



Evolution and Collaborative Development Mechanism of Carbon Peaking Carbon Neutrality, Economy and Society Complex System

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Abstract. Based on complex system theory, self-organization theory and ecology theory, this paper constructs a theoretical model for the Carbon Peaking-Carbon Neutrality, Economy and Society (CES) system. Adopting the Haken model in synergetics, this paper establishes the analytical framework of the CES system, explores its dynamic evolution rules and internal collaborative mechanisms, and analyzes the influences of technological innovation, energy system and ecological system on the coordinated development. The results show that the CES is an open, non-equilibrium self-organizing dissipate complex system with dynamics, symbiosis, diffusion and guidance as its core characteristics. It evolves from disorder to a new ordered state via four major mechanisms: evolution, selection, spillover and guidance. Technological innovation serves as the core engine for coordinated development; the energy system exerts negative constraints during the green transformation stage and will become a driving force after full maturity; the ecological system provides long-term fundamental support. This research enriches the theoretical studies on complex system evolution, and offers references for the coordinated and sustainable development of carbon reduction, economic growth and social progress.

Keywords: Carbon Neutrality, Carbon Emission, CES System, Self-organization Theory, Haken Model.

1 Introduction

Against the backdrop of advancing carbon peaking and carbon neutrality goals and deepening regional economic agglomeration, the coordinated and sustainable development of the Carbon Peaking-Carbon Neutrality, Economy and Society (CES) system has attracted growing attention[1]. The coordination of carbon reduction, economic and social development is a complex systematic project with intricate evolutionary laws. Therefore, exploring the collaborative development mechanism of the CES system from a systematic perspective possesses important theoretical and practical value.

Research on the evolutionary mechanism of the economy-environment-society system has aroused widespread academic attention, and numerous relevant studies have

been carried out [2-4]. Scholars have adopted diverse models to explore the evolutionary mechanism of environmental systems and made innovations in research methodologies. Up to now, fruitful achievements have been obtained in the research on the evolutionary mechanism of the economy-environment-society complex system [5-7].

In terms of research methods, existing studies mainly focus on the interactions between individual elements within subsystems. Few scholars adopt systematic scientific approaches to investigate the dynamic evolution and interactive relationships of the carbon peaking and carbon neutrality, economic and social subsystems. It is necessary to analyze the evolutionary process and interactions of the three subsystems, and summarize the essential laws of system evolution from the evolutionary characteristics of complex systems [8-9].

To fill the research gap, this paper constructs the theoretical framework of the CES system based on the Haken model of synergetics. On the basis of evolution theory, complex system science, self-organization theory and ecology theory, this paper explores the green collaborative development mechanism of the CES complex system, analyzes its dynamic evolutionary behaviors, and discusses the impacts of technology, energy and ecology on the system, so as to supplement the theoretical research on complex system evolution.

2 Analytical Framework of CES Complex System Evolution

Evolution theory provides fundamental methods for studying system dynamic evolution. The general evolutionary structure follows the Darwinian "variation-selection-inheritance" framework. Different from it, Haken's synergetics classifies system variables into fast variables and slow variables to interpret the self-organization process. From the perspective of self-organization theory, the CES is an open and non-equilibrium self-organizing system. Its self-organization evolution means that the system transforms from disorder to a new ordered state within a nonlinear range through interactions between internal and external subsystems, namely shifting from the mode of high-carbon and rapid development to low-carbon, carbon-neutral and coordinated development. Slow variables dominate the evolutionary process and control fast variables, thus acting as the order parameters of the new system[10-11].

In accordance with complex system theory, the CES system not only conducts internal metabolism, but also continuously exchanges factors with the external environment[5]. Such exchanges affect internal entropy and system order, forming a dissipate structure and finally evolving into an ordered organization. The CES consists of three interrelated adaptive subsystems with cross interactions and dynamic evolutionary features. Based on ecological principles, the CES is an artificial ecosystem coupled by carbon peaking & carbon neutrality subsystem, economic subsystem and social subsystem. It optimizes resource utilization to improve economic and environmental performance and maximize overall system efficiency.

The carbon peaking and carbon neutrality subsystem sets fundamental constraints and determines the low-carbon and carbon-neutral evolutionary direction of the CES

system. The evolution of the CES is not a simple restructuring of structural diversity, but the unification of new diversity. The three subsystems have distinct characteristics and network structures. Their mutual adaptation and interaction drive the dynamic evolution of the whole system, and changes in elements of one subsystem will reshape the evolutionary paths of others.

