博士論文

Low carbon transition based on economic and technological perspectives: The combination of agent-based modeling with socio-technical approaches

(経済的及び技術的観点からの低炭素移行：社会技術的方法論と融合したエージェントベースモデリング)

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List of abbreviations and acronyms

Acronym	Full term
LCT	Low carbon transition
MLP	Multi-level perspective
M0	Mark 0
M1	Mark 1
PE	Punctuated equilibrium
ABM	Agent based modeling
ST	Social technical
CO2	Carbon dioxide
ETS	Emissions Trading System
EU	European Union
SDG	Sustainable Development Goal
DS	dynamical system
PD	Population dynamic
CRISIS	Complexity research initiative for systemic instabilities
DES	Distributed energy system
CM	Carbon market
IAM	Integrated assessment modeling
ST-MLP	Social technical-multi level perspective
WCI	West climate initiative
EU-ETS	European Union emissions trading system
US ETS	United states emission trading system
UK	United Kingdom
3E	Energy-environment-economy

OI	Open innovation
FU	Full unemployment
FE	Full employment
EC	Endogenous crises
RU	Residual unemployment
FDI	Foreign direct investment
T1	Transition pathway 1
T2	Transition pathway 2
T3	Transition pathway 3
R1	Regime 1
R2	Regime 2
ESG	Environment, Social, Governance

List of parameters

Parameter	Description
$E(t)$	Amount of energy that a firm has retained
$r_h\ (t)$	Rate of high-carbon-energy’s development
$r_l\,(t)$	Rate of low-carbon-energy’s development
$i_{n,h}^{eff}\ (t)$	Effective high carbon energy capacity for the firms at node n
$i_{n,l}^{eff}\ (t)$	Effective low carbon energy capacity for the firms at node n
$s_h\ (t)$	Number of firms that purchase high carbon energy
$s_l\ (t)$	Number of firms that purchase low carbon energy
$\rho_n^z(t)$	Local firm number within the vicinity *z* of node n
e_{con}	The amount of industrial firm’s energy consumption
e_{sub}	The threshold of firm’s reproduction
i_h	The amount of energy provided by one unit of high carbon energy.
i_l	The amount of energy provided by one unit of low carbon energy.
β_h	Market sensitivity coefficient for high carbon energy
β_l	Market sensitivity coefficient for low carbon energy
b_h	Market sensitivity coefficient for high carbon energy
b_l	Market sensitivity coefficient for low carbon energy
c	The amount of industrial firm's energy consumption
d_h	The amount of energy provided by one unit of high carbon energy
d_h	The amount of energy provided by one unit of low carbon energy
a_h	Rate of high-carbon-energy’s development
a_l	Rate of low-carbon-energy’s development
e_h	Amount of high carbon energy
e_l	Amount of low carbon energy

N	Amount of firm
N_f	the indicator of economic prosperity
R_l	the implementation of low carbon transition.
c	The coefficient of consumption budget
β	Market sensitivity coefficient
η_+	Hiring propensity
η_-	Firing propensity
δ	Dividend’s ratio
ϕ	Revival probability
γ_p	Price changing efficiency
Θ	Financial bankruptcy threshold
dep_n	Firm’s deposit
Θ'	Bankruptcy threshold for energy
t_b	Life of firms in energy shortage
E_n	Energy obtained by firm n
m_f	Environmental cost
f_h	High carbon technology adopter
f_l	Low carbon technology adopter
G_h	Total performance of the high carbon technology
G_l	Total performance of the low carbon technology
ξ	Basic performance uncertainty of the low carbon technology
D	Total performance gap
η_h	Probability of choosing high carbon technology
η_l	Probability of choosing low carbon technology
α	Execute rate

α_{lh}	Execute rate switching from low carbon technology to high carbon technology
α_{hl}	Execute rate switching from high carbon technology to low carbon technology
β	Uncertainty degree of selection probability
$\boldsymbol{\Omega}$	Potential function of the system transition
P_h	Basic performance of high carbon technology
P_l	Basic performance of low carbon technology
b_h	Externality benefit of high caron technology
b_l	Externality benefit of low carbon technology
$\bar{p}_h$	Performance ceiling of high carbon technology
$\bar{p}_l$	Performance ceiling of low carbon technology
c_h	Learning characteristics of the high carbon technology
c_l	Learning characteristics of the low carbon technology

List of terminology

Term	**Meaning**
Low carbon transition	Society shifts from fossil fuel-based economy to low-carbon energy-based economy
Multi-level perspective	The Multi-Level Perspective (MLP) is an analytical tool that attempts to deal with the complexity in social change.
Mark 0	Minimal macroeconomic model
Mark 1	Macroeconomic model
Punctuated equilibrium	Punctuated equilibrium predicts that a large number of evolutionary changes occur within a short period of time linked to the speciation event.
Agent based modeling	Agent-based simulation modeling focuses on the individual active components of a system, making it a natural step toward understanding the complexity of business and social systems.
Economic cycle	Economic cycles are fluctuations in the economy during expansion (growth) and contraction (recession).
Distributed energy system	Distributed energy system is a term that includes a variety of energy generation, storage, monitoring and control solutions.
High carbon energy	Coal, oil, natural gas, and other fossil energy are known as high-carbon energy
Low caron energy	The water, nuclear, wind, solar, geothermal, ocean, biomass energy, and other renewable energy are known as low carbon energy
Social technical approach	A methodology to analyze relationships between people, environment, and technologies, etc. in society
Technology diffusion	The process of spreading innovation through certain channels among the members of a social system over time
Spillover effect	A spillover effect is usually the impact experienced in a region or the world at large as a result of an independent event that

	occurs as a result of a seemingly unrelated event. Spillover effects can result in negative or positive outcomes.
Emission trading system	The ETS operates on a "cap-and-trade" principle. A cap is placed on the total amount of certain greenhouse gases that can be emitted by the facilities covered by the system.
Integrated assessment modeling	In climate change assessment, integrated assessment refers to activities that consider the social and economic factors that drive greenhouse gas emissions, the biogeochemical cycles and atmospheric chemistry that determine the fate of these emissions, and the consequential impacts of greenhouse gas emissions on climate and human well-being.
Leverage	Leverage is generally defined as the ratio of total assets to equity capital in the balance sheet

Chapter 1 Introduction

1.1 Low carbon transition (LCT)

1.1.1 Introduction of LCT

The urgent need to mitigate climate change requires the transition to a low-carbon society. Such a LCT is characterized by major changes in the energy supply and demand systems, accompanied by the energy trilemma (i.e., safety, fairness, and sustainability) and is related to rapid economic growth, energy consumption, and environmental pressure (i.e., the energy-economic-environmental dilemma). It is a big challenge to find a reasonable LCT trajectory for society and the policymakers and to establish suitable tools and frameworks to guide initiatives for the sociotechnical change and economic impact [1-4].

The number of local governments nationwide that have declared that they will become a "Zero Carbon City" is increasing. In 2020, Prime Minister Yoshihide Suga declared, "Japan aims to realize a carbon-free society that will eliminate greenhouse gas emissions as a whole by 2050." South Korea has launched a Green New Deal and committed to net-zero greenhouse gas emissions by 2050, and China also committed to achieving carbon neutrality before 2060. In addition, the Biden administration returned to the Paris Agreement and made similar commitments. These new commitments are a cause for celebration, but the real work is just beginning. It is not easy to achieve both decarbonization and regional revitalization. In what has been and continues to be a difficult period for the government, policymakers refer to the best academic output to make the decision of what and how to design the political strategy in terms of technological and economic concerns.

LCT is a complex process involving the dynamics of technological evolution, social changes, culture discourses, and political struggles. The difficulties in providing rational policy suggestions for LCT lies in the fact that it is a goal-oriented transition involving interactions between multiple societal groups [5-7]. To describe and analyze the evolution of human society on such a vast scale, Geels developed the concept of sociotechnical systems using a multi-level perspective (henceforth ST-MLP) [8]. Unfortunately, using a multi-level perspective (MLP) framework, the concepts and tools used to niche-level investigate innovation dynamics and regime-level economic crisis impact are less elaborated. Such limitations make it difficult to determine further details about transition dynamics.

To tackle the shortcomings of MLP, as a powerful and complementary method to solve the co-evolution of technology, the economy, and society and to increase the knowledge regarding LCT, scholars have pointed out that a connection between computational models and the MLP conceptual frameworks is highly recommended [9]. Furthermore, since the integrated assessment method (IAM) is too simple and makes it difficult to consider technology and the economy together [2], there are many reasons for adopting a model based on complex system theory such as agent-based modeling (ABM), because it is a powerful tool for forward-looking and systematic analysis. ABM can examine the co-evolution of technology, the economy, and the environment to achieve predetermined goals under given policies and social conditions, and the model can also generate quantitative and forward-looking scenarios to describe the future state of non-linear social technological systems.

Therefore, because there is no existing review systematically reflecting on what integrative research has done thus far in the case of LCT and climate mitigation strategies that combine MLP and ABM [2], in this thesis, it is seek to develop a co-evolutionary framework that takes advantage of the richness of these two methods while providing a flexible framework to analyze the current topics of theoretical and policy interests related to LCT.

More detailed research challenges and solution strategies are provided in Section 1.2 and 1.3.

I. New mechanisms for LCT

LCT needs new mechanisms such as the combination of a carbon market, energy market, and environment market. In addition, a new energy system that can cultivate the low-carbon energy, such as a distributed energy system, is required.

An emissions trading system (ETS) is a market-based energy efficiency and emissions reduction policy tool for reducing greenhouse gas emissions. Following "cap-and-trade" principles, the government imposes a cap on carbon emissions from one or more industries. Companies participating in the carbon trading system are then required to have a one-unit carbon allowance for every ton of carbon dioxide emitted. They can acquire or buy these allowances or trade them with other companies.

The current relatively mature international carbon trading systems are as follows [10]:

(1) The European Union Emissions Trading System (EU ETS) was the world's first major carbon trading system.

(2) The Regional Greenhouse Gas Initiative (RGGI) was the first mandatory emissions reduction system with a carbon trading market in the United States (US).

(3) The Western Climate Initiative (WCI) is a comprehensive carbon market for multiple sectors.

(4) The Korea Carbon Emissions Trading Market is the first carbon market trading market in East Asia.

(5) New Zealand's carbon emissions trading market.

(6) China's carbon emissions trading market was officially opened in June 2021.

Taking the EU as an example, the ETS is an economic guarantee for advancing their LCT.

The impact of EU carbon trading on the energy industry is as follows. Since the implementation of the EU ETS, overall carbon emissions in the EU have dropped significantly, and the EU has developed an energy and climate policy package for 2030 and implemented the "European Green Deal" to support the goal of climate neutrality by 2050.

The impact of EU carbon trading on the market is as follows: The implementation of the EU ETS has impacted product markets, industry competitiveness, corporate performance, and capital markets.

Conversely, the establishment of the global carbon market is one solution to transition toward a low-carbon society. The advantages of introducing financial calculations to measure carbon emissions are obvious, including emissions control and cost control. In 2019, 96 out of the 185 parties that submitted their Nationally Determined Contributions (NDCs) to the Paris Agreement—representing 55% of global greenhouse gas emissions—have stated that they consider using carbon pricing to meet their emissions reduction targets [11]. China, for example, released draft ETS regulations for public consultation. As stated, the power sector will be the first sector to follow an ETS and such obligation will gradually expand to other sectors [12]. With an initial agreement at the landscape level already being achieved based on the Paris Agreement, some design options have emerged in different regions. Scholars and policymakers are working together to support further development of innovation and facilitate the process toward a low-carbon society. For an ideal economic design, a single global carbon market is preferred because every ton of greenhouse gas emitted anywhere in the world will affect everyone in the world. However, this dream seems to be far away, especially when we see a multiplicity of regional, national, and even subnational markets emerging. So instead of the top-down approach introduced by the Kyoto protocol, a more workable policy focusing on a bottom-up "linkage" of multinational, national, and subnational cap-and-trade systems has recently been discussed [13].

Carbon markets look set to spread geographically. The linking of ETS is a widely discussed policy option for future international cooperation on the climate change issue. In the Paris Agreement, adequate collective ambition is emphasized, which calls for a broader range of cooperation among different regional markets. The merits of international emissions trading are internationally recognized, including the aspects of efficiency gains [14], cost savings, and market liquidity. The linkage agreements could also provide mechanisms for countries to coordinate and harmonize their emissions caps, price controls, and other design features. Such decentralized linkages could augment and complement other elements of an international hybrid policy architecture [15]. A transatlantic link between the EU ETS and a potential US ETS is currently a high priority for the EU [16]. The motivation for linkage depends on a variety of economic, political, and strategic factors. Although there have not been enough cases for a successful linkage, the primary goal of linkage is quite clear—to achieve less emissions at a lower cost. Under the emerging consensus that linking ETS has the potential for promoting the further development of LCT, more research must be conducted to figure out the mechanism for such linking.

Linking regional markets requires coordination and the alignment of policy objectives between systems. Because linkages equalize carbon prices, a precondition for linking markets is that policymakers in both systems have similar levels of ambition or expectations about the carbon price [17]. Thanks to the Paris Agreement, more scholars and policymakers are working together to facilitate policy coherence across different regions under the same desire to reduce carbon emissions. But even with linked systems that share the same horizon of expectation when they decide to link, the carbon price of each system can fluctuate at different levels over time. The carbon price may simply indicate additional damage caused by the emissions of an extra ton of carbon dioxide (CO_2). A higher carbon price implies that one system is more mature in its use of low-carbon energy. On one hand, a high cost of carbon emissions will put great pressure on high-carbon industries, making low-carbon industries more competitive in the market. On the other hand, the high cost of carbon emissions indicates that there is a reasonable substitute for high-carbon energy. That means that renewable resources have been widely used in daily life to some extent. The classification is based on the level of the carbon price of the two linked systems, in other words, the level of development in LCT. Different financial strategies should be adapted for different patterns, since there will be different stumbling blocks.

II. New systems for LCT

In addition to carbon markets, other financial innovations such as carbon taxes and green bonds, and social innovations such as distributed energy systems (as shown in Figure 1.1), ESG

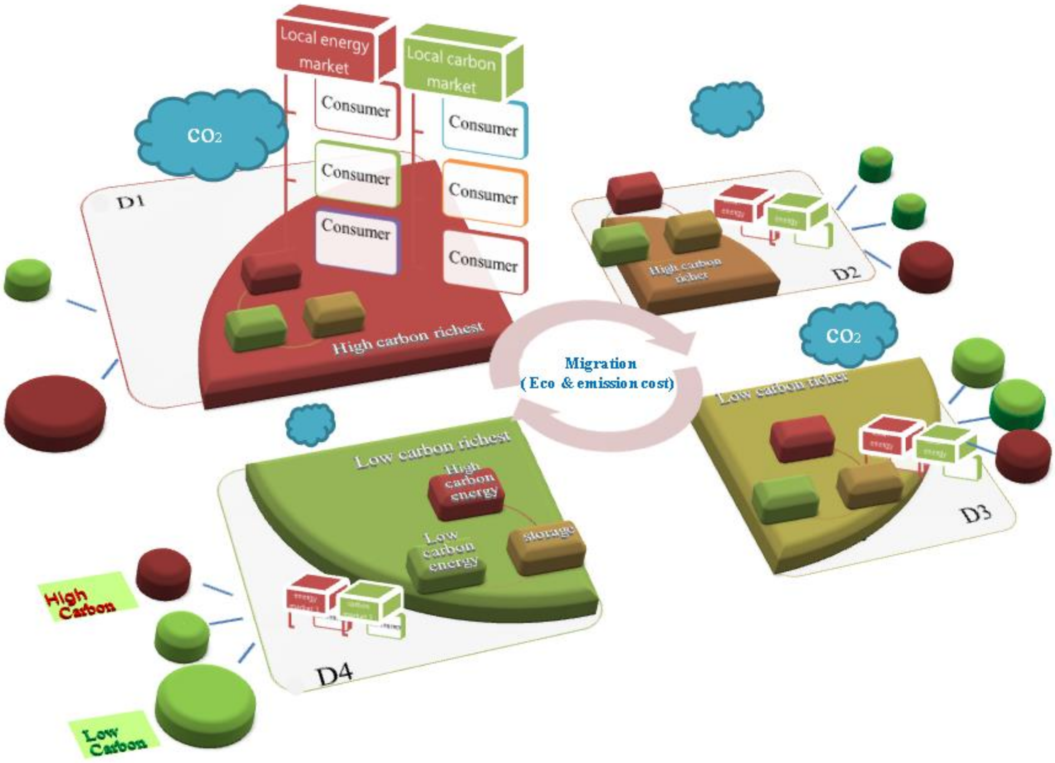


Fig.1.1. A schematic map of distributed energy system combined with localized energy market: Multiple energies distributed in different urban areas [from D1 with the richest high carbon energy to D4 with the richest low carbon energy] and supplied by both the energy produced inside and outside the districts (red: high carbon energy; green: low carbon energy; brown: storage); Various types of consumers carry out transactions in localized energy and carbon market (blue cloud: CO_2 emission); The introduction of carbon, energy use right, and renewable allowance markets favors the development of low carbon energy and restricts the usage of high carbon energy.

(Environmental, Social and Corporate Governance), etc. are important. ESG is an important indicator for evaluating a company's performance on environmental, social, and corporate governance issues. Moreover, international financial, technological, and policy connections and interactions are also becoming increasingly important.

1.1.2 System involved in LCT

The transition is just beginning. Two mutually reinforcing challenges are LCT complexity and the scale determination of the pace of the transition.

The complexity of LCT stems from different components of the system itself and their interdependence with components outside of the specialized system.

This section explores the various dimensions, narratives, and perspectives to help foster a greater understanding of the factors that determine the speed of an LCT. An LCT can thus be seen as a change in the scale of the “system of systems.” [18-20]

1.1.2.1. Economic system

The key challenge of LCT in an economic system is for countries to decouple economic growth from energy consumption and manage rising energy demand while ensuring growth and environmental sustainability. The extent to which energy consumption is decoupled from economic growth depends on an economy’s stage of growth and its development path. For example, the early stages of economic growth are usually associated with increased levels of energy consumption and carbon emissions [21].

Given the urgency of the climate challenge, an important issue is how the governments of advanced economies can cooperate with developing countries to promote sustainable growth in emerging economies. Technological transfer has always been an important element of promoting sustainability [22].

1.1.2.2. Technological system

From a technological perspective, the key goal of LCT is to replace fossil fuel-based technologies that dominate society with more efficient, low-carbon alternatives.

Innovations in an LCT system are either incremental or breakthrough. Accelerating the pace of LCT requires breakthrough innovations. Breakthrough innovations cannot be realized in a short time frame, and they are inherently time- and capital-intensive and vulnerable to uncertainty in the markets and the political climate [8].

1.1.2.3. Political system

Policy is not made in isolation but is closely interdependent with what is happening in economic, technological, and financial systems. What happens in these areas determines the course of LCT policy and vice versa [23].

At the same time, equity and fairness should be sought in the allocation of socioeconomic costs.

Policies also need to promote inclusive growth [24]. This is not an issue limited to developing countries.

1.1.2.4. Financial system

To facilitate LCT, more attention should be paid to the promotion of green finance.

We can see from the Paris Agreement that [25] aside from the development of low-carbon technology, the introduction of financial elements to facilitate greenhouse gas elimination are also urgently needed. It has been reported that about 1,300 companies have disclosed the use of internal carbon pricing, or plan to implement internal carbon pricing within 2 years. In 2019, 46 national and 28 subnational jurisdictions have put a price on carbon [26]. Around the world, markets in permits or credits to emit greenhouse gases are emerging. Attention should be paid to how financial methods are engaging in LCTs. Some researchers have shifted their focus to applying financial mathematics to explore rationality and other characteristics in the establishment of green finance [27,28]. These articles give valuable insight into possible green financial structures.

Green bonds are debt instruments used to finance green projects that deliver environmental benefits. As an integral component of green finance, they aim to support green projects to maintain market reputation. Having emerged in 2007 with the emergence of the European Investment Bank's "climate awareness bonds," the market for bonds with a green label has grown rapidly in the past few years [29]. There has also been an increasing diversification of issuers and investors joining this market.

It is also challenging to examine how the new financial mechanisms and innovations described above intersect with economics, technology, and policy to make LCT more efficient.

1.1.3 Social and academic significance of the LCT study

Current research on LCT has focused on policy and has been very intensely discussed. Denmark, for example, has gone through a long journey with LCT. There have been attempts and failures.

Although Denmark tried to make an LCT in the 1960s, the technology policy and other aspects were immature. Several oil crises in the 1970s made Denmark more determined to promote LCT, but it was difficult to make a successful transition in such a short time. Furthermore, the lack of financial support caused by the economic and energy crises had a negative impact on LCT.

However, at the same time, the establishment and promotion of new mechanisms and systems (e.g., distributed energy system, carbon market, and regional energy market with a peer-to-peer trading system) bring some hope to LCT. Various policies have also started to try new options using new systems and mechanisms.

The question at hand is how to find accurate policy recommendations, while discovering the main factors and reasonable transformation paths, to achieve LCT.

Other countries such as the United Kingdom (UK) face the same challenge; that is, how to find accurate policies to guide the technical, economic, and financial systems to promote LCT [30].

On the other hand, the five major waves of innovation since the Industrial Revolution have been characterized by social, economic, and business reinvention. Now, we can learn from the history of innovation that humanity is facing a new sixth wave, the Green Innovation Wave. Again, innovation is unimaginable until it arrives, and good stories of new mechanisms and systems can help us conceive and achieve smooth systemic change.

Therefore, by conducting research to obtain the accurate policies become even more important.

1.2 Current LCT research and problems

1.2.1 Two existing approaches

1.2.1.1 Conceptual approach: social technical approach

A transition theory framework can be used in a wide range of contexts and clearly focus on participants and dynamic paths to analyze LCT innovation [9]. There are many analytical frameworks that can be used heuristically to express the multidimensionality and complexity of LCT and transformations in sociotechnical systems.

The social–technical approach, called an MLP, is used to view technological transitions. MLP is the study on socio-technical transitions towards low carbon society and find path through which configurations of markets, institutions, infrastructures, technologies, and social practices and can change to fulfil the functions in a more sustainable way. Moreover, MLP can help design policy [31]. MLP distinguishes between three levels of concepts [32]—niche innovations, sociotechnical regimes, and the sociotechnical landscape. MLP argues that the transitions are the outcomes of the interactions between the three levels. It identifies several phases in these transitions, as depicted in Figure 1.2. In the first phase, radical innovations with different design options emerge from the niche level, on the fringe of the existing landscape and regime. In the second phase, market niches provide resources for further development and specialization for unmatured innovations. A dominant design emerges with expectations and associated rules beginning to stabilize. In the third phase, the dominant design breaks through more widely and begins to compete head-on with the established regime. The fourth phase is characterized by regime substitution. The new regime gradually becomes institutionalized and increasingly endogenous [33]. There are similar technologies in LCT, and the kinds of choices made in terms of the actors that are driving the institutions leading to transitional pathways.

