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Research on Low-carbon City Construction Based on the Theory of Social and Technological Transformation

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Abstract: In order to cope with global climate change, solve the resource and energy crisis, alleviate the deterioration of the ecological environment, implement China's emission reduction commitments, and achieve sustainable development, the cogeneration system is the core essence of China's construction of low-carbon cities. The construction of a combined heat and power system means a socio-technical transition from traditional energy technology and heat and power supply systems. Referring to the construction process of Beddington's "zero-carbon community", most cities in China are still in the "low-carbon pilot stage", and have entered the "rapid development stage" after the country vigorously promotes the low-carbon pilot. The transformation of cogeneration system into the construction of low-carbon cities depends on the development path dominated by social and technical institutions. Based on the theory of socio-technological transformation, this paper adopts a multi-level analysis method to further construct the social environment, innovative organization and management institutions, and professional socio-technical institutions from the macro to the micro level from the role of the government, so as to promote the coordination and cooperation of all links and comprehensively promote the universalization of low-carbon cities.

Keywords: Low-carbon City; Sociotechnical Transition; Combined Heat and Power Systems.

1. Introduction

Climate change and environmental pollution have always been problems faced by countries around the world, so it is particularly important to reduce or control carbon dioxide emissions. Some cities in developed countries have been exploring the development of low-carbon economy, low-carbon technology and low-carbon communities since the 70s of the 19th centuries, and the construction of zero-carbon communities in the UK is one of the most successful cases. China's focus on low-carbon cities began in the early 20th century with the publication of a series of policy documents. In 2009, it was proposed to build a "six-in-one" of low-carbon economy, low-carbon buildings, low-carbon transport, low-carbon housing, low-carbon environment and low-carbon society, implying the importance of low-carbon cities. In October 2010, the state launched the pilot work of "low-carbon cities", and since then, the scale of the project has been gradually expanded, and as of 2018, a total of three batches of pilot cities have been released. On September 22, 2020, the "dual carbon" goal was introduced, accelerating the rapid progress of low-carbon city construction. The construction of low-carbon cities is the only way for China's urban development and the common pursuit of all countries in the world. However, the construction of low-carbon cities is difficult, on the one hand, it is necessary to improve the top-level design of the system, starting from industrial transformation, policy guidance, innovation drive, concept change and other aspects; On the other hand, due to the difficulty of changing the high-carbon production and lifestyle of Chinese residents in a short period of time, the market resistance of low-carbon products and the lag of urban green planning have added many obstacles to the construction of low-carbon cities. Therefore, in order to ensure the high efficiency and accuracy of China's low-carbon city construction, it is urgent to start from the basic principles of social transformation and explore the path of social and technological transformation to adapt to global climate change.

2. Research Background

2.1. Background of Low-carbon City Construction

Cities serve not only as symbols of modern civilization but also as crucial spaces and action units for promoting high-quality economic and social development while facilitating a low-carbon economic transformation. They are significant contributors to global greenhouse gas emissions and play a central role in carbon emission reduction. Occupying just 3% of the land surface area, cities account for 78% of energy consumption and 70% of carbon emissions. With their unique characteristics of a highly active economy and dense population, cities also represent concentrated hubs of capital and labor, fostering favorable conditions for the further development of green and low-carbon emerging technologies. Consequently, they should emerge as key participants in global climate governance. Currently, China's urbanization level stands at 64.7% and is projected to reach between 75% and 80% by 2035. The GDP, tax revenue, import and export trade, and carbon dioxide emissions generated by cities and towns represent a significant portion of the national totals, with some regions exceeding 90%. Therefore, to achieve the dual carbon goals, the focus, challenges, and critical areas for energy conservation and emission reduction are concentrated in urban areas, highlighting the importance of this issue. Since 2009, China has been actively promoting the construction of low-carbon cities and has established clear objectives for their development.