The CES complex system has four typical evolutionary characteristics. First, dynamics character: Driven by internal forces, external conditions and order parameters, the system dynamically evolves from the state at time $t-1$ to the state at time t . Second, symbiosis character: Elements flow freely within and across regions, and subsystems interact and interconnect with one another. Third, diffusivity character: The system presents obvious agglomeration and diffusion characteristics in spatial distribution across different regions. Fourth, guidance character: Different subsystems and elements exert disparate influences on system evolution; some core factors act as dominant variables to guide the evolution of fast variables and the whole system.

3 Evolution Mechanism of CES System

The evolutionary mechanism of the CES system based on evolution and self-organization theory is explained as follows. The self-organization evolution means that within the non-equilibrium and nonlinear scope, when external conditions reach a certain threshold, the system will transform from a disordered state into a new ordered state through self-organization [5].

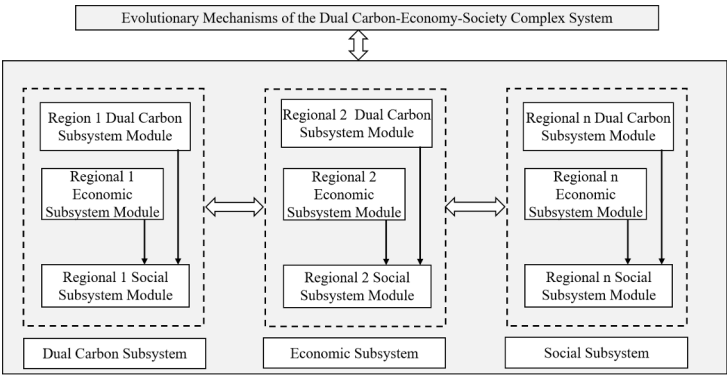


Fig. 1. Evolution mechanism of the CES complex system

The self-organization process of the CES system refers to a transition where the system breaks away from the equilibrium state and evolves from chaos to a new order via the transformation between internal and external subsystems under diverse conditions. The self-organization of the CES system is driven by the interactions among its subsystems, which constitutes the internal evolutionary mechanism of the system, as Figure 1 shows. The dynamic evolution of the CES complex system acts as the fundamental driving force for the evolution of sustainable development systems and embodies

the diversity of evolution. Evolution marks the starting point of systemic development and presents the unification of diverse initial states. Self-growth serves as the prerequisite for system progression, and the evolutionary process complies with market mechanisms and price mechanisms.

CES Evolution Mechanism. Dynamic evolution is the fundamental source for the sustainable development of the CES system and reflects the diversity of system changes. Self-growth is the premise of system evolution, and the operation of the system complies with market rules and price mechanisms.

CES Selection Mechanism. The system selects suitable evolutionary units and reduces diversity, including market selection, social selection and institutional selection. The market selection takes the law of value as the standard; the social selection is guided by social morality and culture; the institutional selection relies on laws, regulations and policies formulated by the government.

CES Spillover Mechanism. Evolutionary units produce cross-regional spatial spillover effects. When the CES evolves into a low-carbon, carbon neutralization, economy and society sustainable ordered state, its development model can be demonstrated and replicated in other regions, which promotes the overall evolution of regional systems.

CES Guidance Mechanism. Triggered by random fluctuations, the CES system will undergo structural mutation and transform from the old structure to a new ordered state when external control variables reach the threshold. Different subsystems and elements have heterogeneous impacts on the evolution of the whole system.

4 External Factors Driving CES Collaborative Development

The core connotation of the coordinated development of carbon peaking & carbon neutrality, economy and society is to achieve carbon reduction goals while guaranteeing high-quality economic growth and improving social benefits, so as to avoid imbalance between carbon reduction and development. This section analyzes the influences of technological innovation, energy system and ecological system on the CES system.

4.1 Impact of Technological Innovation

Technological innovation is the core engine for the coordinated development of the CES system. In the field of carbon reduction, low-carbon crafts, new energy and carbon capture technologies can directly cut production-side carbon emissions. In the economic dimension, technological progress improves total factor productivity, accelerates the transformation of high-carbon industries and fosters emerging green industries, injecting new impetus into economic growth. In the social dimension, the expansion of green industries creates high-quality jobs, and low-carbon renovation continuously improves living environments. Technological innovation effectively resolves the contradiction between carbon reduction and economic growth, and forms a complete transmission chain covering emission reduction, economic growth and people's well-being[12].