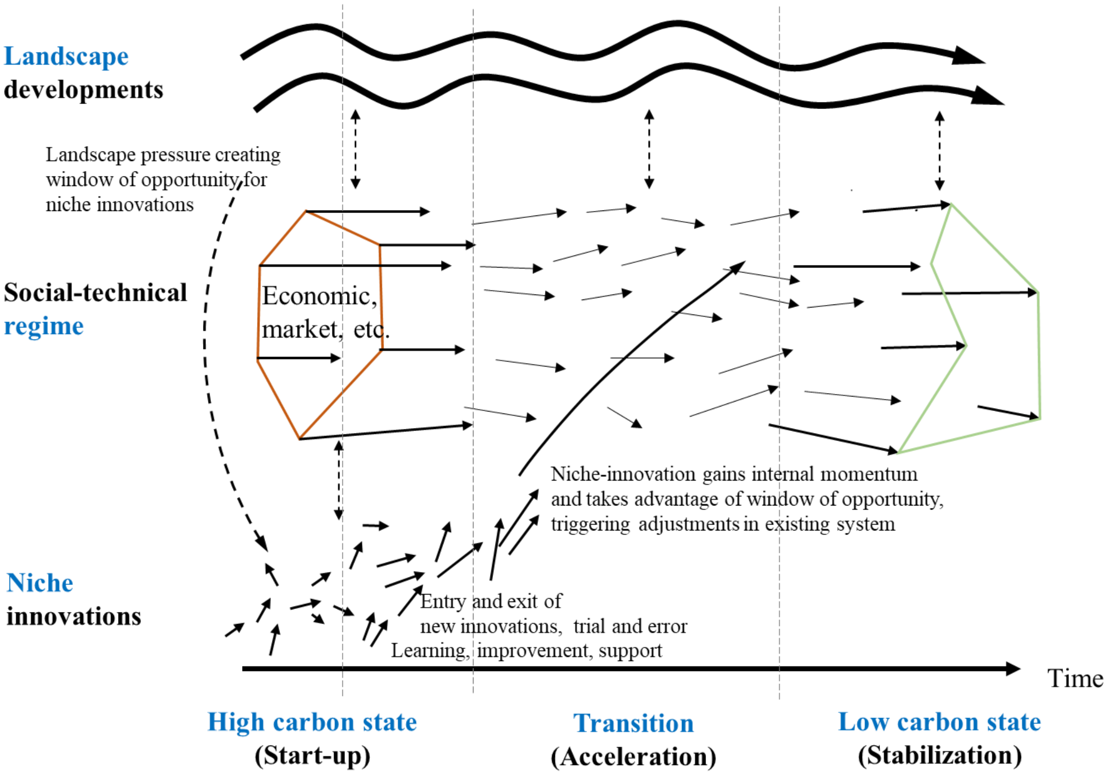


Fig.1.2 An overview of multi-level perspective on technology transition

For a transition with complex actors' activities and strategy formulation (which may be the core driving force for niche evolution), ST-MLP's analytical capabilities are still far from sufficient because the emergence and development of new technologies and innovations on the niche level is still lacking. Empirical analysis with ST-MLP usually reflects the complexity of real-world developments. However, the strength of MLP can also be its weakness. As sociotechnical regimes are a broad unit of analysis, ST-MLP is still quite a complex and comprehensive framework, which makes it difficult to theoretically describe what constitutes the regime and define the boundaries of a specific system [34]. Such ambiguity prevents the ST-MLP approach from giving a detailed description of transition dynamics within a specific field of perspective.

1.2.1.2 Simulation approach: equilibrium and nonequilibrium simulation approach

There are two types of simulation models for LCT research. First, there are equilibrium models, such as IAMs for climate change, that are designed to support climate policy by linking long-run climate goals to the evolution of the energy and the environment. IAM Integrated assessment modelling (IAM) or integrated modelling (IM) is a term used for a type of scientific modelling that tries to link main features of society and economy with the biosphere and atmosphere into one modelling framework. Second, non-equilibrium models like ABM are designed to simulate the co-evolution of society, the economy, and technology, including the interactions and behavior of various actors. The main characteristics of equilibrium and non-equilibrium simulation models are listed in Table 1.1.

Table 1.1 Characteristics of equilibrium and non-equilibrium models.

	Equilibrium	Non-equilibrium
Dominant paradigm	IAM	ABM
System creation	Top-down	Bottom-up
Model characterization	Static	Adaptive
Dynamic	Inputs	Actors, behaviors, relationships, and inputs
Transition and resistance	Invisible	Can be traced back to individual agents
Heterogeneous	No	Yes
Feedback loops	No	Yes
Learning behavior	No	Yes
Emergence behavior	No	Yes
Interaction	No	Yes

I. Equilibrium model

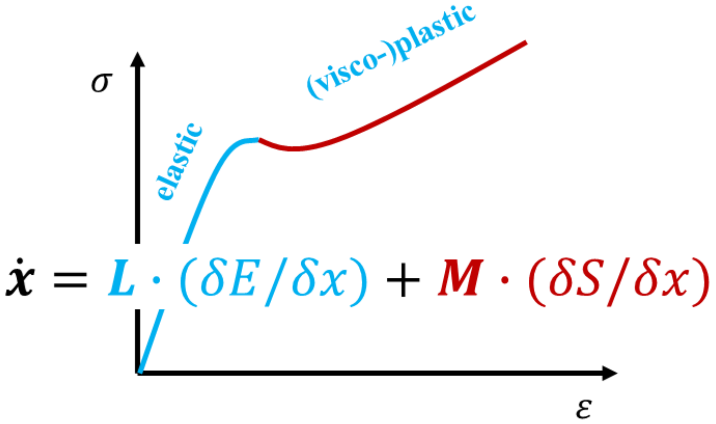


Fig. 1.3. Equilibrium model

Economics became a science in an era in which most social scientists try to imitate Newtonian physics that require human beings to be as predictable as electrons. Adam Smith's *Wealth of Nations*

(1776) [35] was inspired by Newton's *Principles*. Leon Walras transformed Smith's ideas into a Newtonian economic model known as the general equilibrium model [36]. However, at present, most of the predictions about LCT come from equilibrium models, such as IAM, that are simply not suitable for coping with transitions. In addition, using equilibrium models to study LCT has several drawbacks. First, they are static in nature. In the model, it is assumed that external shocks can cause the system to transition from one equilibrium to another, but the transition itself is irrelevant. Second, they are top-down models that assume that "rational" actors can be represented by several "representative" aggregated agents, and these "rational" actors only strive to maximize their utility. Third, capturing related self-reinforcing (positive feedback) processes and mutual interactions or influence among agents (multi-agent interactions) cannot be considered. Fourth, they are unable to represent path-dependency and multiple or co-evolutionary solutions. Finally, they cannot properly take into account heterogeneity of the agent.

II. Non-equilibrium model

Based mainly on modeling various decision-making processes and heterogeneous actors, ABM enables the modeler to estimate the influence of interacting behaviors described by simple rules [37-39]. In ABM, a collection of autonomous agents is modeled within a system, and these agents can make their own decisions to realize complicated interactions based on a set of rules. Thus, since it can reflect the interactions arising from the evolution of technical and economic factors as well as social actors, ABM is suitable for researching socioeconomic and sociotechnical systems [40]. In addition, ABM is a highly flexible method with the ability to change levels of description and aggregation [37], and because it can generate emergency phenomena from the bottom up, it can be used to analyze transitions. By observing the agent's reactions to changes under specified environmental rules, it is possible to find that certain parameters change dramatically both before and after these changes due to agent interactions. By defining proper-order parameters, it is possible to use proportional charts [41], time series diagrams or plots [42], phase diagrams [1,43,44], and other analytical tools to study the conditions and timings for which and when the transitions may occur. Phase diagrams of key systemic variables are powerful tools for studying the potential behavior of dynamic systems over time. Phase diagrams reveal not only the possible existence of equilibrium, but also all potential state trajectories starting from all feasible initial states [45]. Thus, phase diagrams enable us to figure out which regions of a system state can be reliably reached and further illustrates possible transition paths between different states, which makes ABM a powerful tool for conducting transition studies.

In short, systems experiencing LCT are complex adaptive systems [46], including interactions that may lead to the emergence of new phenomena and patterns. In addition, LCT is naturally involved sociotechnical and economic change. This is a highly self-reinforcing and non-linear process with the expectation of locking in drivers that are motivated by the selection and adoption of different agents with diverse perspectives and preferences (e.g., Geels) [47-48]. For such systems, the behavioral and complexity sciences provide an appropriate analytical framework, while equilibrium models do not.

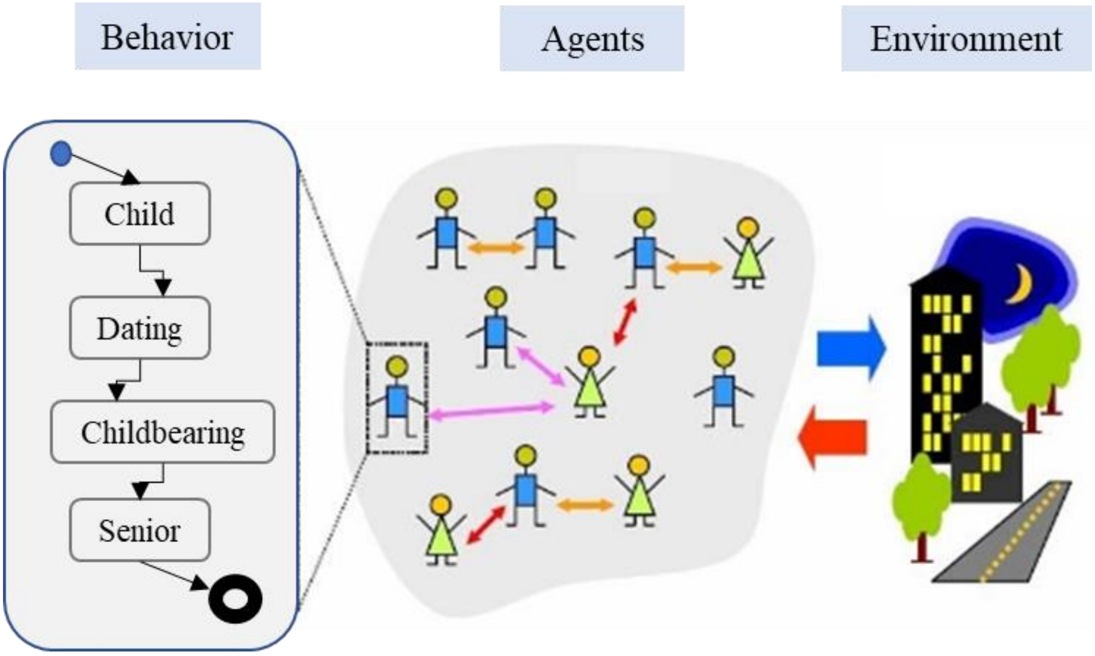


Fig. 1.4. Non-equilibrium model

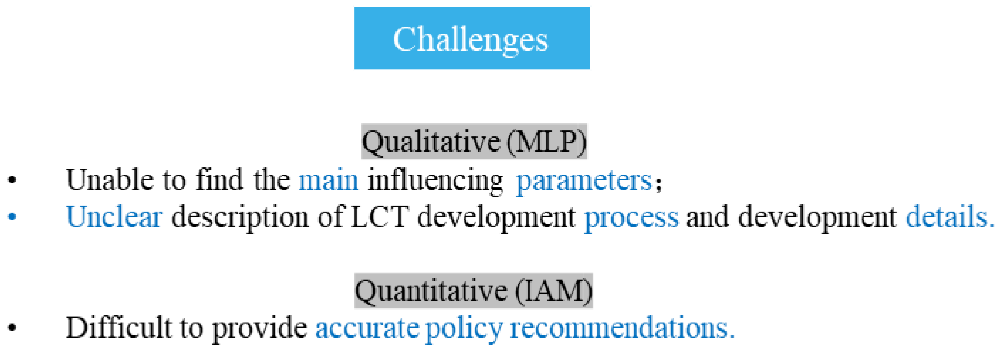
1.2.2 Current problems in the LCT research

In response to the need for LCT policy guidance in social systems such as Denmark and the UK, there are different qualitative and quantitative challenges for academic research (as shown in Figure 1.5).

For currently widely used qualitative research methods, such as MLP, not only is it impossible to find the main influencing parameters, but the description of LCT development processes and development details are also unclear [49].

It is difficult to provide accurate policy recommendations [50] for quantitative models such as IAM, which have been adopted by some scholars.

Therefore, to seek more specific and accurate guidance for social system LCT policies, new combined qualitative and quantitative research strategies and combinatorial modeling strategies (e.g., economic, technological, etc., models) are needed in academic research.



Challenges

Qualitative (MLP)

- Unable to find the main influencing parameters;
- Unclear description of LCT development process and development details.

Quantitative (IAM)

- Difficult to provide accurate policy recommendations.

Fig. 1.5. Analytical challenges of LCT study

1.3 The solution of the thesis

1.3.1 Model selection

ABM is highly correlated with complexity science and econophysics.

Over the last three decades, a new scientific term called “complexity science” has emerged. Complexity is an unequivocal concept [51] whose definition differs from author to author [52]. In the 1990s, an area combining economics with physics called “econophysics” emerged [53,54].

The era of complexity in economics has produced a large number of studies of micro-interaction models in which human behaviors are associated with abstract rules for generating interactions. These studies have given rise to the emergence of ABM, which can be considered a class of models that simulates the actions and interactions of multiple autonomous agents in a complex situation [55,56].

There are four main ABM techniques used in economics [57-60] as follows:

- a deductive approach with perfectly rational ABM (a deductive way of applying ABM associated with classical economic approach based on perfect rationality);
- an abductive approach with adaptive ABM (adaptive ABM and abductive reasoning);
- a metaphoric approach: bottom-up, agent-based econophysics (transfers terms from the physical or biological sciences as the source domain into economics as the target domain through a theoretical bridge between the source and target domains); and
- a phenomenological approach: top-down, agent-based econophysics (associated with macro-laws, such as power laws that are well-known by statistical physicists).

Therefore, ABM has been integrated with tools from econophysics and evolutionary theory, becoming a natural laboratory for theoretical socioeconomic studies.

1.3.2 Combination of different models

To address the academic challenges of LCT research, this section presents an analytical strategy (depicted in Figures 1.6 and 1.7).

- A research program using a combination of methods to find key factors and reasonable paths for LCT.
- Combining different models so that more specific and accurate policy recommendations can be obtained from the newly combined model.

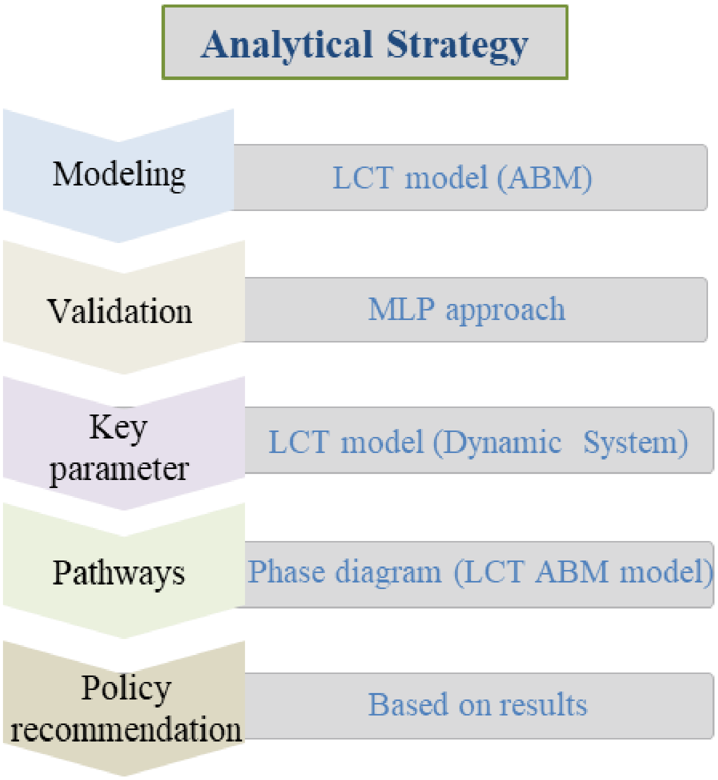


Fig.1.6. Analytical strategy for LCT study

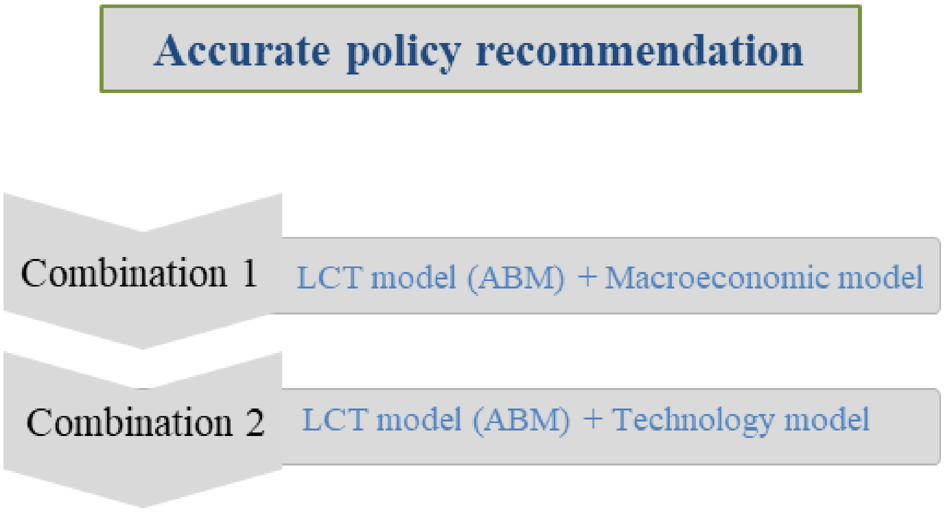


Fig. 1.7. Analytical strategy for LCT study

In conclusion, since the existing methods are too complicated based on data analysis, the research of this thesis focuses on capturing the nature of LCT and, from the viewpoints of the framework model, establishing a simple model to analyze the nature of LCT [50].

To obtain more accurate policy recommendations, it is necessary to build more combination models for research, such as economic, technological, financial, policy, cultural, and other complex system models. Next section will focus on the economic and technological aspects.

1.3.2.1 Economic aspects

I. Economic growth

1) In the view of the **classical economic growth model**, capital accumulation determines economic growth. Historically, most classical economists were physical capital accumulation determinists, who believed that it was the accumulation of physical capital that drove economic growth. They took an agrarian country as the object of study and emphasized the importance of productive capital accumulated from production over consumption, which increases labor productivity and leads to the growth of the national economy by providing plants and machinery.

2) In the view of the **neoclassical economic growth model**, technological progress determines economic growth. Unlike the determinism of physical capital accumulation in classical economics, most neoclassical economists are determinists of technological progress. They introduce the technological progress factor into the economic growth model, and treat both the marginal productivity of capital and the marginal productivity of labor as variables, believing that these two variables depend on the growth rate of labor and capital stock and on the speed of technological innovation, so that technological progress becomes the driving force of economic growth in modern society. Thus, the "innovation economy" becomes the most critical factor driving economic growth in modern societies. As pointed out by Professor Phelps, Schumpeter's *Theory of Economic Development*, published in 1911, broke through the traditional view that economic growth is just a form of capital accumulation (i.e., investment and savings) and discovered that innovation and entrepreneurship play an important role. However, in 1921, Frank Knight found that firms making investment decisions generally face "uncertainty," and Keynes also noted in 1936 that monetary or fiscal policy might help economic growth reach a new equilibrium.

3) Paradigm shift

Energy and environmental economics study the interaction and laws of resources, environments, and economic development. In the process of the sustainable development of human society, the comprehensive advantages of energy and environmental economics and its role and contribution have become increasingly essential, and it has rapidly developed over recent years.

In the study of energy and economic growth models, mainstream economics assumes that energy is realistic and non-exhaustible. In terms of understanding, mainstream economics homogenizes different production factors, ignoring the characteristics of energy and environmental factors. In argumentation, mainstream economics simply abstracts complex and specific energy and environment factor issues as production-cost issues [61].

However, with LCT, the paradigm shift of economics is increasingly considering energy and the environment as the main elements, with the intersection of ecological and environmental economics. The Kennedy School at Harvard University has been working on energy, environmental, and ecological economics in this paradigm shift.

II. Macroeconomic model

The existing macroeconomic models are mainly based on neoclassical growth models, but these models also have the potential to explore research in the process of economic paradigm shifts, such as EURACE, CRISIS, Mark 0, among others. In addition, many scholars have tried to embed information science (IS)-related models, such as data science models, into economic models. It can be predicted that in the future, the new economic paradigm led by energy-related, environmental, and ecological factors and research on economics informed by information science will flourish.

Several ABM of the macro-economy were established such as EURACE [62,63], CRISIS [64] (Complexity Research Initiative for Systemic Instabilities, *http://www.crisis-economics.eu/*), Mark I [65], and Mark II [66].

The Mark 0 model, a typical minimal ABM on the macro-economy, was introduced by Gualti et al. to serve as the skeleton of a macroeconomic ABM in which several different economic statuses can emerge. There are two agents in the model—households and firms. The model is based on the basic assumption of a linear production function with constant productivity as follows:

$$Y_i = \zeta N_i \tag{1.1}$$

where Y_i is output, ζ is productivity determined by technology development, and N_i is labor force. The framework of the Mark 0 model is shown in Figure 1.8.

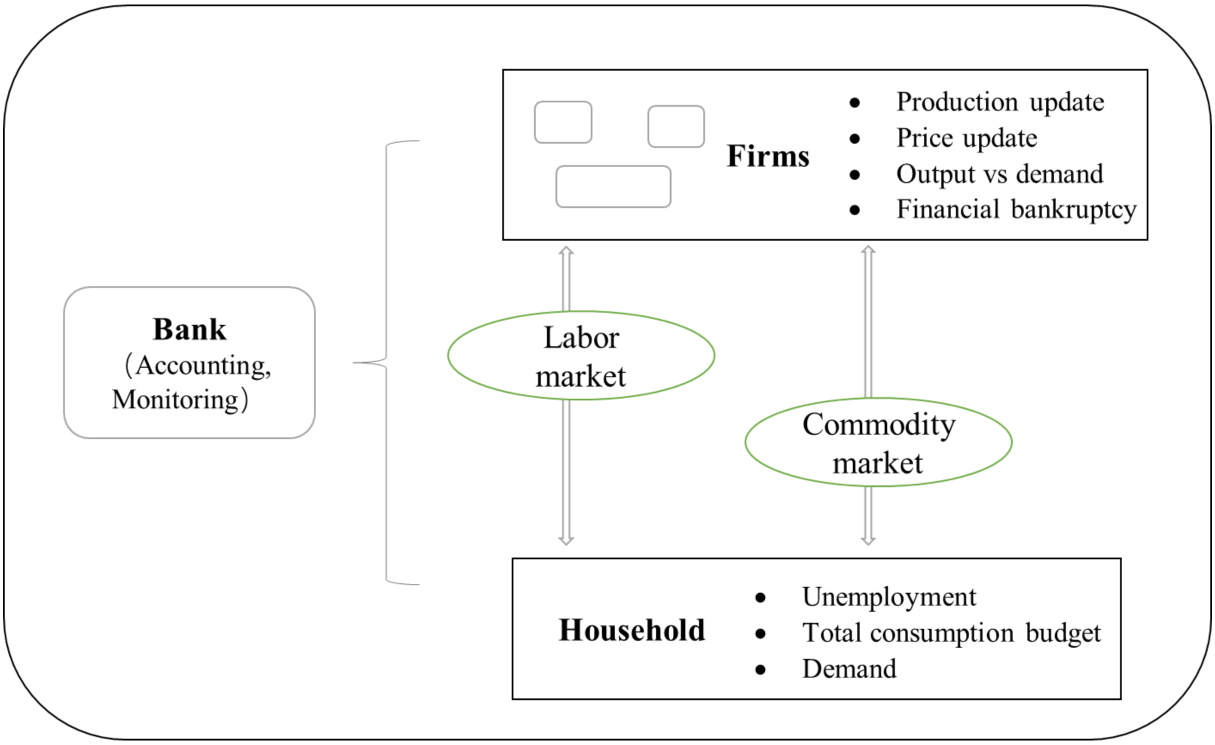


Fig.1.8. The framework of the minimal macroeconomic Mark 0 ABM

III. Decoupling and recoupling of decarbonization and economic growth

1) Decoupling of the brown economy and high carbon energy with environmental considerations

In the past, decarbonization (i.e., environmental considerations) and economic growth were thought to be in conflict. However, in recent years, there has been growing support of separating the two issues and moving forward together. In decoupling economic growth from energy use for transitioning toward a low-carbon economy, the challenge is to find ways in which economic growth can be decoupled from greenhouse gas emissions and fossil fuel consumption. Moreover, the extent to which energy consumption is decoupled from economic growth depends on the stage of the society's economic growth and its development path [67].

2) Recoupling of the green economy and low carbon energy with environmental considerations

As shown in Figure 1.9, traditionally economic growth, energy consumption and environmental protection exist as a 3E trilemma, which is why the decoupling phenomenon exists.

To solve the 3E trilemma to cope with the decoupling phenomenon, LCT is needed to cultivate environmentally friendly low carbon energy [68], as shown in Figure 1.10, while coping with the decoupling phenomenon during the LCT process according to economic growth and the LCT path.