2.2. Development and Research Status of Low-Carbon Cities and Cogeneration Systems

Although China began its development of low-carbon cities relatively late, it has made significant strides in reducing greenhouse gas emissions. Notably, China is the first developing country to implement a national action plan in

response to global climate change, contributing substantially to the reduction of carbon dioxide emission intensity and the advancement of non-fossil energy sources. To accelerate green and low-carbon development and support the nation's energy conservation and emission reduction objectives, the "12th Five-Year Plan" and "13th Five-Year Plan" have been established. Concurrently, research on cogeneration systems in China is advancing rapidly, with the ultimate aim of achieving optimal energy allocation across regions. Combined Heat and Power (CHP) systems recover a portion of the heat exhaust from power plants and distribute it to users via a heat network, thereby significantly enhancing primary energy efficiency. This approach addresses the dual supply of electricity and heat in a unified manner, facilitates cascade energy utilization, and has seen rapid development in other countries[1].

In recent years, several prominent topics have emerged internationally, including research on energy storage, the application of cogeneration units, advancements in large-scale unit capacity technology, energy-saving technologies for central heating systems, and clean energy heating solutions. Concurrently, investigations into system construction from the perspective of technological transformation have been undertaken, leading to a continuous deepening and enhancement of cogeneration system technologies. This evolution encompasses a range of systems, from coal-fired, gas-fired, and waste-to-energy incineration cogeneration systems to biomass and solar cogeneration systems. Each cogeneration system exhibits distinct characteristics, advantages, and disadvantages, while traditional cogeneration technologies undergo updates and iterations in response to varying social environments and government policies, facilitating socio-technological transformation to meet diverse user needs. Currently, research on low-carbon cities in China is gaining traction, encompassing national policies, industrial transformation, low-carbon technologies, and innovation-driven initiatives. Although some scholars have explored foreign thermoelectric systems and policies, studies examining these issues from the perspective of technological transformation remain scarce. Thus, there is a pressing need for in-depth research on the transition of combined heat and power systems from oil combustion to solar combined heat and power systems, viewed through the lens of socio-technological transformation.

2.3. Socio-technical Transformation Theory and its Research

Technological transformation theory provides a systematic description of the historical processes involved in changing socio-technological systems to achieve specific social functions. It dynamically outlines the evolution of these systems through a hierarchical framework, analyzing changes across multiple levels, including technology, market, industry, policy, and culture[2]. Grounded in the multi-level perspective (MLP) developed by Geels et al., which draws from evolutionary economics, social network theory, and institutional economics, this theory posits that socio-technological transformation is a dynamic, nonlinear process. This process involves the interaction of various developments—social, technological, cultural, political, and economic—across three distinct levels[3]. The theoretical framework consists of three components: the micro level, which encompasses the technological innovation niche; the meso level, representing the socio-technical regime; and the macro level, known as the external environment (Landscape). Each level comprises multiple elements, with the elements at the macro level exhibiting greater stability.

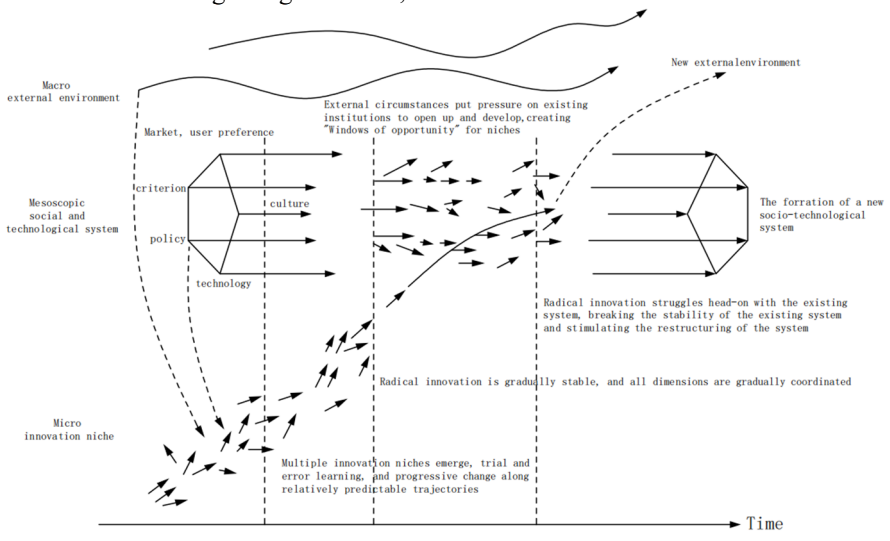

Figure 1. The process of socio-technological system transformation in low-carbon cities

Socio-technological transformation from a multi-level perspective is the interaction between the above three levels of innovation niche, and finally the formation of a new socio-technological system, which gradually tends to be stable and institutionalised, and the non-linear interaction between these four stages promotes the system to complete a fundamental transformation process[4]. The specific characteristics are shown in Table1, and each stage involves the interaction and coordinated evolution of different actors.