In China's practical development, breakthroughs in new energy and carbon capture technologies have effectively reduced carbon emissions from energy and industrial production. The popularization of intelligent manufacturing and digital energy management accelerates the low-carbon transformation of high-energy-consuming industries such as iron and steel. Meanwhile, technological innovation has spawned new energy vehicles, energy conservation and environmental protection industries, creating numerous jobs. It fully verifies that innovation is the primary driving force for the coordinated development of the CES system.

4.2 Impact of Energy System

Energy is the basic element for the operation of economy and society. At present, the energy industry is in the green transformation stage with dual effects. On the one hand, clean energy replacing fossil fuels helps cut carbon emissions and meet the requirements of carbon peaking and carbon neutrality. On the other hand, the construction of clean energy infrastructure requires massive investment with a long payback period, which occupies development resources in the short term. Meanwhile, traditional energy still guarantees the rigid demand of industry and residents, leading to continuous high carbon emission pressure. At present, transformation pains dominate, and the energy system imposes negative constraints on coordinated development. Its positive dividends will be released gradually after the energy system is fully mature[1,13].

China is in the critical period of in-depth energy structure transformation. While promoting coal reduction and expanding the installation and application of wind power, photovoltaic and other clean energy, the supporting industrial chain of clean energy is still imperfect. Rigid energy demand makes high-carbon industries difficult to withdraw in the short run. The negative impacts of traditional energy are still prominent. In the long run, with the comprehensive green transformation of the energy system, it will evolve from a restrictive factor into a booster for coordinated development.

4.3 Impact of Ecological System

The ecological system is the long-term guarantee for the coordinated development of the CES system. Afforestation, wetland restoration and other ecological projects enhance natural carbon sinks and make up for the deficiency of artificial emission reduction. A sound ecological environment fosters eco-tourism, green agriculture and other industries and improves residents' well-being. Although partial ecological governance overlaps with terminal emission reduction of technological renovation, the ecological system always exerts positive enabling effects and serves as the fundamental support for coordinated development[14-15].

At present, the comprehensive benefits of ecological construction in China have been gradually manifested. Carbon sink forests, wetland restoration projects steadily improve carbon sequestration capacity. Ecological resources are transformed into economic advantages and people's well-being. It is proposed to build a dual-driving model of technological emission reduction and ecological carbon sink to further amplify the positive effects of the ecological system.

5 Conclusions and Implications

Based on complex system theory, self-organization theory, ecology and synergetics, together with the Haken model and other systematic scientific theories, this paper investigates the Carbon Peaking-Carbon Neutrality, Economy and Society (CES) complex system, and clarifies its evolutionary laws, collaborative mechanisms and external influencing factors. The main conclusions are as follows:

First, the CES is an open, non-equilibrium self-organizing dissipative complex system composed of carbon peaking & carbon neutrality, economy and society subsystems, featuring dynamics, symbiosis, diffusion and guidance. Internal and external factor exchanges promote system upgrading, and core order parameters dominate the overall evolutionary direction.

Second, the CES realizes self-organization evolution through four core mechanisms: evolution is the source of system development; the selection mechanism screens evolutionary units; the spillover mechanism generates cross-regional demonstration effects; the guidance mechanism triggers structural mutation and forms new ordered states.

Third, the three external factors show differentiated effects. Technological innovation is the core engine; the energy system is a negative constraint during the transformation period; the ecological system provides long-term fundamental support.

To conclude, the CES coordinated development focuses on balancing carbon reduction, economic upgrading and social efficiency. Its three subsystems are deeply coupled and dynamically adapted. Technology, energy and ecological factors serve as the core driver, temporary constraints and long-term support in turn, collectively shaping the system's evolution and coordination level. Based on the evolutionary rules and external influences of the CES system, this paper proposes the corresponding enlightenment for advancing China's economic and social sustainable development amid the dual carbon goals.

Strengthen the leading role of technological innovation and build a full-chain low-carbon development system. Increase R&D investment in low-carbon, new energy and digital technologies, accelerate the low-carbon transformation of traditional industries, and cultivate green emerging industries to resolve the conflict between carbon reduction and economic development.

Promote energy green transformation step by step. Balance traditional energy supply and clean energy layout in the short term to alleviate transformation pains; improve the clean energy industrial chain in the long run to release positive benefits.

Adhere to the dual-driving of technological emission reduction and ecological carbon sink. Continue ecological restoration and carbon sink construction, avoid functional overlap, and convert ecological advantages into economic and social benefits.

Improve multi-dimensional selection mechanisms. Give full play to the roles of market, society and institutional constraints to guide the CES to develop towards low-carbon, efficient and sustainable direction.

Make full use of spatial spillover effects. Promote the replication and promotion of advanced low-carbon models across regions, and build a nationwide coordinated development pattern.

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