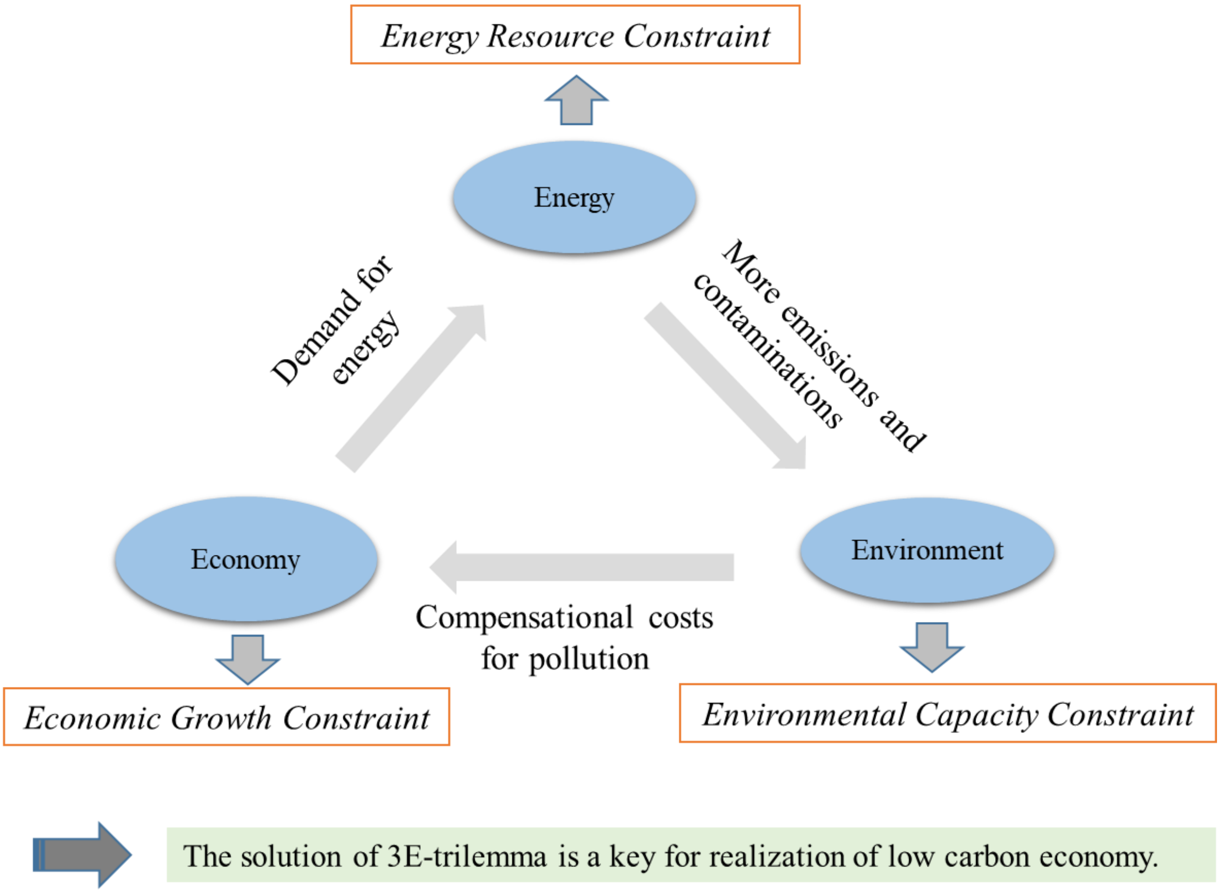


Fig. 1.9. An illustration of the energy, economy, and environment trilemma

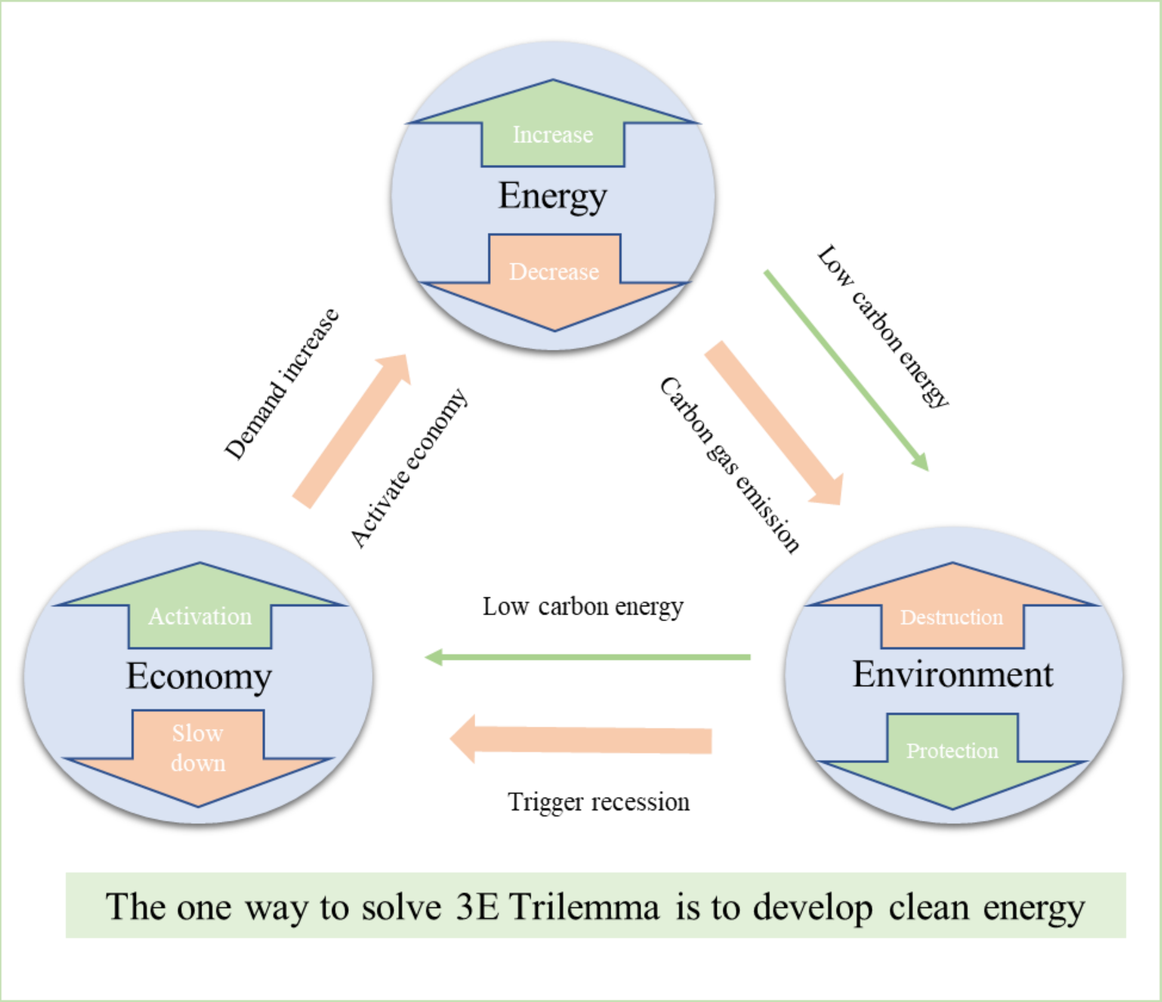


Fig. 1.10. Solving the energy, economy, and environment trilemma.

In enterprise-level microeconomics, environmental protection usually leads to higher production costs, while the basic task of macroeconomics is to achieve the optimal allocation of resources to maximize social welfare.

Under current economic and technological conditions, environmental economics is designed to find the optimal balance between economic and environmental benefits. The problem of environmental pollution can be solved in terms of legal, administrative, and economic aspects. One important tool is to consider certain environmental resources as scarce commodities and trade them in the form of emissions rights and emissions certificates to achieve the optimal allocation of environmental resources, which can be termed “the recoupling of the green economy and low-carbon energy with environmental considerations” (as shown as in Figure 1.11) [69].

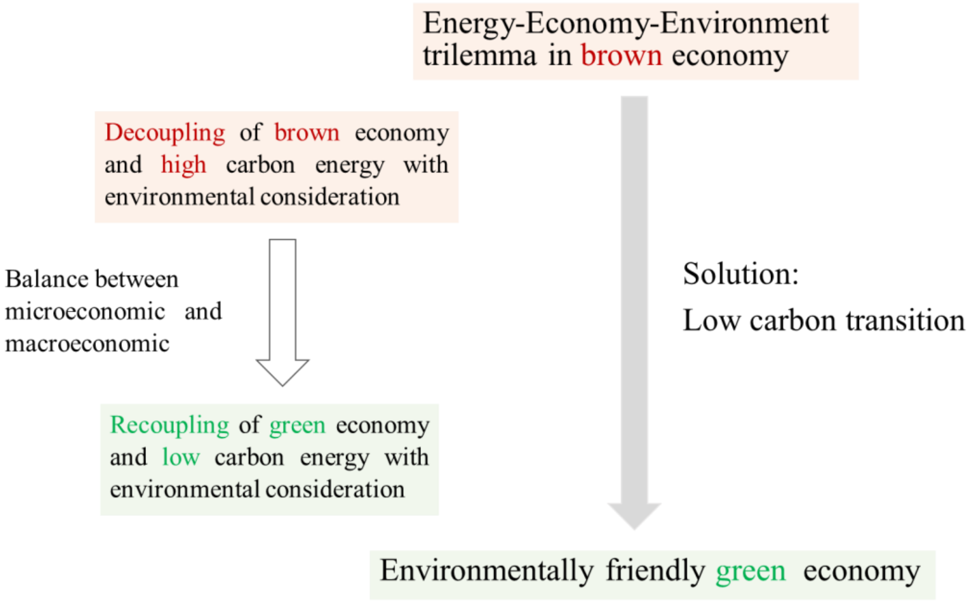


Fig. 1.11. Recoupling of decarbonization and economic development.

Finally, we can see that LCT can also foster green investment, growth, and jobs.

1.3.2.2 Technological aspects

I. The innovation paradigm

In the technological innovation activities for the LCT process, the establishment of technological innovation and the entrepreneurship ecology is particularly important. Technological innovation and management to international cooperation, innovation planning for national and corporate strategies, as well as the cultivation and training of technology entrepreneurs are also important; in addition, an innovation ecology and atmosphere driven by individuals or the entire population will also promote and reduce the cost of innovation and entrepreneurship, forming a sustainable ecological innovation and entrepreneurship cycle.

Existing innovation theories will help us to better understand the details of technological innovation and manage LCT innovation. The innovation paradigm shifts are reviewed by the country or region as follows.

Since Schumpeter introduced his theory of the innovation economy (1934) [70], American scholars have introduced many typical innovation paradigms such as user innovation [71], open innovation [72], and disruptive innovation [73].

Scholars from Europe mainly emphasize the innovation paradigms originating from the integration of technological innovation paradigms and humanitarian, social, and value attributes. For example, design-driven innovation [74], social innovation [75], public innovation [76], and responsible innovation [77,78],

Scholars from major Asian countries have proposed autonomous innovation paradigms based on their own national innovation practices. For example, several important innovation paradigms have been proposed in China, such as indigenous innovation [79]; total innovation [80]; secondary innovation [81]. “Holistic innovation” has been introduced by Chen, as a new emerging innovation paradigm [82]. Japanese scholars have proposed knowledge-based innovation [83,84] and lean production [85]. Korean scholars mainly focus on catch-up innovation [86] and convergence innovation [87].

II. Technology diffusion models

"Disruptive technology" was first introduced by Harvard professor Clayton M. Christensen [88,89]. It is defined as a technology that replaces existing mainstream technologies in unexpected ways, and its disruptive and transformative ideas are traced back to economist Schumpeter’s (1912) “creative destruction.” Disruptive innovation refers to the creation of something from nothing, while most innovations we see in the market today are the result of gradual innovation shown as in figure 1.12 and figure 1.13.

The main models of technological diffusion are the Bass model [90], stochastic cellular automata model [91], Ising model [92] and the punctuated equilibrium (PE) model [94]. The first three models are S-shaped gradual diffusion models (mainly focused on technical demand side), whereas PE is a disruptive innovation model (Technical learning and accumulation with technical demand side are considered).

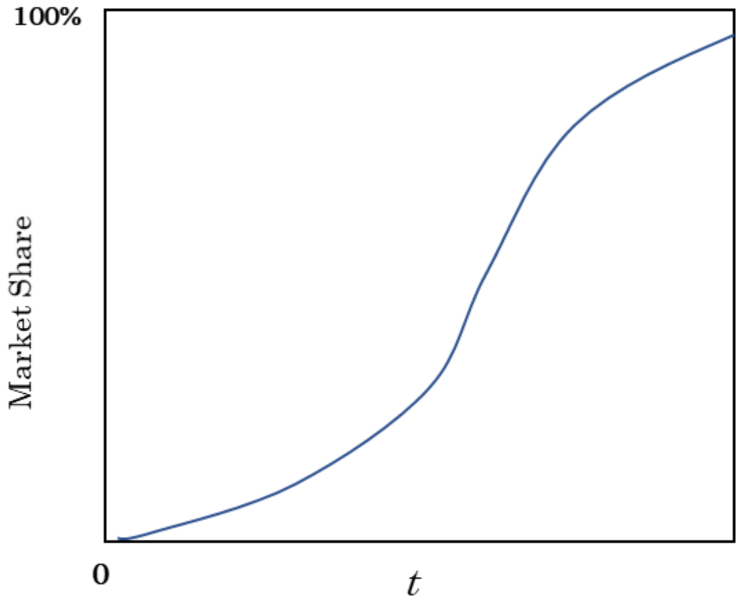


Fig. 1.12. S shape model [90-92].

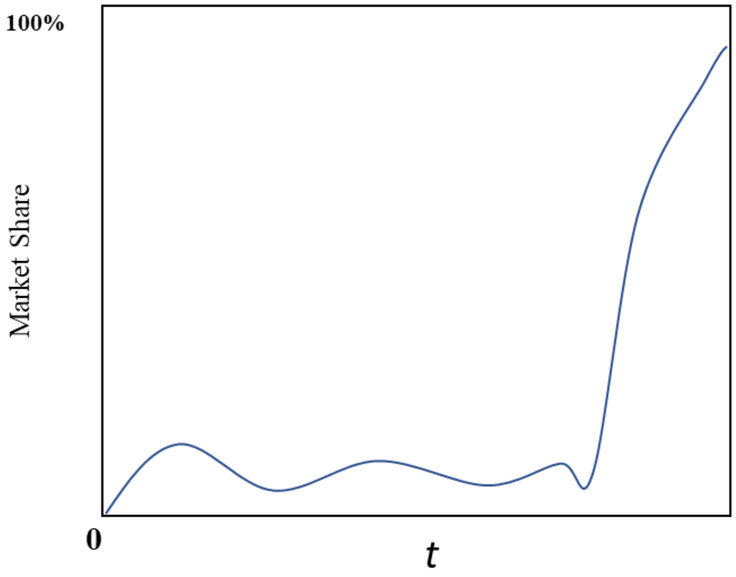


Fig. 1.13. Disruptive model [94].

In addition to the economic and technological research described in Section 1.3.2, it is important to study new policies and laws (especially those related to finance, technology, and economics), as well as new financial mechanisms and how financial innovation intersects with economics and technology.

1.3.3 Models related to thesis

In this thesis, three relevant models are adopted to construct an ABM in terms of the economic and technological views used in different chapters.

1) LCT baseline model (Chapter. 2).

An LCT model is constructed considering localized energy markets through an agent-based simulation. It is able to simulate how market regulation, energy consumption, and energy capacity work in transition for distributed energy systems and show several feasible ways to conduct an LCT [1].

2) One of the extensions of LCT model to combine with the minimal macroeconomic model known as the “Mark 0” (M0) model (Chapter. 3).

To represent the impact of an economic cycle triggered from landscape to regime by LCT, the LCT model is reformed by embedding the minimal macroeconomic model, Mark 0, using the built-in agent-based approach. In the Mark 0 model, there are two kinds of agents—firms and households—that interact with each other in certain ways. This model is so powerful that it can simulate prosperity, recession, crisis, and the whole periodic economic cycles which is rather common in modern society [93].

3) One of the extensions of LCT model to combine with PE technology evolutionary model (Chapter 4)

To describe technological evolution detail with interaction of the regime and niche levels, the PE model is adopted to the LCT model [94]. The PE model is capable of reflecting radical technology evolution patterns and finding the details of radical innovation related to discontinuous and disruptive effects, which are common technological evolution patterns in radical low-carbon innovation and in the MLP [95].

1.4 Thesis objective and structure

1.4.1 Objective

This thesis’s objective is trying to discover the key parameters and feasible LCT pathways in terms of an economic and technological perspective, based on ABM modeling with insight from MLP.

To accomplish this goal; several sub-goals are listed according to chapter as follows:

In Chapter 2., attempt to find key parameters and feasible LCT pathways based on the ABM model.

In Chapter 3., two sub-goals are as follows: 1). In a complex economic cycle, is there an appropriate or right time for policy intervention that can ensure LCT and reduce its impact on the economy? 2). What is the link between LCT and the economic cycle, and how can we balance the energy supply and demand with environmental pressure to respond economic cycle for smooth LCT?

In Chapter 4., the sub-goals are as follows: 1) how to manage interventions to guarantee that learning effects and market returns (cumulative effect) can obtain radical niche innovation (spontaneous transition), especially under the condition in which the basic performance ceiling of low-carbon technology is lower than that of high-carbon technology; 2) how political interventions like distinct technology subsidies (fixed and biased) to protect discontinuous niche innovation to reach a tipping point (punctuation of radical or disruptive innovation); and 3) how to properly manage technological development (i.e., a combination strategy driven by low-carbon technology performance ceiling, level of protection for cultivating suitable punctuation time) to guide society to reasonable transition pathways.

To solve these issues, an agent based LCT baseline model with insight from MLP is built (Chapter 2), and then the LCT model is further refined with economic (M0 model) and technological (PE model) considerations (Chapters 3 and 4) to provide detailed and practical policy recommendations and empower us to discover and manage reasonable pathways.

1.4.2 Structure

The thesis is structured in the following way:

In Chapter 2, an LCT model with insight from MLP is constructed. Distinct phase diagrams are obtained and some LCT strategies are introduced by this model. The dynamic system model based on LCT model and population dynamic model is developed to theoretically verify this minimal LCT baseline model. Finally, a combined MLP and ABM approach is proposed, with structural verification and behavioral validation for the LCT model.

In Chapter 3, the LCT model is extended with the minimal macroeconomic model Mark 0 to reflect the impact of the economic cycle on LCT, which can enrich the interaction between the landscape and regime levels. In addition, the model's use in LCT policy, such as the timing of transition policy intervention and interactions between the economic and LCT system, is explored.

In Chapter 4, the LCT model is extended with the PE model to investigate:

1) whether there is a potential for the emergence of "PE" patterns of low-carbon technology diffusion or adoption in an ABM under the condition of a low-carbon technology performance ceiling ($\bar{p}_l$) that is lower than the high-carbon technology performance ceiling ($\bar{p}_h$).

2) how political intervention like distinct technology subsidy (fixed and biased) to protect discontinuous niche innovation to obtain tipping point (punctuation of radical or disruptive innovation);

3) how to properly manage technology development (combination strategy driven by low carbon technology performance ceiling, degree of protection for cultivating the suitable punctuation time) for guiding the reasonable transition pathways.

In Chapter 5, the findings and conclusions are discussed, and then directions for future research are proposed.

Chapter 2 Key factors and pathways based on the LCT model

Note: The contents of Sections 2.1 and 2.3, including the figures and tables, are adapted from Refs. [1-2].

To tackle the LCT analysis challenge and provide a suitable research framework is essential for managing climate change. As an extensively applied theoretical form, MLP conceptualizes LCTs as a non-linear process and allows a system to be analyzed and organized into multiple dimensions (i.e., landscape, regime, and niche). However, MLP cannot explain the many details of complex transitions, and the simplified conceptual MLP framework leaves room for debate on the dynamic and continuous changes in actual systems on different levels, whereas ABM can estimate the influence of interacting behaviors in a complex system. Therefore, combination studies are in high demand.

This aim of this chapter is to

- 1) construct a baseline LCT model to evaluate the roles of market regulation, energy consumption, and energy capacity in LCT for distributed energy systems through an agent-based simulation and identify key parameters and feasible LCT pathways.
- 2) theoretically verify the LCT model by building a population dynamic (PD) model.
- 3) propose an approach that combines MLP and ABM to further verify the LCT model and better understand the LCT process.

2.1 Multi level perspective and agent-based modeling

2.1.1 Background

Linking computational models and transitional theoretical frameworks to study energy and climate topics is suggested as a strong and complementary way to address the complex and uncertain co-evolution of society, technology, the economy, and the environment. As a widely used theoretical form, MLP allows a system to be analyzed and organized into multiple dimensions (i.e., niche, regime, and landscape), and it conceptualizes LCT as a non-linear process. However, MLP cannot explain the many details of complex transitions, while ABM can estimate the impact of interacting behaviors in a complex system.

In this section, a framework for the combination of MLP and ABM is proposed and a more solid base for the simulation study of LCT processes is provided. It is made clear that MLP can contribute to the overall design of ABM, and ABM can provide a dynamic, continuous, and quantitative description of MLP. The combination of ABM and MLP allow us to achieve a deeper and more detailed analysis of LCT.

2.1.2 Toward a combined analytical framework

A guiding principle that combines the two approaches under a background of LCT to create an integrated strategy is provided in this section by using three procedures (as shown in Figure 2.1)—defining the common concepts, analyzing their interactions, and examining their combination. First, the elements of the pairing are identified in more detail; this step is defined as a *common concept*. Second, in the process of solving the LCT issue, two-way interactions with feedback loops are required, which is the step described as *interaction*; in the long run, it will lead to an active and effective link between the two approaches. Third, the two-way integration of ABM and the MLP is possible. This step is described as *combination*, which involves establishing two-way links between the approaches around detailed modeling and conceptual insights with feedback loops.

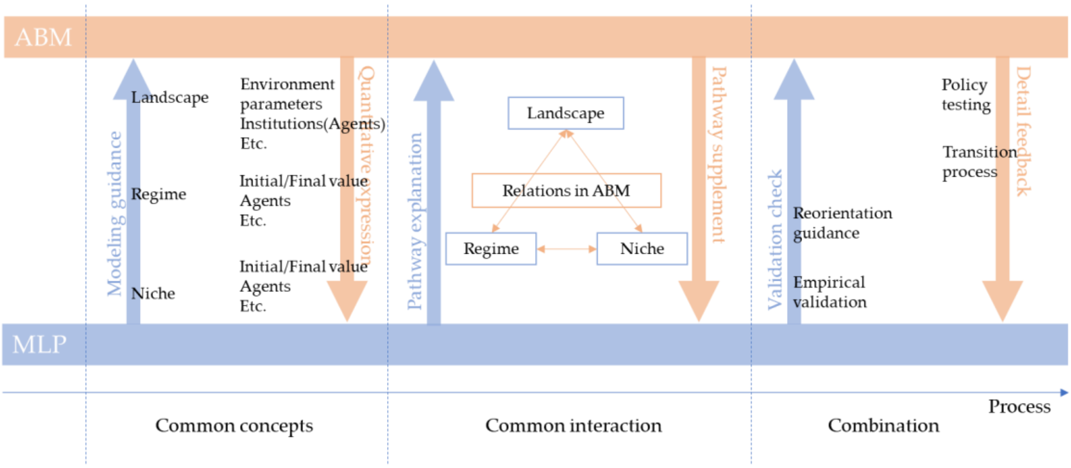


Fig. 2.1. An overview of the combined framework.

2.1.2.1 Common concepts

The first step in the process of combining ABM with MLP is to identify and confirm the common concepts. Some space for conceptual interaction is provided by common concepts, which is important for both analytical methods. These common concepts are described in detail in the following sections.

1) High-carbon states

In both approaches, *niche dynamics* and *system stability* (robustness of system state or regime) is the first common concept applied to explain system evolution.

- In various quantitative indicators over time, niche dynamics and system stability are used to show the predicted rate of change in ABM. Institutions in the landscape and participants or actors at the niche or regime levels are modeled as agents. Corresponding values can be applied to determine the system status at the initial and final stages. The parameter setting usually concerns the implications for the environment at the landscape and regime levels.

- MLP focuses mainly on qualitative factors, and the interaction between social groups and actors or participants can be explained with niche dynamics and system stability, which interpret the emergence of niche innovation.

2) Pathways of LCT

To classify the evolution of the system, a *pathway description* is proposed as the second common concept. Both approaches are designed as policy- and practice-driven research tools for describing the evolutionary process of systems.