Socio-technological transformation is a fundamental change in the socio-technological system to achieve a specific social function, new products, new services, new business models, new organisational forms and new institutional systems; in the process of transformation, the original products, services, business models, organisations and systems are all replaced. Transformation is essentially a three-level interaction, and it is also a non-linear and complex process. From the perspective of building a low-carbon city, energy conservation and emission reduction, industrial upgrading and technological innovation can be controlled by

the government at the macro level, and enterprises, organisations and individuals can be guided to accelerate the implementation of low-carbon cities, so the construction and formation of low-carbon cities will be dominated by social and technical systems.

Table 1. Four stages of development

Development stage	Specific characteristics
Initial stage	In the absence of stable rules and supporting institutions, its social network is very fragile and unstable, and its technical characteristics, user preferences, policies, infrastructure needs and culture are highly uncertain.
Formative stage	Radical innovation has gradually penetrated the protected technology field and established itself in one or more market spaces, creating a strong attraction for new and potential entrants, and the rules and social networks have gradually stabilised.
Development and diffusion stages	Radical innovation has directly confronted and collided with the existing institutional system at various levels, such as the economy, politics, culture and discourse, and creative changes are accumulating and the system structure has begun to emerge.
Maturity and application stage	With profound adjustments in infrastructure, policy, industry, market base and lifestyle, innovation is widely adopted and new systems are formed and gradually stabilised and institutionalised.

3. The Current Situation of Low-carbon urban Construction in China: Taking Beddington Zero Carbon Community in the UK as a Reference

In the practice of low-carbon development in developed countries, the zero-carbon community in the UK is relatively typical and successful. By maximising the use of natural energy and reducing environmental damage and pollution, the whole community has achieved a housing model of zero fossil energy use and recycling of energy demand and waste disposal[6]. Referring to the development of low-carbon cities in the United Kingdom, this paper positions the current situation of low-carbon development in China's cities from the perspective of the specific design idea of "zero energy consumption" and the stage of socio-technological transformation.

3.1. Analysis based on the Design Idea of "Zero Energy Consumption

In terms of urban planning and construction, the UK has taken many measures to improve energy efficiency and reduce energy consumption, and finally developed the concept of "zero energy consumption". Table 2 shows the development process of the "zero energy" concept in urban construction in the UK, and also shows the development policies adopted by the UK government at different stages.

Table 2. The development stage of "zero energy" in the UK

Development stage	Main content
Policy guidance and concept establishment stage	In the 1990s, the UK government began to pay attention to energy efficient buildings and introduced a series of policies, such as the Energy Act and the Building Act, to promote the development of energy efficiency in buildings. At the same time, the government is actively promoting the concept of "zero energy consumption" and raising public awareness of energy conservation and environmental protection through various publicity channels.
Pilot demonstration and experience summary stage	"Zero energy" pilot demonstration projects have been carried out in some areas, including representative cases such as the Beddington Zero Energy Community. Through demonstration projects, we will continue to accumulate experience and gradually improve technical standards and policies.
Comprehensive promotion and application stage	More perfect policies and regulations have been introduced to encourage companies and individuals to participate in "zero energy consumption" construction; various energy-saving technologies and products have been widely used; buildings are being designed with greater emphasis on energy efficiency and environmental performance.
Continuous improvement and innovation phase	With the continuous progress of science and technology and the improvement of environmental awareness, the UK government WILL continues to promote the development of "zero energy consumption", and constantly improve and innovate technical means. For example, the use of renewable energy, the optimization of building design and material selection, etc. In addition, the UK government is actively engaged in international cooperation to research and promote "zero energy" technologies with other countries.
The stage of reaching social consensus	The government and businesses are actively involved in energy conservation and emission reduction work for individuals, and are jointly promoting the sustainable development of "zero energy consumption".

