can be seen that the evolution of the social technological transformation theory and the multi-level perspective analysis framework (MLP) provides us with important tools for deeply understanding the evolution of the social technological system. Despite facing criticism and challenges in its development process, continuous improvement and integration with other theories have made this theoretical system more practical and adaptable, We will continue to play a crucial role in solving complex social and technological challenges and achieving sustainable development goals, providing important theoretical support and practical guidance for China's energy system transformation, highlighting the interaction between social and technological factors, and the importance of multi-level perspective analysis. Although these studies provide useful insights in different fields, there are still some shortcomings: firstly, the limited scope of research. Although these studies cover multiple fields, including power systems, new energy vehicles, smart grids, offshore wind power, shale gas, industrial zone transformation, and fossil energy, there are still issues where other energy subsystems and fields have not been thoroughly studied. For example, the large-scale integration of renewable energy and energy storage technologies are also key issues in energy transformation that require more attention; secondly, the limitations of time scales, although some studies divide energy transformation into short-term, medium-term, and long-term, these time scales are still relatively broad. More detailed time scale analysis and prediction are crucial for formulating practical policies and strategies. In addition, there is a lack of in-depth exploration of potential technological and market changes in the coming decades; thirdly, the shortcomings of interdisciplinary cooperation, energy transformation is a highly complex interdisciplinary problem that requires interdisciplinary research methods and team collaboration. Although some studies have adopted the multi-level analysis method of social technological transformation theory, there is still a need for more interdisciplinary cooperation, including professional knowledge in fields such as social sciences, engineering, and policy sciences; fourthly, although these studies provide policy recommendations and strategic frameworks, they often lack in-depth consideration of policy implementation and actual implementation. Considering that policy implementation and social acceptance are crucial for the success of energy transformation, future research needs to pay more attention to the actual implementation of policies and social feedback; fifthly, The consideration of risk and uncertainty, although these studies have proposed various paths and strategies for energy transformation, lacks in-depth analysis of risk and uncertainty. Energy transformation involves complex market, technological, and policy factors, requiring more risk assessment and strategic research to address uncertainty. Based on this, this article believes that research on the future of China's energy transformation should consider various energy subsystems more comprehensively, adopt more refined time scale analysis, promote interdisciplinary cooperation, better consider policy implementation and actual implementation, and consider risks and uncertainties more deeply.

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