- In ABM, applied mathematics and parameterizations based on complexity theory are usually used to design path descriptions, while scenario-based path descriptions provide an opportunity to attain specific phenomena regarding the interactions between different levels. First, policy actions are analyzed mainly through parameter settings and regulatory tools. Second, pathway descriptions can provide clear, model-based transition suggestions for policy intervention options. Third, by identifying the participants and key factors as control parameters, specific strategies can be proposed based on the phase diagram obtained from an ABM simulation.

- In MLP, the pathway description focuses on the interactions between different levels and provides a way and method to describe a general pathway that reflects technical changes and social phenomena by providing an explanation of the sociotechnical system's complexity.

3) Low-carbon states

To explain system evolution, the third common concepts are *system stability* and *dynamics*, which are applied in both analytical methods.

- Various quantitative indicators reflect that the expected rate of change over time can be implemented by applying the concepts of system stability and dynamics in a LC state to ABM. A detailed representation of system information can be reflected in ABM, thus allowing the numerical tools in the model to explore the system complexity of the LC state under specific policy actions and constraints.

- In MLP, the concept of system dynamics and stability in LC countries is used to explain system stability and the effect of existing systems, and it can explain the successful transition of interaction between actors and social groups. Various quantitative indicators reflect that the expected rate of change over time can be implemented by applying the concepts of system stability and dynamics in a LC state to ABM. A detailed representation of system information can be reflected in ABM, thus allowing the numerical tools in the model to explore the system complexity of the LC state under specific policy actions and constraints.

2.1.2.2 From common concepts to conceptual interactions

Interaction is interpreted as a process that can reflect transitional goals with common concepts and system details [1, 8, 16], and it therefore allows for the establishment of research strategies that interact between the two analytical approaches and can produce iterations of this interaction. To ensure consistency between the two analytical methods, it is identified three typical LCT narratives (system states) that can be used as an analytical combination of the two scientific approaches.

The first system state (i.e., in a HC state, niche details with technological innovation) illustrates the details of the sociotechnical system and opportunities for niche innovation of various conditions to achieve greater market gains in the HC state.

The second system state (i.e., changes in the regime and the niche and continuous dynamics of sub-levels in LCT) discusses the proper way to respond the new requirements of environment, including the different types of new social technological systems transitioning an existing regime caused by breakthroughs of various niche innovations, which involve not only social factors but also technological changes. A complementary type of interpretation is provided by each approach that can be used to develop specific policy suggestions by identifying actors and key factors as control parameters in the phase diagram constructed by the ABM simulation.

The third system state (i.e., a LC regime or a system that develops and describes the influence of the local and external systems of LC states) explains how the emerging niche innovations of the LC state should respond to new chances for greater profitability coming from and influenced by external systems in the market.

2.1.2.3 Combination

Both approaches can identify the details of different levels with complex niche innovations in HC states, as well as the details of regime change in successive sub-level dynamics of LCT. Under these transitional narratives, one can build a framework in MLP to reflect the details of social technology in real life, and ABM can establish a model with detailed and continuous information and dynamics in terms of scale and time.

As one of these narratives, these two analytical methods also benefit from determining the future regime and how its evolution in LC countries is affected by local and external systems. The combination of these methods can describe the LC state of the system (i.e., considerations of quantitative ABM and qualitative MLP) and can explain how the system changes over time under external influences and system complexity. In other words, ABM uses specific instruments or tools to address policy ambitions and niche innovations by considering external influences over time, while

MLP qualitatively explains new niche innovations and new social phenomena to offset potential policy ambitions in the current state.

Figure 2.2 shows the conceptual combination space of these two methods. It describes the basic layout and a shared framework around a HC state to obtain model criteria and normal forms [108]. In Phase 1, disruptive or radical innovation appears in a niche; in Phase 2, innovation enters a small market niche of transition pathways; in Phase 3, the niche innovation breaks through to the LC state; and in Phase 4, a new regime emerges. In different system states, different methods can be used to successively communicate common analytical concepts and the path construction.

The possible interactions between MLP and ABM studies at different levels are indicated by the arrows in Figure 2.2. The entire cycle of different transitional paths can be reflected in the combination, in which MLP can offer insights into landscape changes, actors' strategy in the regime, and niche momentum, while modeling variables or parameter settings in ABM can benefit from the structural guidelines of MLP. The stylized conceptualization of evolution and dynamics of continuous transition abstracted from past data or outcomes in MLP, as well as the specific corresponding interpretation from ABM are also revealed in the different pathways. These different pathways, some of which may even exceed our imagination, can be used as a supplement for the MLP framework. With changes in environmental parameters, ABM can test policy strategies and the results can provide further guidance for policy recommendations provided by MLP.

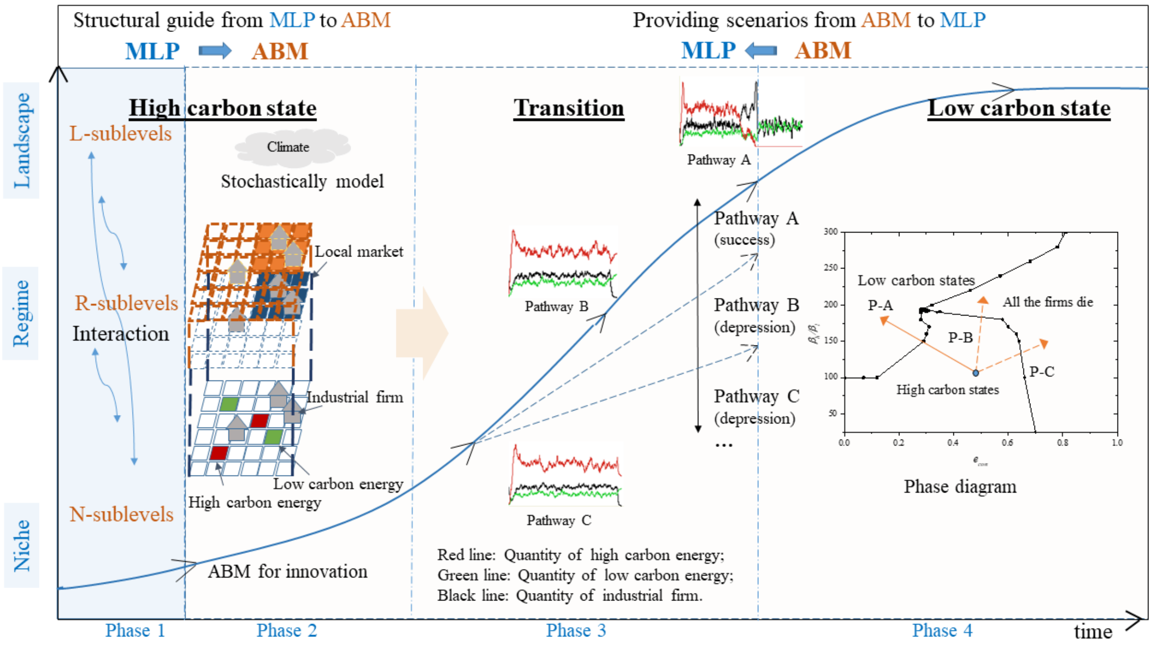


Fig. 2.2. A schematic illustration of the combination of agent-based modeling (ABM) with a multi-level perspective (MLP).

2.2 LCT baseline model

2.2.1 Background

To implement this combination method including ABM and a simulation, a reference-based case study is carried out.

For a narrative in a given empirical field (i.e., a distributed energy system), to estimate the various trajectories for different objectives (e.g., ambitions to mitigate carbon emissions), a combined approach can be used to evaluate the different transition pathways. For both the low- and HC states, the combined method helps MLP orient parameter settings and check ABM models, and also helps ABM provide MLP with specific strategic performance and multi-level details.

In Step One, select a reference-based case study for (1) a typical system, e.g., China; (2) a potential economic field for carbon emissions reduction (i.e., distributed energy system) that needs further research (for an overview, refer to [96]); and (3) a quantitative model (i.e., an ABM) that can be referenced to the findings and results of qualitative study. Based on the field research and the study by Liu, Y [97], an ABM method is used to establish an industry–energy ecosystem.

In Step Two, to better understand the impact of participant behavior or social action and reaction on the green decision-making, an ABM of the industry–energy ecosystem is designed to study the LCT [1]. In the model, the qualitative results and data (sought in the MLP) is convert into the initial settings of the industry–energy ecosystem model and extract the local energy market with environmental market sensitivity to reflect the social emission problem settings as new variables or parameters. The ever-increasing pressure of the carbon pricing system as market sensitivity to make the simulation plan consistent with the domestic goal of reducing greenhouse gas emissions is considered, which can be regarded as a policy strategy that can promote the transition of system behavior to a LC economy [98-99]. Under landscape pressure (carbon price changes), niche innovation (energy and green firms) broke through the window of opportunity and replaced the existing system (from a high- to a LC state). The establishment of the ABM model is only used to study this transition path; it reflects the guidance from MLP to ABM. Eventually, by determining the key parameters and influencing factors as control parameters in the phase diagram constructed by ABM simulation, LCT pathways and corresponding strategies can be easily obtained according to different system conditions. In practice, it is recommended that readjustment and reorientation be a two-way feedback loop between the two methods. The results of ABM can be applied to simulate MLP's forward-looking policy recommendations. Moreover, ABM can describe the LC state. However, the new parametric and qualitative results may be inconsistent, as the qualitative findings cannot be fully translated into a quantitative model.

2.2.2 Model building

The LCT model is based on the industrial energy ecosystem prototype model established by Liu [96], which aimed to study the competing behavior between low-carbon energy (e.g., solar and wind energy) and high-carbon energy (e.g., oil and coal) under the ecological life scheme of industrial firms. There are two types of agents—industrial firms and different types of energy (high- or low-carbon energy).

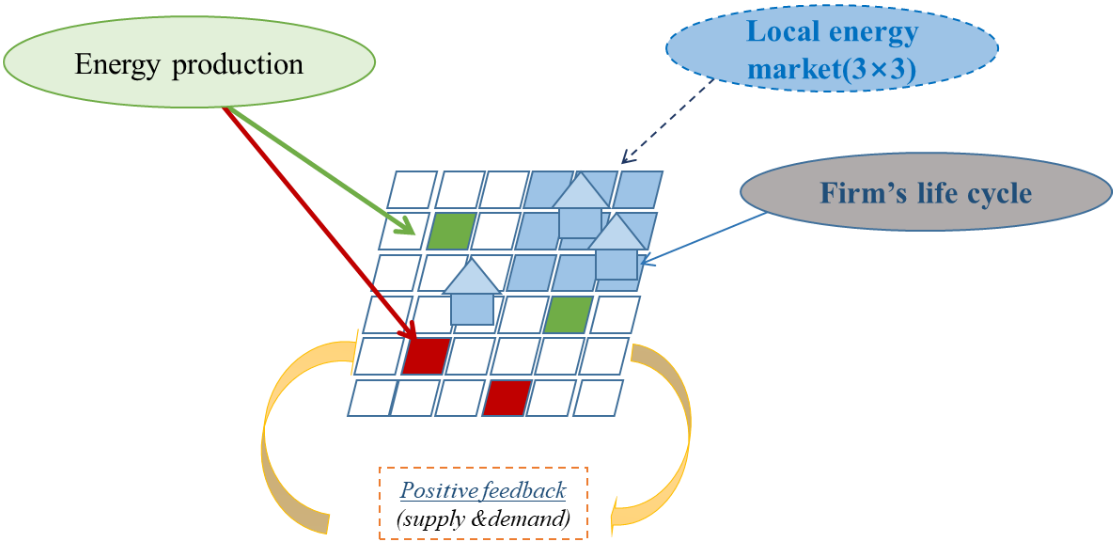


Fig.2.3. Modeling of a distributed energy system combined with localized energy markets.

The model is built on a regular two-dimensional lattice $N \times N$. Multiple industrial firms can thrive on each lattice node to represent the demand space, and one type of energy at most can be produced on it (as shown in Figure 2.3). High- and low-carbon energy are specified by different energy capacities and productivities (production rates). Each firm can buy and consume energy resources locally (in the firm's local area) to obtain economic vitality, which further determines their destiny. If they obtain enough energy, they can establish subsidiaries in the same region (local area). Otherwise, they will die because of the exhaustion of energy. At the same time, all firms can move freely (randomly) to purchase energy from nearby areas to sustain their development.

In the distributed energy system, mainly high and low carbon energy distributed with the localized energy market, and the migration of the firms for buying energies can be equivalent to the real situation that transport actual purchased energies from nearby sites to the firms. For example, the new type of supply of multiple energy sources leads to a new mode of interaction and competition between enterprises [48,100,101], one of the chief benefits of moving manufacturing and other industries to renewables is that they provide enterprises for the best environment and energy solutions [102-103] and the digitalization makes it possible for enterprises to manage virtual mobility

[104]. Furthermore, with new mechanisms such as consumer-oriented, technology-oriented, and government-oriented considerations, supply chain optimization, intelligent design and distributed manufacturing can be demonstrated through enterprise mobility, while migration also demonstrates the search for low-cost energy to improve competitiveness and the search for low-cost optimized production activities (e.g., circular economy industrial parks).

In the model, lattice represents information space, including physical space, business information space, etc., so lattice distance can also have information transfer and physical transfer attributes, such as demand response and interval, etc.

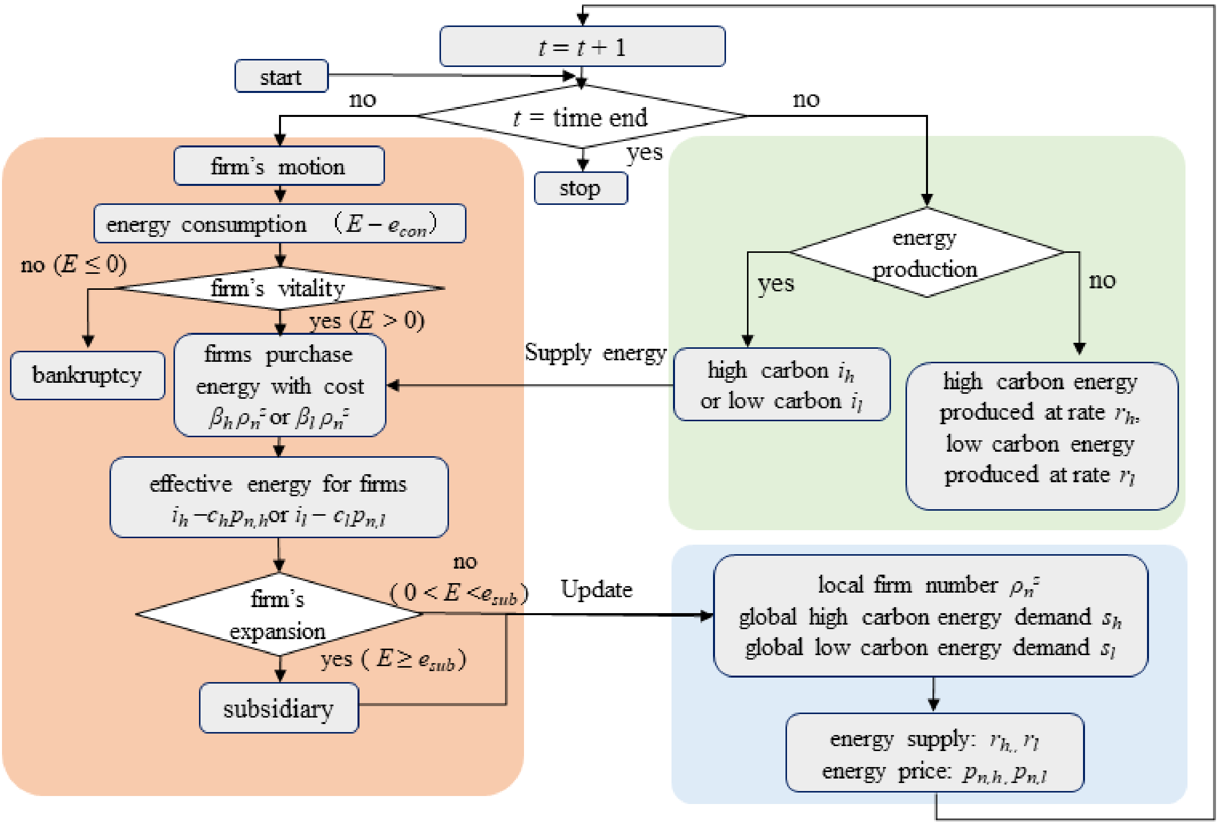


Fig.2.4. Flowchart of agent behaviors on node *n*.

The LCT model incorporates a price formation mechanism that imposes fluctuating costs in the demand space on the firms in energy purchases combined with dynamic feedback on the energy productivity (supply) of the low- (or high-) carbon energy from the total number of firms that purchase the low- (or high-) carbon energy (demand). At each time step t, the flowchart of the complete flow of behaviors at any node n is given in Figure 2.4.

Three behavioral modules—the generation of low- or high- carbon energy (green), the updated energy demand, supply, and price in the local energy market (blue), and the life cycle of the firm (red)—with detailed dynamic explanations of each module as follows:

i) Energy production module:

It can produce either one unit of low-carbon energy with probability r_l or high-carbon energy with probability r_h ($r_h + r_l < 1$), if there are no energy resources to produce in the local area at a previous time. These two probabilities are referred to as the *development rate of energy* hereafter because they characterize how fast energy can be produced, and these rates are influenced by both market performance and technological factors as shown in Eqs. (2.5) and (2.6) below. The amounts of energy provided (referred to as the "energy capacity" hereafter) by one unit is i_l for low-carbon energy and i_h for high-carbon energy, and i_h is set to be greater than i_l. Energy capacity can be improved mainly through the improvement of technology, such as the use of new fuels such as hydrogen can make high-carbon energy and low-carbon energy have a high-capacity increase, but also can accumulate a variety of energy types to improve the capacity and this also requires new technologies such as integration and energy management. If the firm has not yet consumed the existing or available energy, in the following time steps, these resources will be stored.

ii) Local energy market module:

The formation of energy price is designed in order to regulate the supply and the corresponding demand of high (or low) carbon energy. First, the development rate of high (or low) carbon energy will be adapted to the evolution of the demand for the high (or low) carbon energy. Second, certain transaction costs imposed when trading of local energies on the firms, which effectively reduce the capacity of purchased energy.

In the model, for each node n, as a virtual cost (such as demand and supply strategy cost) proportional to the local firm number ρ_n^z, the high- (or low-) energy price is formulated as follows:

$$p_{n,h} = \beta_h {\rho_n}^z \tag{2.1}$$

$$p_{n,l} = \beta_l {\rho_n}^z \tag{2.2}$$

where β_h (β_l) is the coefficient of market sensitivity for high- (low-) carbon energy, and β_h is set greater than β_l because it is believed that low-carbon energy is not very sensitive to the market performance such as the cost resulted from environmental concerns of the distributed energy system[105].

Moreover, setting $\beta_h > \beta_l$ (From equal initial settings to biased settings) implies that the local market would prefer and favor low-carbon energy over high-carbon energy.

The component ρ_n^z is the number of local firms at node n and it is calculated as the number of firms in the vicinity z of the node as sum of the component $\rho_{n,h}^{z}$, $\rho_{n,l}^{z}$, and $\rho_{n,o}^{z}$, here z is set to cover the 3 × 3 area of the node in the current research. The component $\rho_{n,o}^{z}$ is the number of firms that do not purchase energy. $\rho_{n,h}^{z}$ is the number of firms that purchase high-carbon energy, and $\rho_{n,l}^{z}$ is the number of firms that purchase low-carbon energy.

At any step t, the entire system's demand for high- (or low-) carbon energy, that is, $s_h(t)$ [or $s_l(t)$], can be calculated as the total number of firms that purchased high- (or low-) carbon energy at t as follows:

$$s_h(t) = \sum_{n \in N} \rho_{n,h}^{1\times1}(t) \tag{2.3}$$

$$s_l(t) = \sum_{n \in N} \rho_{n,l}^{1\times1}(t) \tag{2.4}$$

where $\rho_{n,h}^{1\times1}(t)$ or $\rho_{n,l}^{1\times1}(t)$ is the number of firms that purchased high- or low-carbon energy on node n at this time step. According to the feedback between demand and supply, the energy supply, that is, the development of high- (or low-) carbon energy $r_h(t+1)$ [or $r_l(t+1)$], will be adapted to the high- (or low-) carbon energy demand at the initial time step (since the energy company need to consider the generation cost), formulated as follows:

$$r_h(t+1) = r_h(t=0)\log_b\left(1 + s_h(t)\right) \tag{2.5}$$

$$r_l(t+1) = r_l(t=0)\log_b\left(1 + s_l(t)\right) \tag{2.6}$$

The characteristic scale of the local firm number that can stabilize the energy supply dynamics is related by the base of the logarithmic transformation b. In all of the simulations below, b is set to 10. It can be easily noticed from Eqs. (2.5) and (2.6) that there is a critical value of the energy demand ($b - 1$), below which the energy supply r_h or r_l will continue to shrink over time and be absorbed to zero in a vicious cycle. One extreme case is that energy production will stop forever when the demand disappears or vanishes.

During the transition period, the positive feedback mechanism between energy supply and demand should be strengthened by temporary policy adjustments to market deviations or energy consumption levels (See equation 2.5 and equation 2.6). However, when high-carbon industries are destroyed by shrinking demand, controlling the speed of positive feedback between supply and demand may mitigate some of the adverse effects of a dramatic shift in social patterns.

iii) Firm's life cycle module:

Firstly, industrial firms are set to randomly walk to one of the neighboring locations in one time interval with a cost of energy $e_{con.}$, which includes all of the entrepreneurial behavior costs of the firms. By moving around, they can search for energy and buy it in a nearby area. In the model, the energy amount e_{con} dissipated at each time step can be regarded as the "survival cost" of the firms, and the migration of firms for buying energy can also be equivalent to the real situation of transporting actual purchased energy from nearby sites to the firms. Then, the firm will receive the effective energy capacity $i_{n,h}{}^{eff}$ (or $i_{n,l}{}^{eff}$), which is the energy capacity i_h (or i_l) subtracted from the energy loss caused by the transaction cost $p_{n,h}$ (or $p_{n,l}$) in the localized energy market, when it successfully purchased the high-carbon (or low-carbon) energy. Therefore, each firm's vitality and fate depend on the amount of energy E that the firm retains after the purchase and consumption of energy. The firm will expand into two subsidiary firms in the same site if the amount of energy is greater than the threshold ($E \geq e_{sub}$). Otherwise, if it does not have enough energy ($E < e_{con}$ namely, retained amount of energy is less than the energy consumption), the firm will go bankrupt and be removed from the simulation space.

By formulating the energy price as a virtual cost determined by the number of local firms, the effective energy amount obtained by a firm that purchased energy on each node n can be expressed as follows:

$$i_{n,h}{}^{eff} = i_h - c_h p_{n,h}, \tag{2.7}$$

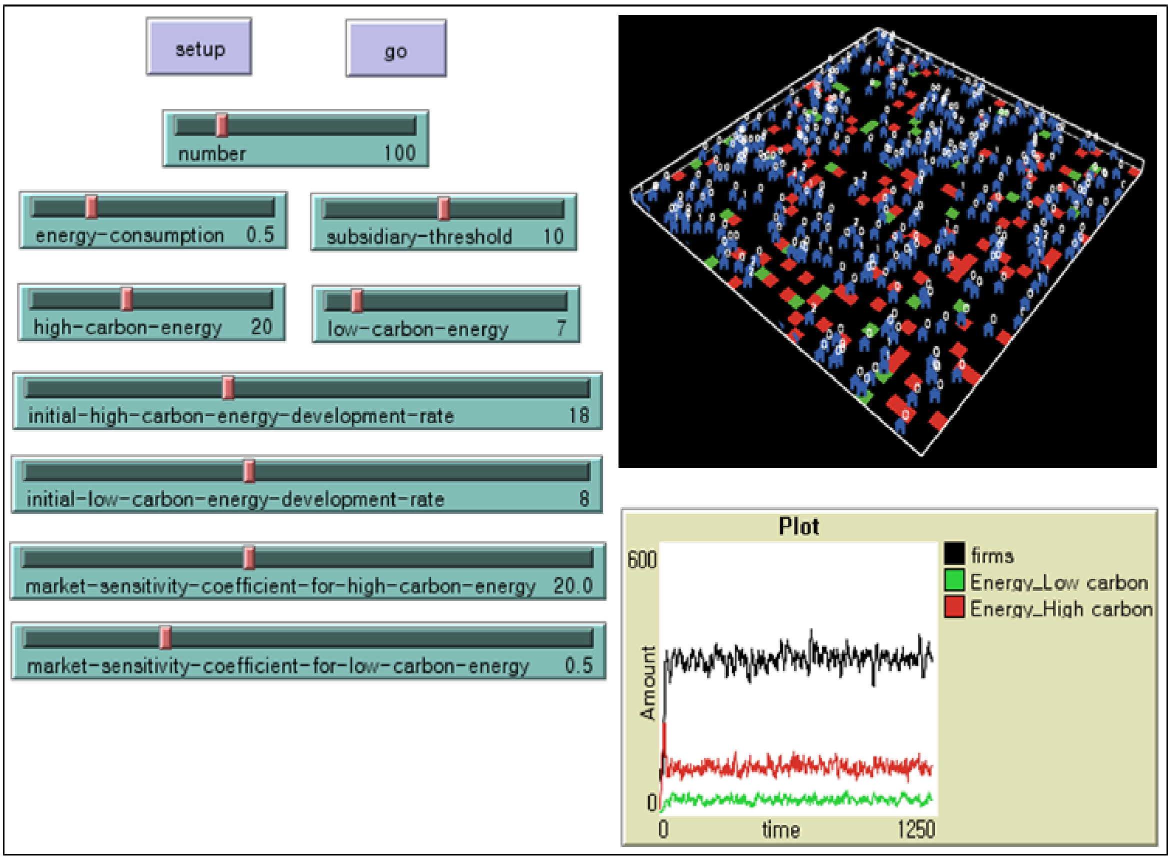
$$i_{n,l}{}^{eff} = i_l - c_l p_{n,l}, \tag{2.8}$$

where the coefficient c_h (or c_l) weighs the trading cost in terms of the loss of energy capacity, and these two coefficients are set to one for simplicity.