3.2. Analysis based on the Process of Socio-Technical Transformation: A Case Study of the Beddington Zero Carbon Community

The most striking feature of the Beddington Zero Carbon Community in the UK is the maximisation of green energy, and its CHP system plays an important role in this[6]. From the perspective of the socio-technical transformation process, the CHP system is currently in the stage of maturity and application, and the overall process is summarised in Table 3.

The evolution of the four stages of the Beddington CHP system is still being updated today[7]. On this basis, a new

CHP system with a broad application perspective is proposed. Before the implementation of low-carbon cities, most cities were still in the high-carbon, high-emission stage, and with the construction of "low-carbon" cities in the country, "institutional pressure" was rapidly formed, corresponding documents, systems, specifications and technical guidelines were issued one after another, and a large number of projects were put into construction. Under the macro social background, most cities in China have immediately entered the "development and dissemination stage", and various localities have started to build low-carbon pilot cities and entered the "maturity and application stage". The renewal of social technology in our country is mainly through a top-down management process, which is different from the development of the UK. The construction of low-carbon cities led by cogeneration systems relies on the "social and technological transformation" driven by the system, so the development path of low-carbon cities in China can better meet the requirements of social and technological progress. However, it should be noted that this process has great advantages over the bottom-up development of the UK, but it also has its shortcomings, which require us to conduct in-depth research and take appropriate countermeasures.

Table 3. Summary of the development stages of the cogeneration system

Transformation stage		Participants who influence conversions	Technological development and strategic objectives
Initial stage	The emergence of a micro-environment of technological innovation (early 90s of the 20th century - 1998)	Small environmental actors: energy companies, researchers	Without the corporate organization of cogeneration systems associated with urban construction, loose, informal links between key players began to emerge. For example, Beddington Community Energy partnered with architect Michael Hopkins to establish the Teacher Training Project
Formative stage	Microenvironment Formation (1998-2001)	Small environmental actors: energy company researchers, a small number of governments and businesses;Institutional Participant: Beddington Government	Energy companies work with local governments, businesses, and other NGOs to help other communities build their own cogeneration systems by providing technical advice and project management support for technology promotion
Development and diffusion stages	Microenvironment: The Process of Institutional Transformation (2001-2012)	Small environmental actors: energy companies, researchers, contemporary government personnel, developers and consultants, etc.; Institutional participants: government agencies, environmental protection agencies, state-owned land development agencies, etc	The technology of cogeneration system has been professionally developed, the relevant industrial chain system has been improved, and relevant systems have been introduced. Energy companies have begun to build cogeneration systems for large-scale commercial projects, and consultants have provided customers with comprehensive energy solutions
Maturity and application stage	Forming an Innovative Microenvironment – Combined Heat and Power for Sustainable Development (2012-present)	Small environmental actors: energy companies, researchers, developers and consultants; Institutional actors: politicians, environmental protection agencies, energy management agencies, etc	Integrate renewable energy and low-carbon technologies into cogeneration systems, and start new research into the use of renewable energy sources such as biomass and solar energy to generate electricity to reduce dependence on fossil fuels

The development of the CHP system in Beddington, UK, has gone through many stages, including demonstration projects, technology diffusion, specialisation and advocacy for sustainable development. This development process not only shows the progress and increasing popularity of CHP technology, but also demonstrates the importance of sustainable development in urban energy planning. Compared with the contents divided in Table 3, the application and development of CHP in China is different from that in the UK, and the development of CHP system in China is currently in the "development and diffusion stage", which is completely different from the development process of Beddington, such as

(1) At the beginning of the development of CHP in China, it was to solve the problem of winter heating in northern cities. After the vigorous development of cogeneration system, it is mainly concentrated in industrial parks and urban centres to solve the problems of local industrial production and heating for urban residents.

(2) After the cogeneration system has been widely used, China has started to try to combine the cogeneration system with new energy technology to achieve sustainable energy development.