The model is implemented in Netlogo [106]. A snapshot of the simulated LCT system in Netlogo is shown in Figure 2.5. The graphical user interface of Netlogo consists of "sliders" and "buttons" (left), an output monitor (bottom right), and a central landscape (top right). In the landscape, high- and low- (red or green square) carbon energy, and firms (blue symbol) are displayed. With periodic boundary conditions, the simulation space is a two-dimensional regular lattice N with $L \times L$.

You click "set up" to use the interface in Figure 2.5, which will initialize the model by running a command, and the occupants (firms, high- and low-carbon energy) are randomly distributed in the space as the corresponding parameters. After that, you click "go" to run the model. In each tick or iteration, the firms move freely in space and consume high- or low-carbon energy. Subsidiaries are created by adding clones of the firm to nearby nodes and providing the cloned subsidiaries with half pf the energy of the parent firm. As a result, the number of firms develops (evolves) over time, generating high- and low-carbon energy in empty nodes. When all firms die, the simulation ends. In the simulation process, you use the corresponding slider to control the parameters and observe the effects through the output monitor.

The selection of initial values of parameters is mainly based on the literature including interviews, surveys, and some relevant references [97], although some parameters are controlled to analyze the behavior evolution of firms in different situations (see Table 2.1 for the parameter settings with the baseline and initial values).



number 100

energy-consumption 0.5

subsidiary-threshold 10

high-carbon-energy 20

low-carbon-energy 7

initial-high-carbon-energy-development-rate 18

initial-low-carbon-energy-development-rate 8

market-sensitivity-coefficient-for-high-carbon-energy 20.0

market-sensitivity-coefficient-for-low-carbon-energy 0.5

Fig.2.5. Netlogo user interface with the LCT baseline model

Table 2.1 Parameter settings with initial and baseline values.

Variable	Description	Initial value (references, interviews, surveys) [96]
$E(t)$	Amount of energy that a firm retains	Random integer within [1,8]
$r_h(t)$	Rate of high-carbon energy's development	18%
$r_l(t)$	Rate of low-carbon energy's development	8%
$i_{n,h}^{eff}(t)$	Effective high-carbon energy capacity for firms at node *n*	
$i_{n,l}^{eff}(t)$	Effective low-carbon energy capacity for firms at node *n*	
$s_h(t)$	Number of firms that purchase high-carbon energy	
$s_l(t)$	Number of firms that purchase low-carbon energy	
$\rho_n^z(t)$	Local firm number within the vicinity *z* of node *n*	

Constant		Baseline value
e_{con}	The amount of industrial firm's energy consumption	1.0
e_{sub}	The threshold of firm's reproduction	10
i_h	The amount of energy provided by one unit of high-carbon	9
i_l	energy	4
β_h	The amount of energy provided by one unit of low-carbon	0.1
β_l	energy	0.1
	Market sensitivity coefficient for high-carbon energy	
	Market sensitivity coefficient for low-carbon energy	

For the parameter settings (dimensionless parameters), since e_{con} represents the amount of energy consumed per unit of GDP and takes a value between 0.1 and 1 to account for technological differences in different systems like developed and developing countries; β_h/β_l measures the market regulation bias on the two kinds of energy， for example, β_h represent the environmental cost like carbon tax, and β_l reflect environmental income like Tesla Inc. obtain extra revenues from environmental instrument. Therefore, to realize the biased characteristics of market regulation, β_l takes a fixed value of 0.1, and then β_h takes a range of values from 0.1 to 25 to represent environmental pressure; i_h and i_l representing the high and low carbon energy capacity. The initial values of i_h and i_l are set to 9 and 4 because the current capacity of high-carbon energy is higher than that of low-carbon energy, and Both high- and LC energy capacity can be improved through energy efficiency, storage capacity, and the application of advanced energy systems (such as combined cooling, heating, and power in a distributed energy system), therefore, with technology development, the values of i_h and i_l can be considered in the range of 9-18 and 4-9.

2.2.3 Validation

In this section, the validity of the LCT model is verified, as one part of the combination. In ABM models, structure rationality is responsible for the authenticity of its behavior. Both ABM and MLP give insight into social transformations: the former abstracts the key factors that are transformed into specific parameters, while the latter provides a theoretical framework to locate various elements. Therefore, the system dynamics and formulation of the ABM model with behavioral and structural validity should be in agreement with the MLP framework under the same targets. This method is used to verify the LCT model introduced in Chapter 2, and the validity can be tested.

1) Structural verification

The evaluation of structural verification concentrates on (1) macroscopic determination of how the model appropriately represents phenomena of the initial problem and the relevant descriptive knowledge [107], and (2) microscopic identification of the potential elements involved in the conceptual model and its internal linkages. Model testing should determine whether the model includes important structures and concepts in the LCT to meet the adequacy of the boundary. To meet the requirements of structural verification, the dynamic processes and assumptions used in the model should be consistent with real life [108].

First, the parameters in the model are explained compared with MLP. In MLP, the urgent need to rapidly reduce greenhouse gas emissions is the result of landscape pressure [8], because new technologies using clean and renewable resources are expected to improve the performance of regulating LCT. These factors are abstracted as a pair of parameters, β_h and β_l, reflecting the public's willingness to adopt low-carbon energy in ABM [109]. At the regime level, a set of stable and consistent rules forces the energy supply to move along a specific trajectory, and these deep-rooted and shared rules guide the participant's behavior [108]. In ABM, traits of the market actors are represented by $E(t)$, e_{con}, and e_{sub}, which determine the vitality and fate of each firm. In addition, $s_h(t)$, $s_l(t)$, and $\rho_n^z(t)$ describe the number of actors in the localized market from various market perspectives. Another pair of variables, $i_{n,h}^{eff}(t)$ and $i_{n,l}^{eff}(t)$, reflect the viability expectations under this set of rules. At the niche level, the expectations of the niche actors contribute to the establishment of market-like distributed energy systems or niche systems, because they establish a constituency for fundamental change to fill specific market gaps [4,114]. These factors are abstracted into two pairs of parameters in the model: (1) $r_h(t)$ and $r_l(t)$ and (2) i_h and i_l, respectively. In Table 2.2, the correspondence of these ABM parameters to the MLP is summarized. The same table also summarizes the assumptions used in ABM, which is consistent with MLP.

A mathematical translation of the interactions between the three levels of analysis of the MLP can be represented as the dynamic equations formulated in ABM [1]. Eqs. (2.1) and (2.2) show that the energy price is the combined result of the regime property and landscape environment, which is accurately reflected in the interactions between the regime and the landscape in MLP. Eqs. (2.5) and (2.6) assume that total high- and low-carbon energy demand (as shown in Eqs. (2.3) and (2.4), which is the sum of all energy purchased by the firms in question) is derived from a separate positive feedback effect on its energy supply. The interaction between the niche and the regime can be reflected by adopting this positive feedback.

Finally, Eqs. (2.7) and (2.8) define the expression for the amount of effective energy obtained by the firm as a combination of the amount of energy provided per unit and the energy price. These two equations show how the landscape trends affect niche market participants based on the amount of energy that each firm ultimately receives. These relationships are shown in Figure 2.6.

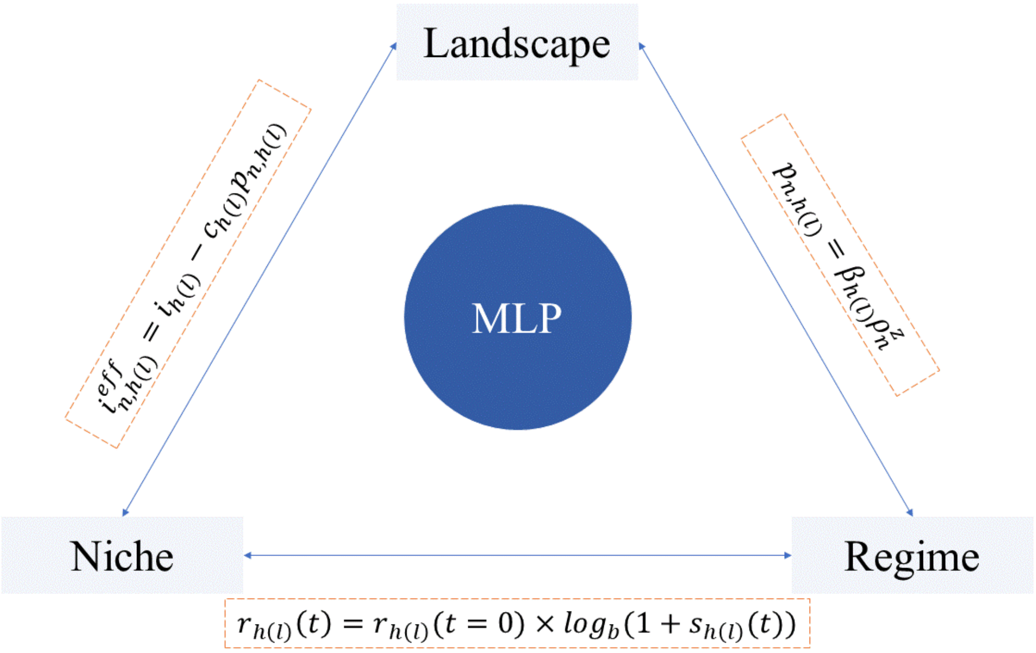


Fig. 2.6. ABM structure corresponding to MLP interactions.

Table 2.2. Structural comparison of MLP and ABM.

	MLP	ABM Model Parameters		ABM Model Assumptions
Landscape	Environmental pressure for carbon emissions mitigation	β_h, β_l	β_h (β_l), carbon emission pressure for high-carbon (low-carbon) energy consumption	Environmental pressure impacts the regime level and market sensitivity coefficient for high- (low-) carbon energy
	Technological development for emissions reduction [8,110]		Long-term technical innovation supported for high (low) energy capacity	Technological development impacts the niche level, cultivating distributed energy systems, etc. [109]
Regime	Localized market, carbon tax, and subsidy policies [111]	$\beta_{h(l)}\rho_n^z$	Localized energy market	$\beta_h > \beta_l$: Low-carbon energy is thought to be less sensitive to market performance in distributed energy systems [112,113] $\rho_n^z(t)$: The local firm number represents the potential demand
		$s_h(t), s_l(t)$, $i_{n,h}^{eff}(t)$, $i_{n,l}^{eff}(t)$	Participant's market property	$s_h(t), s_l(t)$: Real demand (number of firms that purchase high-carbon (low-carbon) energy). $i_{n,h}^{eff}(t), i_{n,l}^{eff}(t)$: Effective high-carbon (low-carbon) energy capacity reflects the firm's real gains
		e_{con} $E(t)$	Participant's nature property	e_{con}: Energy consumption reflects the efficiency and life cost. $E(t)$: Amount of energy retained by a firm
Niche	Niche innovation and distributed energy system [109]	i_h, i_l	The amount of energy provided by one unit of high-carbon (low-carbon) energy	$i_h > i_l$ & $r_h(t) > r_l(t)$: Supply (at this time, high-carbon energy can perform with higher efficiency) [1]
		$r_h(t), r_l(t)$	Rate of high-carbon (low-carbon) energy development	

From the perspective of MLP, to facilitate some kinds of transition, the focus must often be expanded to cover a combination of social systems and multiple innovations, including sociopolitical drivers, consumer acceptance, and business models [111]. Under different parameter settings, transitions are observed in the ABM model. The results indicate that higher market sensitivity, higher energy capacity, and lower energy consumption can all contribute to increased penetration of low-carbon energy [1], which can verify the fact that successful LCT involves many factors such as market adjustments and technological evolution or development.

Distinct transitional paths that respond to the nature of interaction and different timings are specified in MLP [110]. The transitions proceed to different purposes and end depending on the order of the participants, and the phase diagram results from the LCT model matching these different pathways qualitatively. As with the MLP approach, the different transitional pathways also require different responses at the three levels. In turn, ABM provides quantitative support for MLP.

2) Behavioral validation

Behavioral verification aims to compare the behavior generated by the model with that of a real system. The baseline model uses a specific case: data for China's case was obtained from available interviews and references on real systems [97]. The LCT model also adopts a sub-model, such as feedback between energy demand and supply and environmental sensitivity in the market. The sub-model adopted by the existing model can be used as a structural verification of ABM, and Denmark's system can be used as a representative of the LCT model in which feedback between energy demand and supply and environmental sensitivity have been conducted [1]. Therefore, here the simulated data is compared with actual changes that occurred in Denmark.

After a decade's efforts, the energy system has been integrated with a localized energy market in Denmark [114], and a carbon tax has been introduced to limit high-carbon energy and promote low-carbon energy. The Danish standard carbon tax rate over time is shown in Figure 2.7 [115–117], demonstrating that the Danish carbon tax has increased overall.

In the LCT model, the parameters β_h and β_l are used to represent the carbon tax. The higher the carbon tax, the higher the $\frac{\beta_h}{\beta_l}$ ratio, as it measures the regulation bias on different types of energy. To avoid catastrophic frustration and ensure a smooth transition, in parallel with Regime 2, set $i_h = 18$ and $i_l = 8$. The simulation conducts with an interval of 10 in gradually adjusting β_h/β_l from 100 to 150, and to mimic the steadily increasing carbon tax. At each stage, as shown in Figure 2.9, one can see a significant increase in the penetration of low-carbon energy, which implies that increasing the carbon tax is expected to promote the diffusion of low-carbon energy under certain conditions.

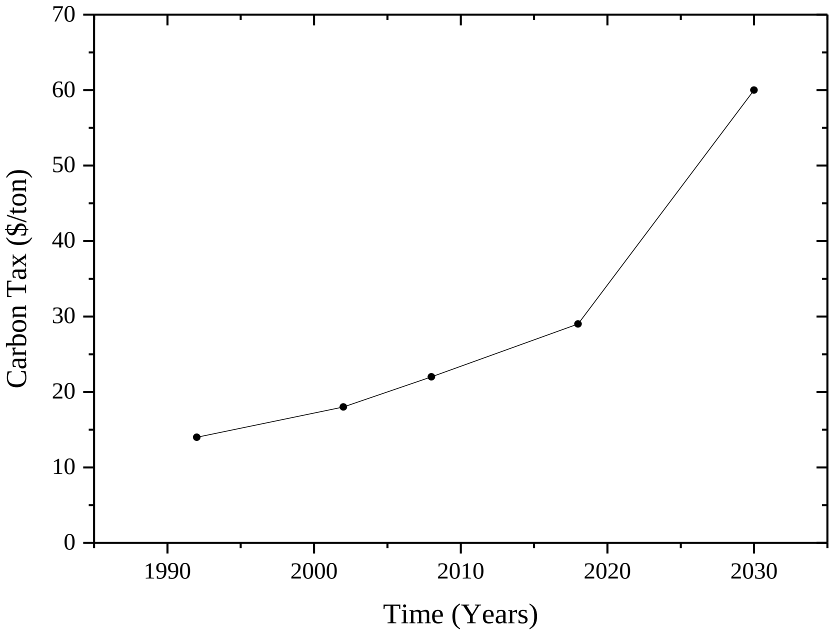


Fig. 2.7. Denmark’s carbon tax rate over time.

The widespread consumption of wind energy, highly integrated biomass, and the environmentally friendly tax system are contributing to the LCT in Denmark [118-119]. Figure 2.8 shows the proportion of low-carbon energy in the final energy consumption in Denmark, which indicates that the fraction of renewable energy is expected to grow steadily (from 1900 to 2050) [120].

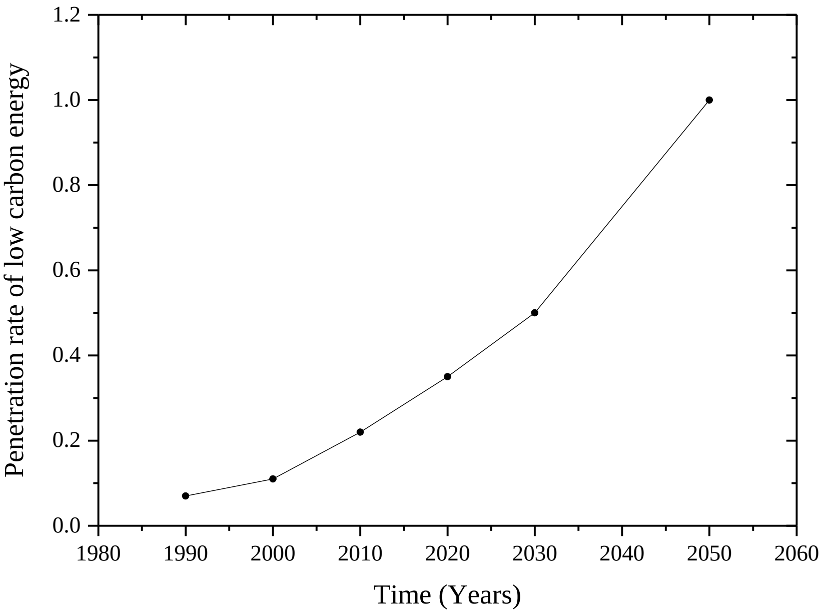


Fig. 2.8. Denmark’s low-carbon energy penetration rate over time.

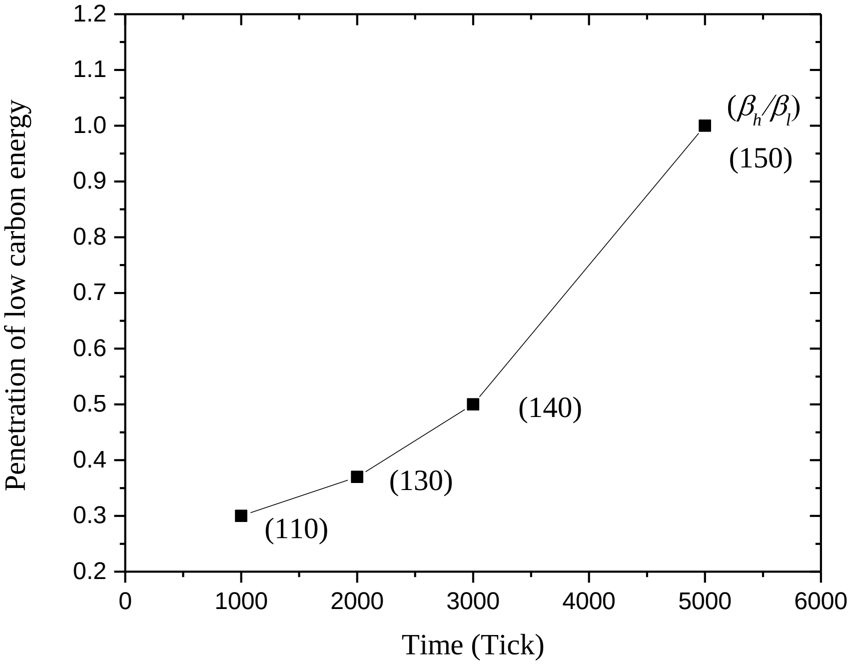


Fig. 2.9. Low-carbon energy penetration rate in ABM.

Since carbon tax is a financial instrument to limit high-carbon energy, therefore, β_h/β_l can reflect the carbon tax in the model. The values of β_h/β_l are taken as shown in Table 2.3. First, the results of the LCT model are calibrated using the Danish data (shown in Figure 2.9), where β_h/β_l represents the biased market regulation ratio to restrict high-carbon energy. The behavior is then validated for different times and low-carbon energy penetration rates with reference to the correspondence between the Danish data and the model (as shown in Table 2.3).

Table 2.3. β_h/β_l value to represent the Danish carbon tax.

Years	2010	2020	2030	2050
β_h	11	13	14	15
β_l	0.1	0.1	0.1	0.1

From Table 2.3 with Figure 2.8 and Figure 2.9, the Danish case is consistent with the general trend of the ABM model results and the preliminary validation of the ABM is provided by the qualitative verified study (the system transited toward a low-carbon state from a high-carbon state, increasing the fraction of renewable energy).

2.3 Key factors and pathways

2.3.1 Dynamic system model

The dynamic model of economy–energy system based on the population dynamic model (Eqs. 2.9–2.11) is established in this section and will be applied to verify the LCT model. For the population dynamic model, more details are provided in section 2.4.

The LCT model focuses on a distributed energy system with locality consideration, however, locality cannot be considered in dynamic system model. Three agents—low-carbon energy (LC), high-carbon energy (HC), and firms—are included in the system, in which the relationship between them is very similar to sheep and two kinds of grass in a field. With sheep, or firms, as the predators and grass, or energy, as the prey, the prey is consumed by the predators and the number of predators will grow by predation.

$$\frac{de_h}{dt} = a_h N - b_h e_h N \tag{2.9}$$

$$\frac{de_l}{dt} = a_l N - b_l e_l N \tag{2.10}$$

$$\frac{dN}{dt} = -cN^2 + d_h e_h N + d_l e_l N \tag{2.11}$$

e_h and e_l represent the number of HC and LC that has been mined or excavated and can be used by humans. N indicates the number of firms and represents economic prosperity. $e_h, e_l, N \geq 0$, and coefficients a_h, a_l, b_h, b_l, c, d_h and d_l are positive constants. The four assumptions of this model are as follows:

1). Unlike biological self-reproduction, the quantity of energy is decided by economic activity; more economic activity means more energy demand, and when there is no economic activity, energy will no longer be generated. Term $a_h N$ and $a_l N$ represent the generation of LC energy and HC energy, respectively, which is very similar to the positive feedback mechanism in the ABM model. a_h, a_l is the generation rate of two types of energy.

2). Consumption by firms is the only reason leading to the decrease in energy, the terms $-b_h e_h N$ and $-b_l e_l N$ describe the consumption in which b_h and b_l can be treated as the market factors for two different types of energy. The market factors can be adjusted by certain policies or market rules that finally lead to LCT. This also corresponds to the species favored by the natural environment.

3). With the absence of energy, firms will gradually decrease, and economic activity will gradually disappear. Term $-cN^2$ reflects this process, it can be seen as the restrictions on economic growth by the natural environment. Economic activity uses energy and cannot grow indefinitely. The parameter c represents the influence of the external environment, and firms also compete with each other to accelerate energy consumption, so this becomes a non-linear term. This part is the same as sheep on land with no grass, it will die out at a certain speed (the rate of resource consumption).

4). The consumption of energy will cause the growth of companies, which are terms $d_h e_h N$ and $d_l e_l N$. d_h and d_l are the energy capacity, or it can be understood as the effect, of some LC energy that is usually unstable such as solar and wind. Therefore, LC energy offers poor effects, or low energy capacity. The counterpart in biology is the contribution of grass as food to the growth of sheep.

5). The parameters used in the LCT model have their counterparts in the dynamic system (DS) model (as shown in table 2.4).

Table 2.4. The parameters used in the LCT model with their counterparts in the (DS) model.