(3) After the beginning of the 21st century, the national government began to promote the adjustment, transformation and upgrading of the energy structure. Vigorously develop clean energy and high-efficiency energy utilization technologies. Cogeneration has gradually become an important part of China's energy structure optimisation and low-carbon development. At the same time, China continues to promote technological innovation and industrial upgrading of the cogeneration system to improve energy efficiency and reduce environmental pollution.

Some problems are gradually emerging in the construction of low-carbon cities in China, such as the low level of development and use of low-carbon energy in low-carbon city pilot projects, the lack of motivation for low-carbon city innovation systems and policies, the low popularity of low-carbon city concepts, and the failure to fully implement low-carbon management[8]. In a sense, these problems are related

to the "top-down" socio-technological transformation path and rapid development by leaps and bounds. Therefore, it is necessary to compare China with the bottom-up development process of low-carbon cities in the UK to find out China's shortcomings. Work more effectively.

4. Promoting the Construction of Low-carbon Cities based on the Theory of Socio-technological Transformation

From the above analysis, we can see that some of the problems in building low-carbon cities in China are caused by the top-down transformation process. The role of the government in solving this problem is crucial. According to the theory of socio-technological transformation, the government plays an active role in the construction of the CHP system at all three levels of transformation, as shown in Figure 2 [4].

From the perspective of the overall development of CHP technology in China, the policy formulation and implementation process of low-carbon cities has played an important role in promoting the transformation of social technology. At present, more attention should be paid to the combination of macro, meso and micro levels of management. This includes:

(1) Paying attention to the implementation of relevant systems and policies for the construction of low-carbon cities. China, like the UK, should pay sufficient attention to low-carbon city laws and policies and, on this basis, establish a sound legal system to provide a good institutional guarantee for the construction of low-carbon cities. At the macro level, the government should actively respond to the low-carbon policy, adopt clean, efficient and low-carbon energy by optimising the energy structure, adopt clean, efficient and low-carbon energy, develop relevant energy-saving and emission reduction technologies, improve energy efficiency and reduce energy consumption; at the same time, through the innovation of thermoelectric technology, promote energy-saving technology and equipment to achieve energy conservation in the production process.

(2) Strengthening administrative control. Through the use of energy efficiency standards, energy efficiency labelling, energy conservation certification, carbon labelling and other administrative regulatory means, the energy consumption and carbon emissions of enterprises will be regulated. This includes monitoring and evaluating the carbon emissions of enterprises, and carrying out energy-saving and emission-reducing transformation in public transport, buildings and other areas. At the same time, the technical level and innovation ability should be improved. The government can encourage enterprises and research institutions to innovate and apply low-carbon technologies by increasing support for R&D and innovation of low-carbon technologies. For example, the government can invest in the construction of low-carbon science and technology parks, establish low-carbon technology incubators, etc., to support and guarantee the development of low-carbon technologies.