LCT model	DS model	Implication
$\boldsymbol{\beta_h}$	$\boldsymbol{b_h}$	Market sensitivity coefficient for high-carbon energy
$\boldsymbol{\beta_l}$	$\boldsymbol{b_l}$	Market sensitivity coefficient for low-carbon energy
$\boldsymbol{e_{con}}$	$\boldsymbol{c}$	The amount of an industrial firm’s energy consumption
i_{h}	d_h	The amount of energy provided by one unit of high-carbon energy

i_l	d_l	The amount of energy provided by one unit of low-carbon energy
r_h (t)	a_h	Rate of high-carbon energy's development
r_l (t)	a_l	Rate of low-carbon energy's development

2.3.2 The extraction of key factors

System reaches an equilibrium where $\frac{de_h}{dt}=0$, $\frac{de_l}{dt}=0$, $\frac{dN}{dt}=0$, for the model in this section, that means giving a certain initial value of LC, HC, and firms, the system will finally achieve balance and never change. This section will find and prove the equilibria of the system.

Solving the equation system (Eqs. 2.12–2.14)

$$\frac{de_h}{dt}=a_hN-b_he_hN=0 \tag{2.12}$$

$$\frac{de_l}{dt}=a_lN-b_le_lN=0 \tag{2.13}$$

$$\frac{dN}{dt}=-cN^2+d_he_hN+d_le_lN=0 \tag{2.14}$$

For the above system, two equilibrium solutions (e_h, e_l, N) is obtained under the existence conditions a_h, a_l, b_h, b_l, c, d_h and d_l are positive constants.

$$P_1(\frac{a_h}{b_h},\frac{a_l}{b_l},\frac{a_hb_ld_h+b_ha_ld_l}{b_hb_lc}),\ P_2({e_h}^*,{e_l}^*,0)$$

where ${e_h}^*$ and ${e_l}^*$ are arbitrary real numbers $e_h, e_l \geq 0$.

From the solution of $P_1(e_h, e_l, N)$, namely $P_1(\frac{a_h}{b_h},\frac{a_l}{b_l},\frac{a_hb_ld_h+b_ha_ld_l}{b_hb_lc})$, When a_h, a_l, d_h and d_l are constant, then, the following conclusions can be drawn as follows:

- The value of e_h is determined by the parameter b_h;
- The value of e_l is determined by the parameter b_l;
- The ratio of b_h / b_l controls the value of N; and
- The parameter c controls the value of N.

Therefore, b_h / b_l and c are the key parameters. From table of the parameters used in the LCT model with their counterparts in the DS model, we can find that the key parameter in the LCT model is the ratio of market regulation (β_h/β_l) to energy consumption (e_{con}).

2.3.3 The construction of phase diagram

To ensure that the sample mean of partial results is getting closer to the mean of the overall sample, a sufficient number of samples are taken to ensure a lower standard error when calculating the results, so that the mean obtained is representative and the reliability is improved.

The phase diagrams in this section have two control parameters: the ratio of market regulation β_h/β_l and the energy consumption of firms' e_{con}. β_h/β_l measures the market regulation bias on the two kinds of energy (for example, β_h represent the environmental cost like carbon tax, and β_l reflect environmental income like Tesla Inc. obtain extra income from carbon market), and energy consumption is critical to the vitality of firms.

The low carbon energy penetration rate (total amount of low carbon energy over total amount of high and low energy) R_l at equilibrium is used as the order parameter. Under two different energy capacity levels, namely the amount of unit of energy, (9:4 and 18:8), two distinct regimes (Regimes 1 and 2) with different ratio of high and low carbon energy capacity are shown in Figure 2.10. The value of order parameter R_l (at each data point) was obtained from the average over 50 sessions of simulation of 2,000 time steps. It is recorded as zero for the nearly zero value of R_l . Note that the three phases represented as different values of the order parameter (Represented by different color bars: red for high-carbon energy dominance, green for low-carbon energy dominance, and black for no production activity) can be identified in both the regimes namely, the *HC economy* phase (low R_l, red), the *LC economy* phase (high R_l, green), and the *catastrophic depression* phase (near-zero R_l, black). However, Regime 1 (left) and Regime 2 (right) show totally different phase structures. The snapshots of the three phases in the two regimes are shown in Figure 2.9 (the blue nodes are the firms, while each green or red node represents one unit of low- or high-carbon energy), from which one can observe that all firms go bankrupt in *catastrophic depression*. However, in the *low carbon economy* phase, only firms using LC energy survive, and in the *HC economy* phase, firms using HC energy coexist with those using LC energy. In addition, from the comparison of the top panels (a)–(c) and the bottom panels (d)–(f) in Figure 2.11, it can be found that the total number of firms N_f in Regime 2 is significantly higher than that in Regime 1.

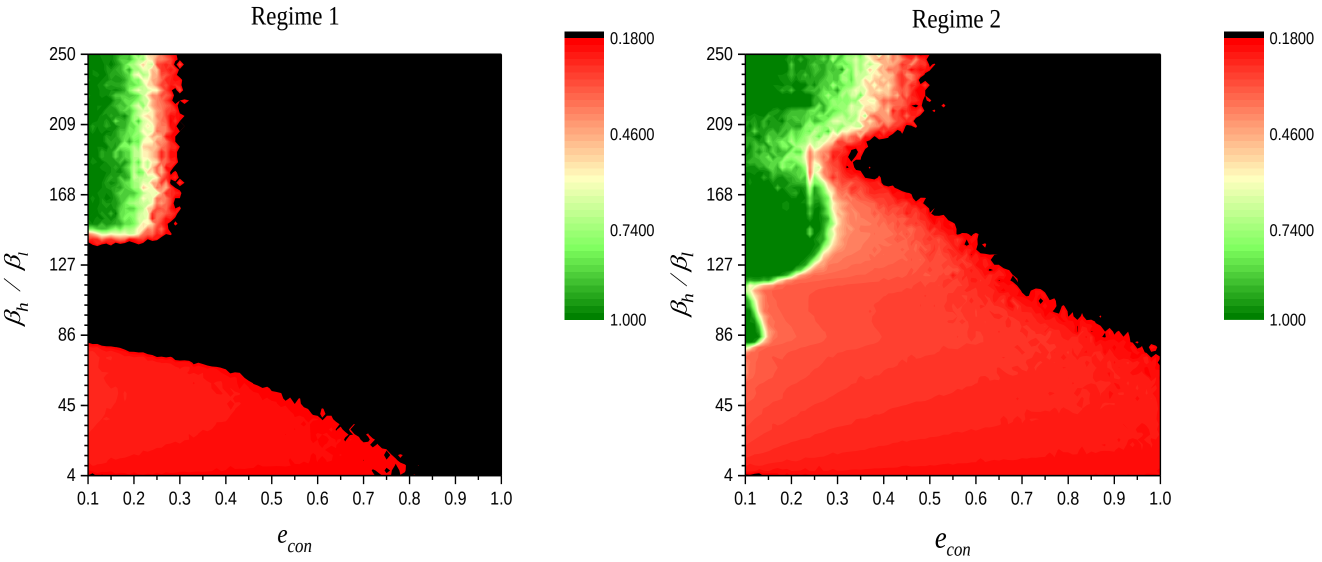
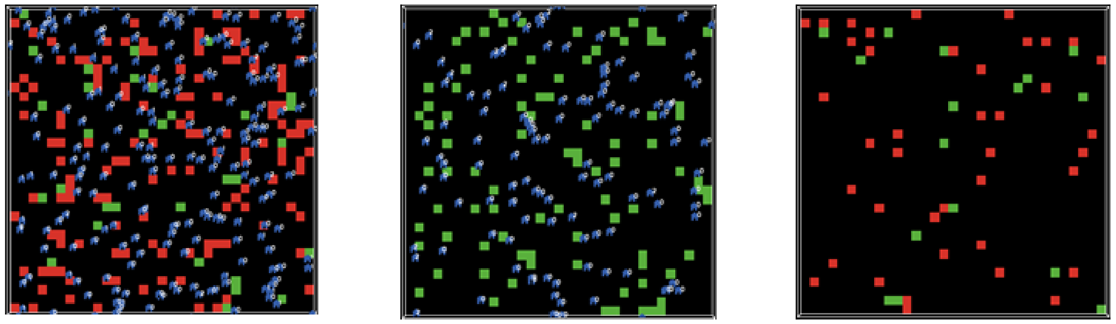


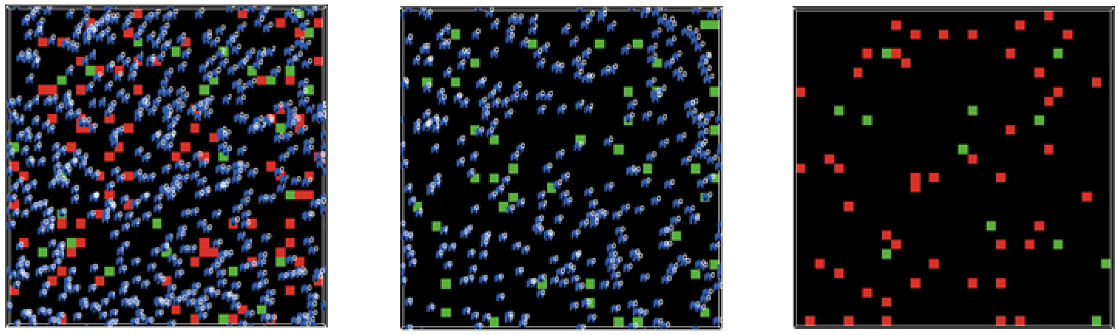
Fig. 2.10. Phase diagrams of Regime 1 with $i_h = 9$, $i_l = 4$ (left) and of Regime 2 with $i_h = 18$, $i_l = 8$ (right), respectively (Regimes 1 and 2 represent distinct systems with different conditions). The color bar is the value of order parameter R_l obtained from the average over 50 sessions of simulation of 2000 time steps for each data point. Three phases represented by distinct values of the order parameter can be well identified, namely the phase of *catastrophic depression* (near-zero R_l, black), the phase of *high-carbon economy* (low R_l, red), and the phase of *low-carbon economy* (high R_l, green).



(a) High carbon economy (e_{con} = 0.5, β_h/β_l = 25)

(b) Low carbon economy (e_{con} = 0.25, β_h/β_l = 150)

(c) Catastrophic depression (e_{con} = 0.8, β_h/β_l = 150)



(d) High carbon economy (e_{con} = 0.5, β_h/β_l = 25)

(e) Low carbon economy (e_{con} = 0.25, β_h/β_l = 150)

(f) Catastrophic depression (e_{con} = 0.8, β_h/β_l = 150)

Fig.2.11. Snapshots of Regime 1 [(a), (b), (c)] and Regime 2 [(d), (e), (f)]. Each red (green) node represents one unit of high (low) carbon energy, while the blue noded are the industry firms. In regime 1, $i_h = 9$ and $i_l = 4$, while in regime 2, $i_h = 18$ and $i_l = 8$.

1) Regime 1

In Regime 1, the energy capacities are set relatively lower as $i_l = 4$ and $i_h = 9$. In Figure 2.12 (left), the phase diagram of Regime 1 is schematically redrawn, where two phase boundaries separate the three phases without a triple critical point. In addition, when energy consumption is low, the market regulation ratio β_h/β_l is crucial for two phase transitions (from *catastrophic depression* to a *LC economy* and from a *HC economy* to *catastrophic depression*), while energy consumption e_{con} is more critical to the phase transition for a higher β_h/β_l.

Note that there is no LCT path from a HC economy to a LC economy in this regime. To prove this, a virtual experiment is carried out by increasing β_h/β_l (the market regulation ratio) for the systems in the *HC economy* phase. Figure 2.12 (bottom right) shows that even after tuning or adjusting β_h/β_l from 55 (HC economy) to 200, which is supposed to drive the system into the *LC economy* phase, the transition from a *HC economy* to a *low- carbon economy* still failed because the system encountered *catastrophic depression* before reaching the LC state. Figure 2.12 (top right) shows that after the market regulation ratio β_h/β_l went from 55 to 125 at time step 1,000, the system encountered a catastrophic depression with all of the firms going bankrupt.

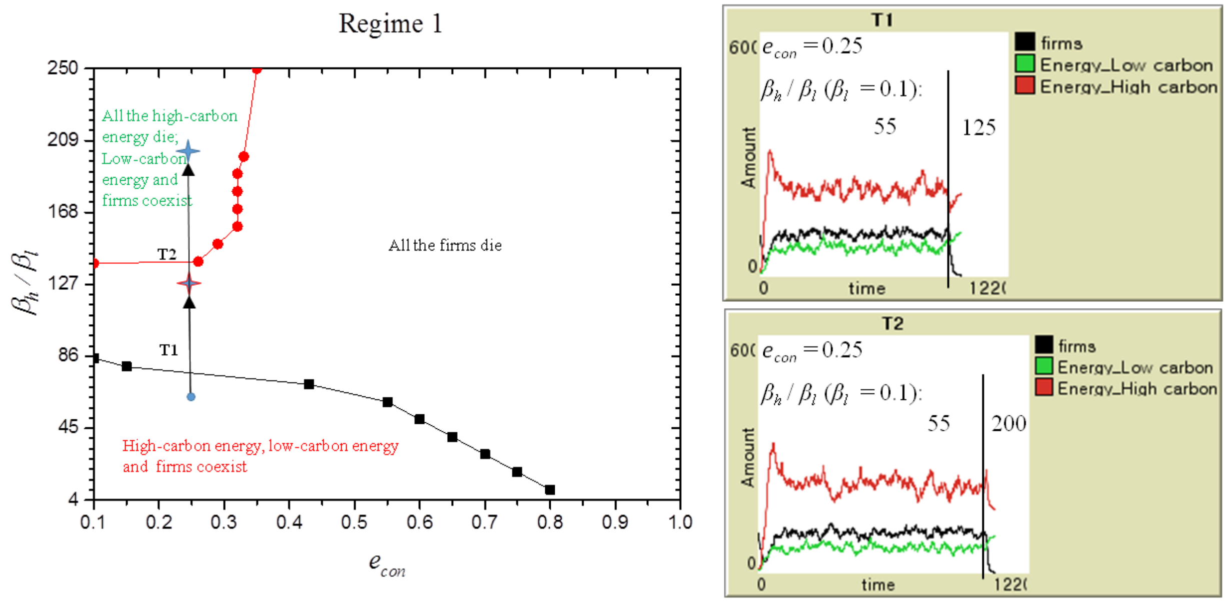


Fig.2.12. Schematic phase diagrams of Regime 1 with a failed dynamic transition. (*Left*) Schematic phase diagram of Regime1. (*Right top,* transition 1, T1 that system transit from HC state to all firms die state) Dynamic transition through the changing the market regulation bias β_h/β_l from high carbon economy to catastrophic economic depression; (*Right bottom,* transition 2, T2 that system transit from HC state to LC state) Unsuccessful dynamic transition through the market regulation favoring low carbon energy from high carbon economy to low carbon economy.

2) Regime 2

Both high- and LC energy capacity can be improved through energy efficiency, storage capacity, and the application of advanced energy systems (such as combined cooling, heating, and power in a distributed energy system). Thus, in Regime 2, a higher set of energy capacities can be considered (i.e., $i_h = 18$ and $i_l = 8$), and the phase diagram of Regime 2, which radically changes from that of Regime 1, is drawn schematically in Figure 2.13 (left). Nevertheless, with three phase boundaries between any two of the three phases, three phases can still be identified with a triple critical point ($e_{con} = 0.3$, $\beta_h/\beta_l = 193$). Moreover, for energy consumption e_{con} beyond 0.3, a market regulation ratio β_h/β_l in the range below the triple critical point is more critical to the phase transition between the *HC economy* and *catastrophic depression* phases. For energy consumption e_{con} below 0.3, the market regulation ratio β_h/β_l controls mainly the phase transition between the *LC economy* and *HC economy* phases. With a

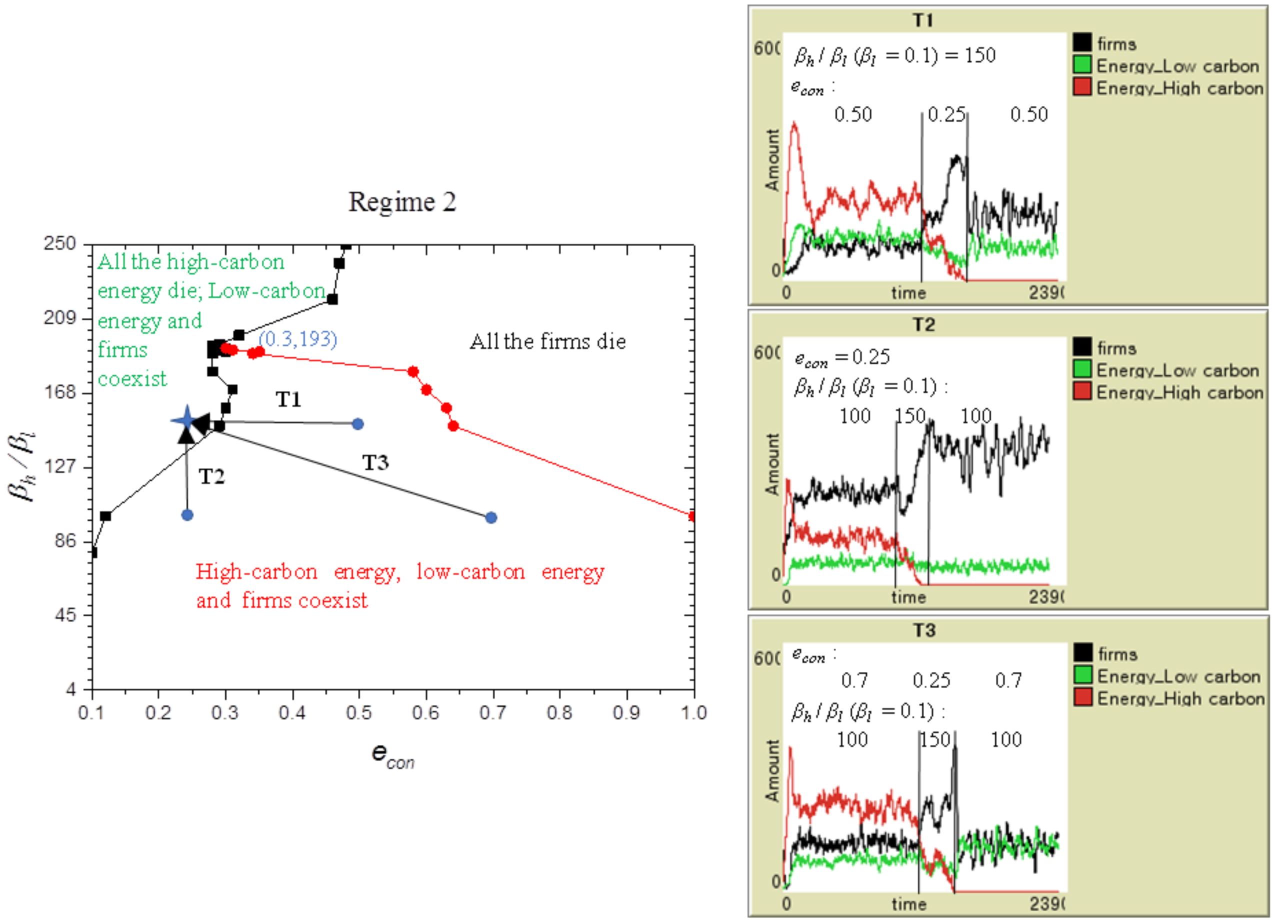


Fig.2.13. Schematic phase diagram of Regime 2 with three examples of low carbon transitions. (*Left*) Schematic phase diagram of Regime2. (*Right-Top*, transition 1, T1 that system transit from HC state to LC state) Dynamic LCT by lowering the energy consumption; (*Right-Middle*, transition 2, T2 that system transit from HC state to LC state) Dynamic LCT by elevating the market regulation ratio; (*Right-Bottom*, transition 3, T3 that system transit from HC state to LC state) Dynamic LCT by adjusting both the energy consumption and market regulation ratio.

higher β_h/β_l over the triple critical point, energy consumption e_{con} controls the transition between the *catastrophic depression* and *LC economy* phases.

There are three possible ways, different from Regime 1, to achieve the transition from a *HC economy* to a *LC economy* without risking economic disaster or catastrophe, according to the system's position on the phase diagram. Basically, LCT can be achieved by three temporary adjustments: 1) adjusting both (Figure 2.13 (bottom right)]; 2) reducing energy consumption e_{con} (Figure 2.13 (top right)); and 3) increasing the market regulation ratio β_h/β_l [see the example in Figure 2.13 (middle right)). If the system currently has a weak market regulatory bias ($\beta_h/\beta_l = 100$) and a high energy consumption ($e_{con} = 0.7$), then reducing energy consumption alone may not work and should be accompanied by a mild or moderate increase of the market regulation ratio β_h/β_l to reach the LC phase as efficiently as possible (see the example shown in Figure 2.13 (bottom right)). If the system currently has a strong market regulatory bias ($\beta_h/\beta_l = 150$) and relatively high energy consumption ($e_{con} = 0.5$), reducing energy consumption must be the first priority (see the example shown in Figure 2.13 (top right)); otherwise, the system may fall into a catastrophic depression before adjusting into a *LC economy*. Lastly, if the system currently has a relatively weak market regulatory bias ($\beta_h/\beta_l = 100$) and low energy consumption ($e_{con} = 0.25$), then elevating the market regulation ratio β_h/β_l becomes an effective way to move toward a LC society (see the example shown in Figure 2.13 (middle right)).

Furthermore, for all the three cases in Figure 2.13, it may be noted that the LC economy is stable after the completion of LCT (even if the adjustments are subsequently removed). For instance, the system will never return to a *HC economy* when the parameters are re-tuned to their pre-adjustment values. In the model, this irreversibility of LCT is attributed to the positive feedback between the reduction in demand and the reduced supply of energy during the period when the critical parameters are adjusted (see Eqs. 2.5 and 2.6). According to the formulation of the equations, the supply will fall (drop) continuously to zero once the demand declines to a level far below the characteristic value or scale of firm density $b - 1$ shown as in equation 2.5 and 2.6, when the demand of energy is below the critical value), and the system will not be able to escape from the absorbing dynamics, even though the parameters return afterwards to a level favoring HC energy. Therefore, it is implied that by facilitating or promoting some of specific positive feedback between energy demand and supply, an LCT could possibly be secured.

Based on the results, it is found that the best policy intervention for promoting a sustained economy in LCT is to implement a strong market bias in favor of LC energy ($\beta_h/\beta_l > 1$) integrated with a limitation on the energy consumption (small e_{con}). However, an LCT can only be successfully achieved under Regime 2 with relatively high energy capacity i_h or i_l. Therefore, it is necessary to first recognize which state the system may be in to avoid a transition that causes a catastrophic depression like in R1. For the developing countries (such as those in Africa) that currently do not have advanced technologies with sufficiently high generation capacity, increasing energy capacity should be the top priority before launching any LCT projects. Moreover, it is indicated that a system might be in Regime 2 if it has a relatively high energy capacity, and a totally different pathway (as shown in Figure 2.13) with different policy preferences should be adopted.

2.4 Theoretical Analysis

Inspired by the LCT model and the DS applied in ecology that is described in detail in Section 2.4.2 [118-119], a DS model to analyze LCT in the energy–economic system can be established and used to verify the LCT model. In this section, the DS model is established first, and then this method is applied to research on the economy–energy system, which uses simple mathematical equations to express the relationships of complex systems clearly through a stability analysis of the system. In such models, one can determine the impact of various parameters on the system. DS methods can quickly find the equilibrium point (or a fixed point) of the system, whether it is stable or not, and quickly determine the characteristics of the system. Moreover, the results obtained by the two methods (the LCT model and the DS model) can be compared with each other, thereby promoting further optimization of the two methods to make the results and the LCT model more credible.

2.4.1 Global LCT model

In the previous sections, the global LCT model was used instead of the local in order to allow the DS model to be compared with the LCT model (because the DS model cannot achieve the complex system content that the ABM model can represent, such as locality). In this section, the local and global relationships of the LCT model are explained to further understand this relationship between the LCT model and the DS approach. Also, a realistic global LCT model is equivalent to a system that collects information from a local domain to resist risks on a global scale, as in the case of virtual energy management systems such as VPP.

In the LCT model, the market sensitivity coefficients β_h and β_l have local attributes. This feature can be only realized when using the ABM method. In the ABM model, there is a difference between individual and spatial locations, but in the DS model everything is homogeneous (i.e., it represents the global average attributes). Because of this discrepancy, the local LCT model results show results identical to the DS model in the qualitative analysis, but the results also show different characteristics in terms of quantitative analysis and parameter sensitivity. Here, an explanation of the difference between the local and global LCT models is provided.

In the LCT model, the energy purchase cost is p_h (HC) or p_l (LC).

$$p_h = \beta_h \rho_h^z \tag{2.15}$$

$$p_l = \beta_l \rho_l^z \tag{2.16}$$

β_h and β_l represent the market sensitivity coefficients for high- and LC energy, ρ_h^z and ρ_l^z are the number of firms purchasing high- and LC energy where the number is decided by the number of firms in a 3 × 3 local area covering the node. The calculation method in this study removed the local attribute where the number of firms purchasing high- and LC is decided by the total number of firms in the global area.

$$p_h = \beta_h \rho_h \tag{2.17}$$

$$p_l = \beta_l \rho_l \tag{2.18}$$

Table 2.5. Simulation results of local and global conditions of the LCT model.

Method		S1	S2	S3	S4	S5
Local ABM	R_l	0.18	0.19	0.21	0.24	0.29
	N_f	281	239	361	217	398
Global ABM	R_l	0.17	0.20	0.16	0.21	0.23
	N_f	248	107	566	253	338

It should emphasize that the ABM method is not exactly the same as the LCT model by comparing the LCT model and the DS model using global LCT results (Since ABM can build and simulate more complex social models, while DS cannot simulate details such as locality). In addition, from the comparison of the local and global results obtained from the LCT model, the results for LC energy penetration and the total number of firms have the same trends (shown as in table 2.5).

2.4.2 Derivation

I. The Lotka–Volterra model and its extension

A pair of equations (Eqs. 2.19 and 2.20) was separately proposed by A.J. Lotka (1925) and V. Volterra (1931) [121-123]. This DS is used to describe the relationship between prey and a predator in biology. x and y represent the number of prey and predators at time t and $x \geq 0 \;\; y \geq 0$, coefficients a, b, c, and d are positive constants.

This model has four assumptions:

1) If $y = 0$, which means there is no predator, the prey will increase with no limitation, so term ax will reflect this.

2) The presence of a predator is the only reason that causes the decrease in the prey, which is represented by the term $-bxy$.

3) With the absence of prey, the number of predators will always decrease, as described by the term $-cy$.

4) The presence of prey is the only reason that causes an increase in prey, which is represented by the term dxy.

$$\frac{dx}{dt} = ax - bxy \tag{2.19}$$

$$\frac{dy}{dt} = dxy - cy \tag{2.20}$$

Their pioneering work has evolved in different ways. M.F. Elettreby [120] proposed a two-prey, one-predator system (Eqs. 2.21–2.23). The system reflects the interaction between three species in which there are two kinds of prey that cooperate with each other.

$$\frac{dx}{dt} = ax(1 - x) - xz + xyz \tag{2.21}$$

$$\frac{dy}{dt} = by(1 - y) - yz + xyz \tag{2.22}$$

$$\frac{dz}{dt} = -cz^2 + dxz + eyz \tag{2.23}$$

A similar method was also applied to study of infectious diseases, competitive species analysis and aquatic harvesting this thought was even used to the area of economy [124-125]. They present a macroeconomic model that combines the economic impact of climate change with the pivotal role of private debt in which they use a Stock-Flow Consistent approach based on the Lotka–Volterra logic. The Lotka–Volterra logic applied in Stock-Flow Consistent approach was first proposed by Keen S [126]. This three-dimensional system shows the relationship between $\dot{\omega}$ wage bill rate in real output, λ employment rate and $\dot{b}$ rate of firms borrowing from banks in real output, α, β, π denote productivity, workforce and profit share respectively. This model is constantly evolving and is representative of the application of Lotka–Volterra model in economics.

$$\dot{\omega} = \omega[\Phi(\lambda) - \alpha] \tag{2.24}$$

$$\dot{\lambda} = \lambda[g(\pi) - \alpha - \beta] \tag{2.25}$$

$$\dot{b} = \kappa(\pi) - \pi - bg(\pi) \tag{2.26}$$

Therefore, using the thought of A.J. Lotka and V. Volterra, this section is going to establish a DS model that can describe the relationship between the economy and energy.

II. Derivation of DS model from LCT model

The DS model of economy–energy system based on population dynamic model (Eqs. 2.9–2.11) is established in given in Section 2.3.1 and will be applied to verify the LCT model. The LCT model focus on a distributed energy system. Three agents— LC, HC, and firms—are included in the system. The relationship between the three agents is very similar to sheep and two kinds of grass in a field. The sheep, or firms, is the predator and the grass, or energy, is the prey; the prey is consumed by the predator and the number of predators will grow by predation.

In these equations, e_h and e_l represent the amount of high carbon and low carbon energy that has been mined or excavated and can be used by society. N is the number of firms and represents economic prosperity. $e_h, e_l, N \geq 0$ where coefficients $a_h,\ a_l,\ b_h,\ b_l,\ c,\ d_h$ and d_l are positive constants. The four assumptions of this model are also given in Section 2.3.1.

2.4.3 Explanation global LCT results

I. Local stability analysis

The system reaches equilibria where $\frac{de_h}{dt} = 0$, $\frac{de_l}{dt} = 0$, $\frac{dN}{dt} = 0$, for the model in this section, that means giving certain initial value of LC, HC, firms, system will finally achieve balance and never change. This section will find and prove the equilibria of system.

Solving equation system (Eq.2.27-Eq. 2.29) as follows:

$$\frac{de_h}{dt} = a_h N - b_h e_h N = 0 \tag{2.27}$$

$$\frac{de_l}{dt} = a_l N - b_l e_l N = 0 \tag{2.28}$$

$$\frac{dN}{dt} = -cN^2 + d_1 e_h N + d_2 e_l N = 0 \tag{2.29}$$

For the above system, two equilibrium solutions (e_h, e_l, N) are obtained under the existing conditions $a_h,\ a_l,\ b_h,\ b_l,\ c,\ d_h$ and d_l are positive constants,

$$P_1\left(\frac{a_h}{b_h}, \frac{a_l}{b_l}, \frac{a_h b_l d_h + b_h a_l d_l}{b_h b_l c}\right),\ P_2({e_h}^*, {e_l}^*, 0)$$

where ${e_h}^*$ and ${e_l}^*$ are arbitrary real number, and $e_h, e_l \geq 0$.

Proposition. The system (Eq. 2.9-Eq. 2.11) *has one stable equilibrium solution* P_1(*sink*) *and one non-hyperbolic equilibrium solution* P_2 *under the analysis of local stability.*

Proof. For the system (9-11), the Jacobian matrix is:

$$J = \begin{bmatrix} -b_h N & 0 & -b_h e_h + a_h \\ 0 & -b_l N & -b_l e_l + a_l \\ d_h N & d_l N & -2cN + d_h N + d_l N \end{bmatrix} \tag{2.30}$$

Substituting (e_h, e_l, N) with the point $P_1\left(\frac{a_h}{b_h}, \frac{a_l}{b_l}, \frac{a_h b_l d_h + b_h a_l d_l}{b_h b_l c}\right)$ in the J, the eigenvalue of the matrix is as follows:

$$\lambda_i(i = 1,2,3) = -\frac{a_h d_h b_l + a_l d_l b_h}{b_h b_l}, \quad -\frac{a_h d_h b_l + a_l d_l b_h}{b_l c}, \quad -\frac{a_h d_h b_l + a_l d_l b_h}{b_h c} \tag{2.31}$$

These are three negative eigenvalues because all of the constants are positive. According to the linearization theorem [127], this point is the sink point and is asymptotically stable. Numerical simulation as shown in Figure 2.14 (The time step is set with reference to whether the system reaches a stable state or reaches a converged state, as in Figure 2.14 the time step is 200 time units for the simulation) and directional field, as shown in Figure 2.15. The condition $a_h = 30$, $a_l = 0.0015$, $b_h = 15$, $b_l = 0.0015$, $c = 0.4$, $d_h = 0.5$, and $d_l = 0.25$ is consistent with the results.

Substituting (e_h, e_l, N) with the point $P_2(e_h{}^*, e_l{}^*, 0)$ in the J, the eigenvalue of the matrix is as follows:

$$\lambda = 0,\ \ 0,\ \ e_h{}^* d_h + e_l{}^* d_l$$

When the real part of the two eigenvalues is 0, this point is a non-hyperbolic equilibrium point.

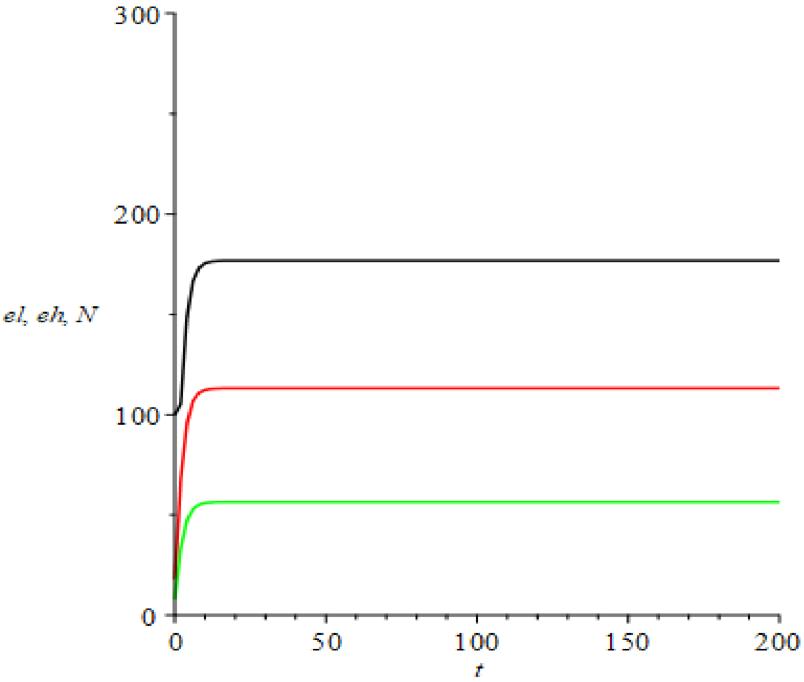


Fig. 2.14. Numerical simulations result of the system where $a_h = 20$, $a_l = 10$, $b_h = 0.1$, $b_l = 0.1$, $c = 1$, $d_h = 1$, and $d_l = 0.5$.

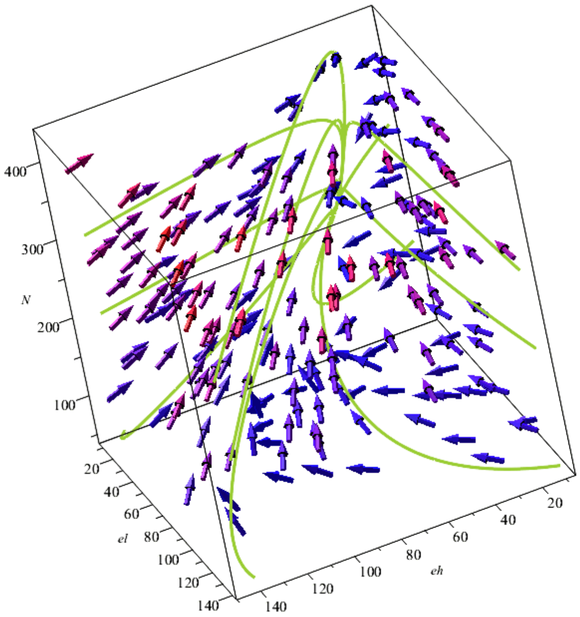


Fig.2.15. Directional field of the system where $a_h = 20,\ a_l = 10,\ b_h = 0.1,\ b_l = 0.1,\ c = 1,$ $d_h = 1$, and $d_l = 0.5$.

According to the description and proof in this Section, from any initial point above plane x-y, the system will finally become stable at point $P_1(\frac{a_h}{b_h}, \frac{a_l}{b_l}, \frac{a_h b_l d_h + b_h a_l d_l}{b_h b_l c})$ Here, two indices are chosen to analyze and evaluate the low carbon transition.

1). Time evolution of the number of surviving firms, N_f, in the system is the value of numbers of firm at stable point P_1, namely $N_f = \frac{a_h b_l d_h + b_h a_l d_l}{b_h b_l c}$.

2). The penetration rate of low carbon energy, R_l, is the proportion of low-carbon energy at stable point P_1, $R_l = \frac{\frac{a_l}{b_l}}{\frac{a_h}{b_h} + \frac{a_l}{b_l}}$. Different parameters combinations represent different countries and locations or can refer to different policies in the same area. For example, a system of energy-rich countries will have a higher energy generation rate a_h, a_l and by increasing b_h, b_l through certain policies in the same country, the ratio adjustment of different types of energy can be realized. N_f is the indicator of economic prosperity and R_l is used to represent the implementation of LCT.

II. LCT model verification with DS results

This study takes N_f and R_l as the evaluation index and designs five computational scenarios (see Table 2.6). The market sensitivity coefficient for HC energy in case S2 is 5 times greater than case S1. Also, case S4 is 5 times greater than case S3. The purpose of this comparation is to examine the effect of energy market rules in LCT. Cases S3 and S4 change the energy capacity to 2 times that of cases S1 and S2. In case S5, the amount of energy consumption is set to one-quarter that of case S4 to investigate its influence on the system.

Table 2.6. Simulation scenarios with different parameter settings in DS model.

Parameter	S1	S2	S3	S4	S5
a_h	20	20	20	20	20
a_l	10	10	10	10	10
b_h	0.1	0.5	0.1	0.5	0.5
b_l	0.1	0.1	0.1	0.1	0.1
c	0.5	0.5	0.5	0.5	0.125
d_h	1	1	2	2	2
d_l	0.5	0.5	1	1	1

Table 2.6 exhibits the computational results, and the results show five conclusions:

1) S1 is the scenario corresponding to the one in the LCT model. Two points can be derived from the LCT model and DS correspondence in Tables 2.6, 2.7, 2.8, 2.9, and 2.10: correspondence of parameters and correspondence of results (basic relationship between firms and energy supply when both market strengths are weak). The validity of S1 can be confirmed by the comparison with ABM.
2) From the comparison of S1 and S2, an increase in the market sensitivity coefficient for HC energy can lead to an elevation of the penetration rate of LC energy. This is the same result that is concluded from a comparison of S3 and S4.
3) In S4, with strong market rules or energy use policy, economic activity will decrease.
4) An increase in energy capacity can lead to a huge increase in economic activity.
5) From the comparison of S4 and S5, energy consumption is drastically reduced, and the economic activity will enjoy growth.

Table 2.7 Simulation results of five scenarios.

Scenario		S1	S2	S3	S4	S5
Dynamical system	R_l	0.33	0.71	0.33	0.71	0.71
	N_f	500	180	1000	360	1500

The evaluation indices are the same as the LCT model in Section 2.2, in the LCT model six computational experiments were performed to reproduce six representative scenarios of distributed energy systems. In the six different scenarios, the ABM model used different parameters. All of these parameters have counterparts in the DS model, which are listed in Table 2.8.

Table 2.8 Parameter correspondence and implication

ABM (LCT) model	DS model	Implication
β_h	b_h	Market sensitivity coefficient for high-carbon energy
β_l	b_l	Market sensitivity coefficient for low-carbon energy
e_{con}	c	The amount of industrial firm's energy consumption
i_h	d_h	The amount of energy provided by one unit of high-carbon energy
i_l	d_l	The amount of energy provided by one unit of low-carbon energy
$r_h(t)$	a_h	Rate of high-carbon-energy’s development
$r_l(t)$	a_l	Rate of low-carbon-energy’s development

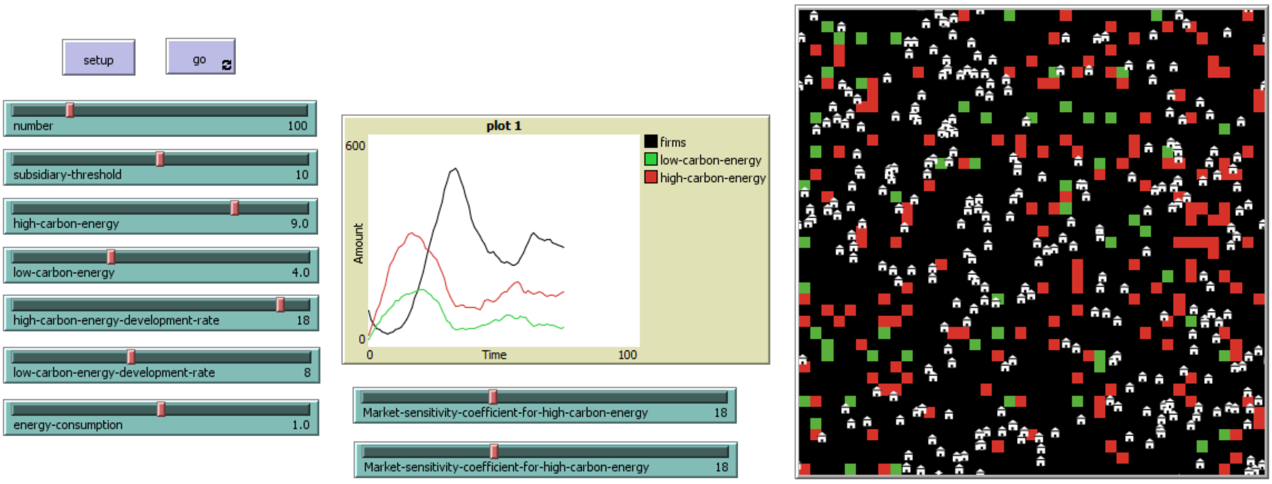

number 100
subsidiary-threshold 10
high-carbon-energy 9.0
low-carbon-energy 4.0
high-carbon-energy-development-rate 18
low-carbon-energy-development-rate 8
energy-consumption 1.0
Market-sensitivity-coefficient-for-high-carbon-energy 18
Market-sensitivity-coefficient-for-high-carbon-energy 18

Fig. 2.16. Netlogo user interface with the present model.

To verify the results of the DS model, the simulation conditions (Table 2.9) and results (Table 2.10) of the agent based LCT model are also listed. The agent based LCT model is implemented in Netlogo. The model interface, input conditions, and output results can be seen in Figure 2.14. A detailed model description can be seen in a paper by Xifeng Wu et al. [1] or in Section 2.2.2. Through the results of both methods, is it found that limiting the use of HC energy through certain market rules and reducing energy consumption simultaneously is the best way to achieve LCT.

Table 2.9. Simulation scenarios with different parameter settings in LCT model.

Parameter	S1	S2	S3	S4	S5
β_h	0.01	0.05	0.01	0.05	0.05
β_l	0.01	0.01	0.01	0.01	0.01
e_{con}	0.8	0.8	0.8	0.8	0.2
i_h	9	9	18	18	18
i_l	4	4	8	8	8

Table 2.10. Simulation results of five scenarios.

Scenario		S1	S2	S3	S4	S5
LCT model	R_l	0.17	0.20	0.16	0.21	0.23
	N_f	248	107	566	253	338

It is particularly important to emphasize that the DS model in this section is not exactly the same as the LCT model. The ABM method can simulate the locality of the system in space; however, the DS model is a global system that has difficulty showing the locality of the system, so in this study we compare global ABM simulation results with DS simulation results. From the comparison of S1 and S2, in the LCT model the penetration rate of LC energy increases from 0.17 to 0.20. The DS model shows more radical growth; the penetration rate of LC energy increases from 0.33 to 0.71. The same phenomenon can be also found between S4 and S5; the number of firms in the DS model is more sensitive to the energy consumption rate. Nevertheless, the results of the LCT model can be quantitatively verified by the DS model.

2.4.4 Phase diagram

From Section 2.4.3, the data results reflect the affection of different parameters of the LCT process. In this part, the phase diagrams will be made to analyze the pathway of LCT. As shown in Figure 2.18, the market regulation ratio $\frac{b_h}{b_l}$ and energy consumption rate c are set as control parameters. The LC energy penetration rate R_l is described by a color change, going from red to green means transitioning from a HC to a LC economy. From Section 2.4.3, increasing the values of $\frac{b_h}{b_l}$ and c will curb economic activity, which is demonstrated as a decrease in N_f. According to the stability analysis, N_f can come infinitely close but not equal to zero. The ABM model has a situation in which all companies go bankrupt. But in the DS model, the results will always fall to a certain point; it can come infinitely close but not equal to zero. The ABM model emphasizes individual characteristics, and it has strong spatio-temporal randomness. Each simulation result may be different, but the average of many simulation results is stable. The DS model emphasizes global homogeneity. Using a simple method it will yield stable results, but sometimes it has difficulty describing complex phenomena. Through further optimization of the model, the results of the two methods may be close. So, this part takes $N_f = 25$ as a critical point, when the equilibrium point falls to $N_f \leq 25$, economic activity in this system will be considered stopped, which is depicted as the black area. Figure 2.17 shows phase diagrams of the two regimes; all simulation parameters are listed in Table 2.10.

According to Figure 2.17, it is found that an increase in the market regulation ratio will make the system achieve LCT, but this process is limited by the energy consumption rate. In a system with a high energy consumption rate, overly aggressive LC policies or market rules will make the system suffer a catastrophic depression (i.e., the economic activity will stop). With a decrease in the energy consumption rate, obtaining a higher LC energy penetration rate is more likely. From Figure 2.15, one can find that the energy capacity does not make a direct contribution to the LCT, but it will help reduce the black-colored area, which means that it will offer the possibility of LCT in a system with a high energy consumption rate.

The phase diagrams were split into two regions by a critical line, which is shown in Figure 2.17. In the area above the critical line, the system will suffer a catastrophic depression (i.e., where the economy stops). This line also determines the maximum value of the LC energy penetration rate; for example, at point $c = 10$ (point A), the system can only achieve $R_l = 0.33$, when $c = 4$ (point B) the max R_l of the system becomes 0.66. The R_l will go up to 0.9 when c is smaller than 2 (point C), which means that the system basically reached a complete LCT. When increasing the energy capacity of the system by two times, the R_l will increase from 0.33 to 0.57 (from point A to D).

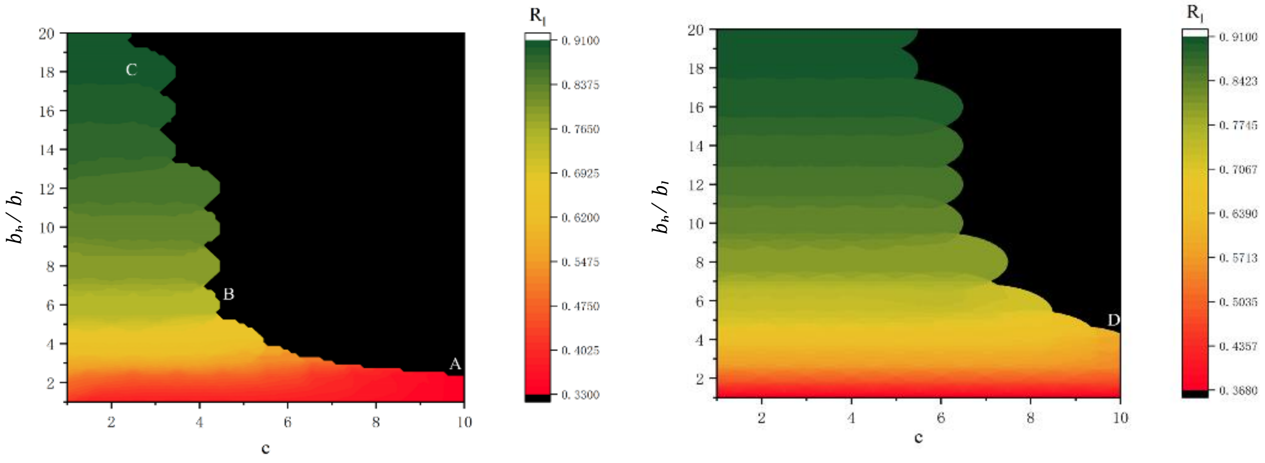


Fig. 2.17. Phase diagrams of Regime 1 (left) and Regime 2(right).