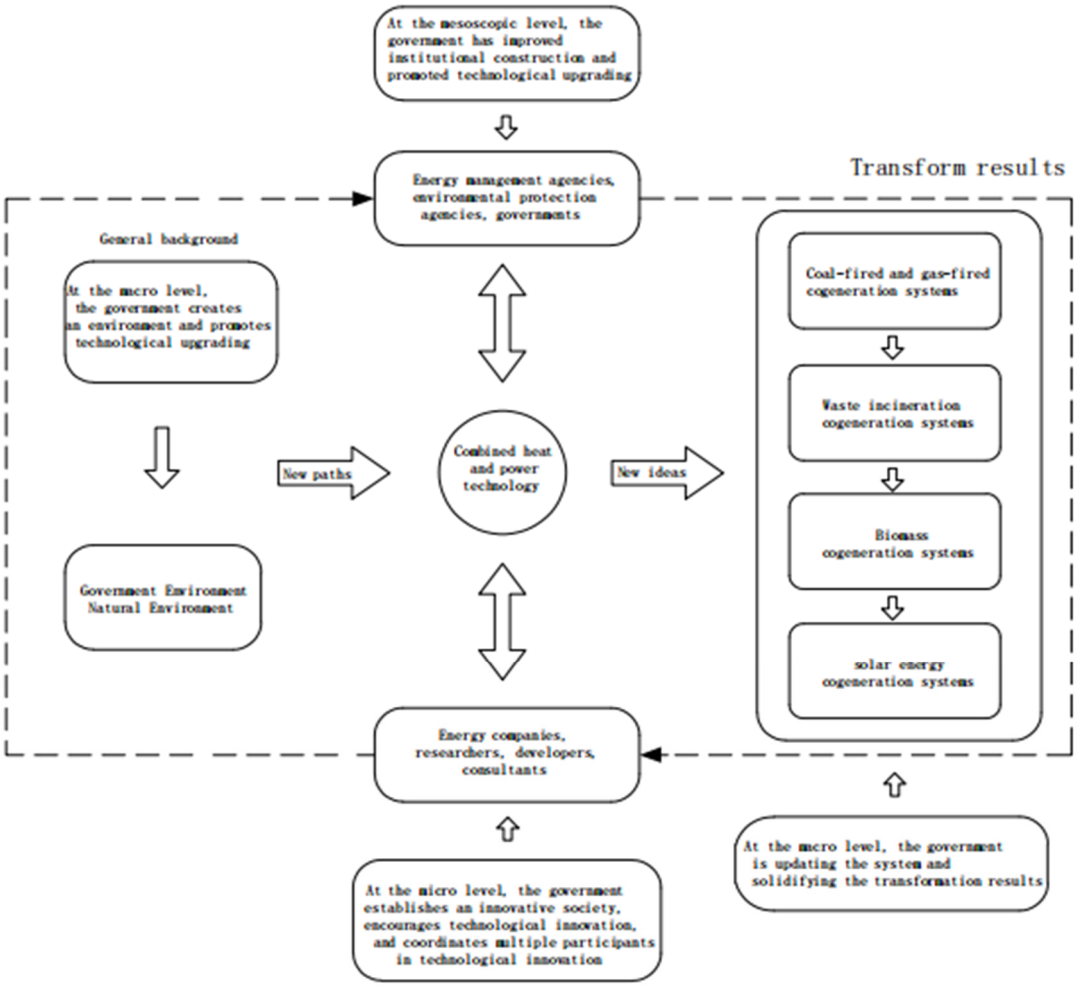

Figure 2. Transformation process

(3) Focus on low-carbon market to promote energy optimisation and transformation. Focusing on low-carbon development models, low-carbon technologies and low-carbon institutional innovation, we will jointly promote high-quality economic development and high-level ecological environmental protection, jointly build a low-carbon development industrial chain, and participate in industrial development. Under the active guidance of the government, enterprises, social groups and the public should actively participate in the construction of low-carbon cities. For example, manufacturing enterprises are actively fulfilling their social responsibilities and incorporating green and low-carbon development into their development strategies, and some leading industrial enterprises have even taken active measures to actively build zero-carbon supply chains.

(4) Promote the concept of low-carbon living. Building low-carbon cities is closely linked to business production and household consumption. The construction of low-carbon cities requires broad public participation. At present, China is vigorously building a low-carbon institutional environment, comprehensively guiding enterprises and residents to pay attention to low-carbon development issues, advocating low-carbon lifestyles through education and publicity, and encouraging people to reduce energy consumption and carbon emissions. For example, promoting energy-saving home appliances and green travel methods to increase public awareness and participation in low-carbon environmental protection. Units or individuals that actively engage in low-carbon practices such as information disclosure and voluntary emission reduction and have achieved fruitful results should be commended, rewarded and publicized, and a model should be established to create an atmosphere in which the whole of society can participate.

5. Conclusion and Discussion

China's low-carbon urban planning and construction is still in its infancy, and all localities need to adapt policies to local conditions, build relevant planning and design with local characteristics, and jointly promote cities to move towards low-carbon and sustainable development, and form a green, low-carbon, high-quality and sustainable new development model. This requires governments at all levels to review, attach importance to and comprehensively implement. Based on the theory of socio-technological transformation, it is an effective way to successfully promote the construction of low-carbon cities by further building the social environment, carrying out institutional innovation based on multiple perspectives, and comprehensively promoting multi-level and multi-role guidance, standardization, coordination and service.

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