Table 2.10. Simulation parameters of phase diagrams.

	a_h	a_l	b_h	b_l	c	d_h	d_l
Regime 1	20	10	0.1–2	0.1	1–10	1	0.5
Regime 2	20	10	0.1–2	0.1	1–10	2	1

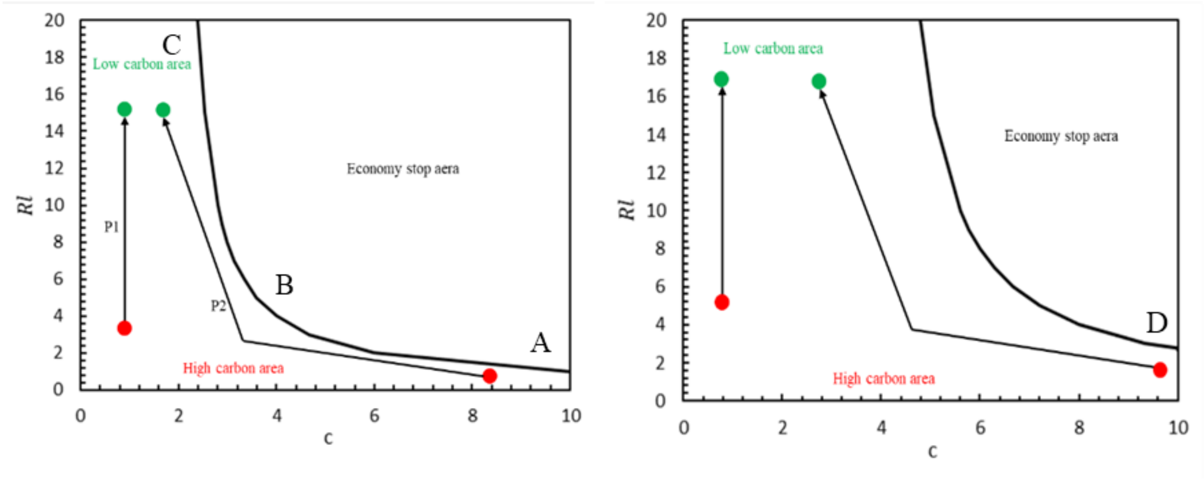


Fig. 2.18. Schematic phase diagram of Regime 1 (left) and Regime 2 (right).

From the phase diagrams, it is apparent that there are three possible pathways to realize LCT with no harm to the economy. The first is directly raising the market regulation ratio (see P1 in the Figure 2.18); this is the most direct and easy way. However, if the system currently has a relatively high energy consumption rate, directly raising the market regulation ratio will make the system suffer a catastrophic depression. In this case, a lower energy consumption rate become the first priority. When the energy consumption rate drops to a lower level, increasing the market regulation ratio can work (see P2 in the Figure 2.18). Reducing energy consumption may not always be feasible. In this situation, finding some methods to increase energy capacity becomes more important. In Figure 2.19, one can find that increasing the energy capacity can elevate the critical line, making the transitional process more flexible. Therefore, increasing the energy capacity and then raising the market regulation ratio seems to be another good pathway (see P3 in the Figure 2.19).

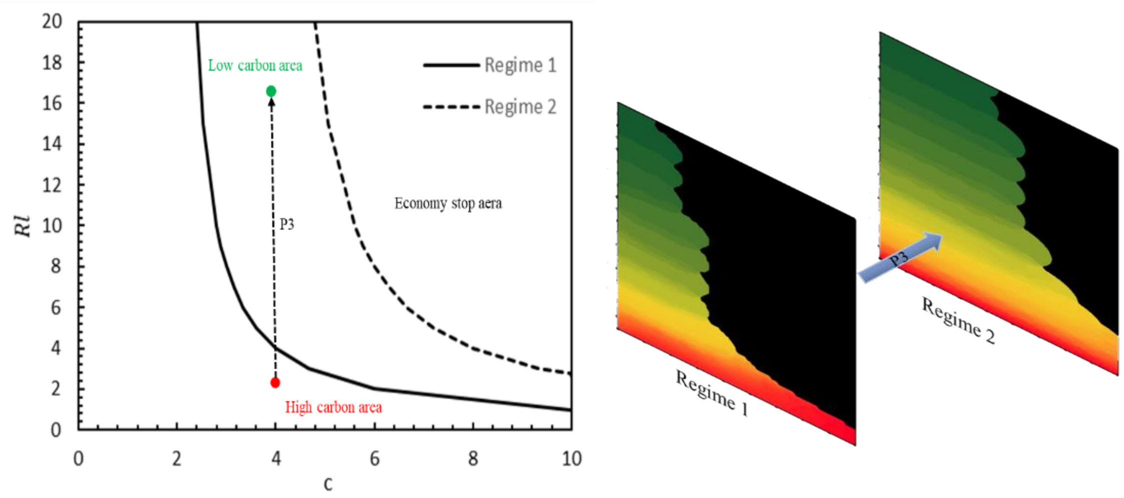


Fig. 2.19. Systemic transition with a change in energy capacity.

According to the results of the mathematical model, it is found that the best pathway for the LCT is not simply carrying out a strong policy favoring LC energy (with a high value of $\frac{b_h}{b_l}$). The combination of multiple means becomes crucial according to the various pathways. The current results are a good verification of the LCT model, although the methods and results are different, both methods conclude the same pathways for the LCT.

The DS model in this section evolved from the simplest two prey–one predator model in PD. It is highly homogenous in its description of the features of energy and the economy. To get closer to the real situation, competition and selection mechanisms between energy types can be introduced [99]. To better describe the market feedback mechanism, a discrete model approach is also available as an option. With all of the extensions of the model, the equilibrium point will no longer be a simple point. Sink, bifurcations, and chaos phenomena may occur.

2.5 Summary of Chapter 2

First, an ABM of LCT was established to simulate a distributed energy system coupled with localized energy markets to explore the relationship between some key factors and their combined effect on LCT. The roles of energy capacity, energy consumption, economic regulations, and their combined effects on LCTs for distributed energy systems were investigated. By scanning the parameter space of energy capacity, energy consumption (e_{con}), and market regulatory bias (β_h/β_l), two distinct types of phase diagrams (Regime 1 and Regime 2) were obtained, on which three phases were constructed: *catastrophic depression*, *HC economy*, and *LC economy* can be distinguished by the LC penetration rate at equilibrium. Moreover, the dynamic processes of LCTs under different regimes were studied and positive feedback loops between the energy supply and demand were found to be critical for securing LCTs. The simulation results show that under the condition of increased energy capacity with a positive feedback loop between supply and demand, LCT can be facilitated by the combination of market adjustments favoring LC energy and policy adjustments encouraging low energy consumption. By contrast, with a low energy capacity and high energy consumption, the transition from a high- to a LC economy inevitably causes a catastrophic economic depression.

Second, theoretical verification is performed with reference to the PD. Inspired by the method of PD (Lotka–Volterra model) and the ABM, for distributed energy systems, a DS model with a positive feedback mechanism was established. The parameters in the model reflect the characteristics of the distributed energy system, such as the generation rates of different energy types, the preferences of market rules and policies for different energy types, energy consumption rates, and the energy capacity of the distributed energy system. The model in this paper has only one stable solution (i.e., the sink point), no matter what initial value is set, the result will fall to the same point for the same set of parameters. Moreover, computational experiments were performed, and phase diagrams constructed to reproduce representative scenarios and LCT pathways. The effect of different parameters on LCT is quantitatively analyzed and the results are compared with the LCT model at the same time. The proposed population dynamic model and LCT model mutually verify each other.

Third, a framework for the combination of MLP with ABM is proposed and succeeds in providing a more solid base for the simulation study of LCT processes. It is made clear that MLP can contribute to the overall design of ABM, and that ABM can provide a dynamic, continuous, and quantitative description of MLP.

Chapter 3 Timing LCT policy interventions with the economic cycles

3.1 Background

Because the transition to a LC economy will bring the risk of economic recession and even cause an economic crisis due to energy shortages. Moreover, in a modern society that is filled with periodic economic crises, the answer to the questions of how to grasp a reasonable timing for LCT policy intervention, what kind of impact LCT has on the economic cycle, and whether LCT itself can be realized naturally and how the economy will respond accordingly are still lacking. More specifically, it is urgent to understand the following points. 1). In a complex economic cycle, is there an appropriate or right time for policy intervention that can ensure LCT and reduce its impact on the economy? 2). What is the link between LCT and the economic cycle, and how can we balance energy supply and demand with environmental pressure to respond to economic cycles for a smooth LCT?

Although many achievements have been made in both the economics and energy resources fields, there is no model that can simulate the economic system and the energy system simultaneously and examine the interactions between them. Although previous scholars have theoretically and qualitatively studied the impact of the financial crisis on LCT based on MLP analysis [128], MLP only gave some conceptual explanations of the impact of the economic crisis on LCT. Therefore, further simulation methods are needed to explain these principles in detail.

In this chapter, a Mark 0 minimal macroeconomic model is embedded into the LCT model to study the impact of the economic cycle at the regime level and accomplish this task.

3.2 Model

Currently, an integrated study of the economic and energy systems based on ABM has been introduced separately, for example, the Mark 0 model is a minimal macroeconomic model that contains two types of agents—households and firms—that interact with each other (for more information, see Section 3.2.2). The model can reproduce the booms, recessions, and periodic economic cycles that are quite common in our life. In the field of energy and environmental research, an LCT model with local energy markets is proposed to show the relationship between energy capacity, energy consumption, and market regulation, and the model results can provide insights about transition policy [1].

Thus, by coupling the Mark 0 and LCT models, a new model is built to find the various interactions between the economy and the energy system, and to provide insights about a suitable transitional strategy for policymakers.

In the following, the two models are briefly described, and the coupling of the Mark 0 and LCT models is presented.

3.2.1 The LCT model

As introduced in Chapter 2, an LCT baseline model is built with several groups of agents (such as firms, energy industries, etc.), all of which display complex behaviors by using some sub-models such as energy production, the local energy market, and firm life cycles. As previously discussed, the LCT baseline model allows one to investigate crucial interactions and diverse behaviors between agents.

3.2.2 The Mark 0 macroeconomic model

There are two types of agents—firms and households—in the closed economy described by the Mark 0 model [93]. In the model, firms are treated separately with heterogeneity, while households are treated as a homogeneous whole. Firms and households interact through labor and commodity markets, while banks play a role in management activities such as accounting and finance (e.g., bankruptcy management, financial statements, etc.). The structure of the M0 model is shown as in Figure 1.8.

At each time t, each firm $\mathrm{n} = 1, \dots, N_F$ produces goods with a quantity of $Y_n(t)$ and sells them at price $p_n(t)$. The relationship between the number of employees of each firm $N_n(t)$ and its production $Y_n(t)$ is $N_n(t) = Y_n(t)/\zeta_n$, where ζ_n is the productivity of firm n (for simplicity set to 1). At each time t, each firm pays each employee a wage $W_n(t)$. The demand $D_n(t)$ for each commodity or good i depends on the household's global consumption budget $C_B(t)$, which is determined as a part of the household's total savings, and the demand is a decreasing function of the quoted price $p_n(t)$ as follows:

$$D_n(t) = \frac{C_B(t)}{p_n(t)} \frac{e^{-\beta p_n(t)/\overline{p}(t)}}{Z(t)} \tag{3.1}$$

$$Z(t) = \sum_n e^{-\beta p_n(t)/\overline{p}(t)} \tag{3.2}$$

where β is the price sensitivity coefficient, which can be adjusted.

Like the real world, firms will evaluate their output by production Y_n and demand D_n, if $Y_n < D_n$, it will hire employees and raise their output, and vice versa. In addition, the adjustment speed can be asymmetric. The propensity to fire η_- and the propensity to hire η_+ are not necessarily the same due to the labor laws restricting firing. The ratio R between the propensity to hire and fire turns out to become one of the most important control parameters affecting the fate of the entire macroeconomic system.

Output and the prices of each firm are random and have a uniform distribution around the average price and size in the initial state of the economy (when $t = 0$), and each firm offers the same wage to each employee for simplicity. The initial setup is designed to establish heterogeneity between firms, while randomness itself has little effect on the results because the system will eventually reach a statistical equilibrium independent of the initial state.

The profitable firm will return part of their profits to households in proportion to δ after the settlement at each time t. Firms with a deficit must take loans to sustain business. The indebtedness level of a firm is measured by the ratio of negative net deposits over payroll as follows:

$$\Phi_n = -\frac{\epsilon_n}{W_n Y_n} \tag{3.3}$$

If $\Phi_n(t)$ is less than the bankruptcy threshold Θ, in the Mark 0 economy, firms are allowed to take debt from bank in interest-free money. If $\Phi_n(t) > \Theta$, then firm n has a default probability f at each time step. However, a bankrupt firm has the opportunity ϕ to return to the market as a new firm and allocate their debt to the remaining companies.

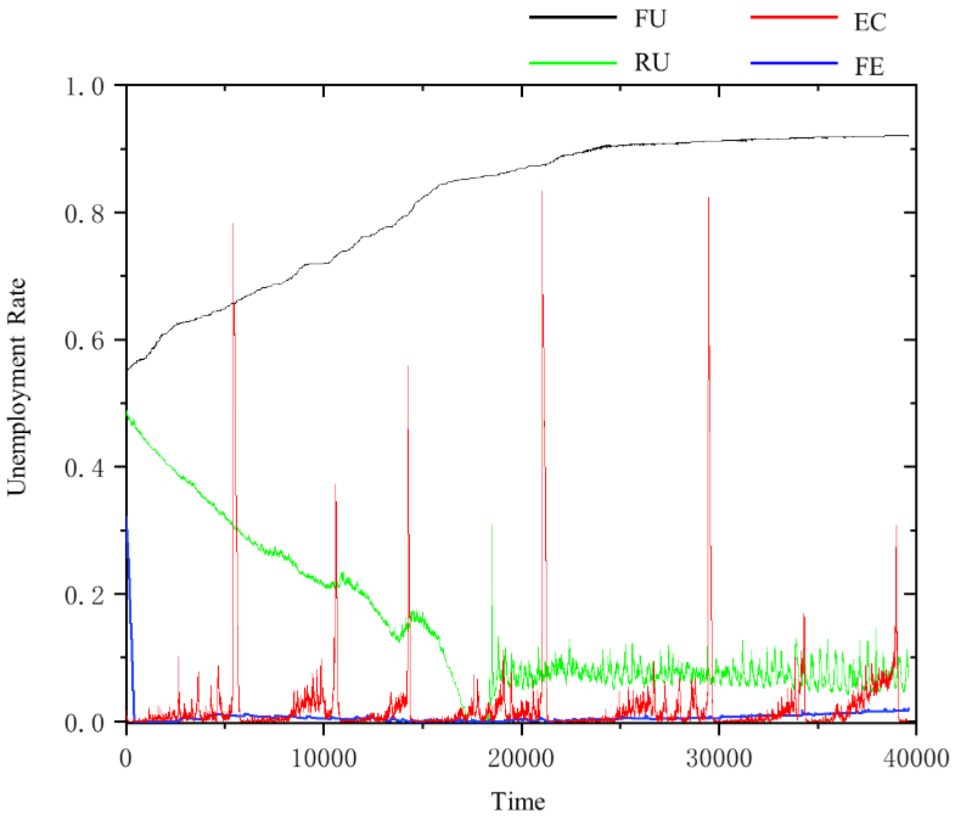


Fig. 3.1 Typical time series of the unemployment rate for each of the phases.

Figure 3.1 shows the four phases and the properties of each phase in a time series of the unemployment rate. There is a critical value R_c of $R = \eta_+/\eta_-$ that separates the full unemployment (FU) phase ($R < R_c$) from the other three phases. Here, $R_c \leq 1$ depends on all of the other parameters. The full employment (*FE*) phase ($R > R_c$, Θ large) is characterized by average positive inflation, whereas there is deflation in the FU phase ($R < R_c$). Endogenous crises (EC) are characterized by alternating cycles of inflation and deflation and occur for $R > R_c$, Θ intermediate. Finally, when $R > R_c$, a small Θ corresponds to a region of small inflation and residual unemployment (RU).

While there are a total of nine parameters to define the Mark 0 economy, only R and Θ determine the model's phase diagram, and the others only have a quantitative effect.

Note that the periodic economic cycle can be reproduced in the model, and in the following section, the Mark 0 model is adopted to reproduce the different phases of the business cycle and keep the parameters fixed to reflect the invariance of an economic system over a relatively short time period.

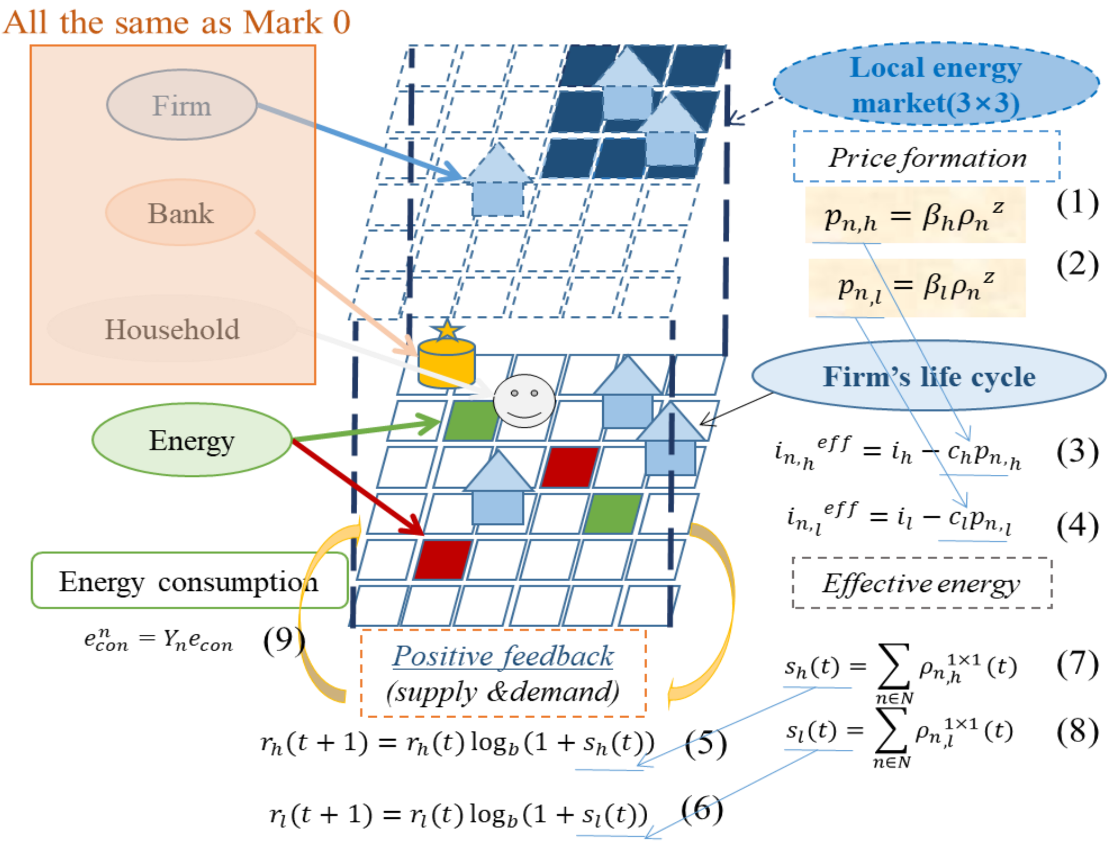


Fig. 3.2. Modeling of the Mark 0 model combined with the LCT model.

3.2.3 Combination of the Mark 0 model and the LCT model

By coupling the Mark 0 and the baseline LCT models, the economic ecosystem model is constructed with the aim of studying the interactions between these two systems (as shown in Figure 3.2), and the new model features the main mechanisms of these two models. Figure 3.3 shows the complete flow of behaviors at any node *n* at each time step *t*.

In the model, each company faces two independent markets: the energy market as LCT, and the commodity market as Mark 0. To reflect the different energy consumption of firms based on their distinct sizes, the energy consumption e_{con}^{n} of each firm n is proportional to its output Y_n as follows:

$$e_{con}^{n} = DY_n e_{con} \tag{3.4}$$

where e_{con} represents the inherent energy consumption in the LCT model, and D is the proportional coefficient. For simplicity, D is set to 1.

The successful running of the Mark 0 model requires that the total number of firms (*including* both the functioning and collapsed firms) is fixed, so the mechanism of creating subsidiaries in the former LCT model is eliminated in the new model. No upper limit is put on the amount of energy that one firm holds, since a distributed energy system is able to allot energy efficiently. None of the other mechanisms in the Mark 0 and LCT models are modified, except for how to decide bankruptcy and extra environmental costs.

Since these two former models have their own mechanisms and it would be controversial if the two mechanisms were arbitrarily combined, a new mechanism for bankruptcy determination ought to be created. The stepping up of energy capitalization makes it possible to borrow energy from the government, resource providers, or other industrial firms, so an energy borrowing mechanism is added to the new model. If interest-free energy debt is below the threshold, an energy firm's holdings can be negative, which can be expressed as follows:

$$-E_n < W_n Y_n \Theta' \tag{3.5}$$

where Y_n and W_n represent the output and wages, and the firm's overall scale is reflected by $W_n Y_n$. Θ' is a factor representing the limit of energy support from the energy industry or the government. Note that a firm of a larger scale will gain more of such support. One can easily find that this bankruptcy determination mechanism is almost the same as the mechanism in the Mark 0 model.

So, there are two possible reasons for a firm collapsing in the new model—financial bankruptcy or a serious energy shortage. Financial bankruptcy will occur when $-\frac{\epsilon_n}{W_n Y_n} > \Theta$. If an industrial firm lacks energy in the real world, all of its production will cease until they collect adequate energy to support its operations. So, when the energy reserves of firm n in the coupled system satisfy $-\frac{E_n}{W_n Y_n} > \Theta'$, the firm will experience a shortage, in which firms have no consumer market behavior, and they just try to find enough energy to get rid themselves of the energy shortage. When these firms obtain adequate energy as $-\frac{E_n}{W_n Y_n} < \Theta'$, they will be restored and rejoin the consumer market. Otherwise, in time step t_b they will collapse due to the severe energy shortage. Because there is a revival mechanism in the Mark 0 model, bankrupt firms still have a chance of revival at each time step, but when they recover, their initial amount of energy will be set to zero.

In the previous LCT mode, the firm's retained energy E_n was the only variable used to judge its vitality. On behalf of the variables regarding energy reserves, there are also economic attributes. Furthermore, ${i_n}^{eff}$ can even be negative in some cases to reflect the system's penalties for purchasing HC energy firms. But for the new model, because of the addition of the Mark 0 model, we can have independent parameters to describe the firm's financial status. Therefore, it is necessary to eliminate the economic meaning from ${i_n}^{eff}$, which means that the effective energy amount obtained by firm E_n is no longer allowed to be negative and the additional financial items like the environmental cost can be considered simultaneously when the firm buys HC energy under severe environmental punishment.

Correspondingly, in the new model, effective energy consists of the amount of energy and environmental costs, and the energy variable E_n obtained by firm *n* is seen as a simple measure of the energy state, and its minimum value is *d* (for simplicity, it is set to 0.1), and the financial variable m_f (fine) suffered by firm *n* is treated as a measurement of the environmental cost. Now, there are two cases when we divide effective energy into two parts—energy variables and financial variables—as follows:

(1) $if\ E_n = (i_h - \beta_h \rho_n^z) > d$, then, $m_f = 0$,

$$E_n = {i_n}^{eff} = i_h - \beta_h \rho_n^z \tag{3.6}$$

(2) $if\ E_n = (i_h - \beta_h \rho_n^z) < d$, then, E_n set as constant *d*, and,

$$m_f = d - \gamma_h \rho_n^z \tag{3.7}$$

where $d - \gamma_h \rho_n^z$ is the value of the fine (m_f) for each firm that consumes HC energy and γ_h is the market sensitivity coefficient of HC energy in terms of the fiscal meaning, and this negative value is transferred to the firm's deposits as a line item of financial accounting.

$$dep_n = dep_n + D * m_f \tag{3.8}$$

To ensure the amount of money is converted, an equal amount of money will be added to household savings as a kind of welfare from the government for supporting climate policy.

$$hh_{n,s} = hh_{n,s} - D * m_f \tag{3.9}$$

Since the LCT and Mark 0 models' parameter magnitudes are inconsistent, to balance the fines, we need to multiply the original value by a factor D to convert the parameters of these two models to the same magnitude to facilitate processing.

So, the bankruptcy threshold (Eq. 3.3) is correspondingly revised as follows:

$$\Phi_n = -\frac{\epsilon_n - m_f}{W_n Y_n} \tag{3.10}$$

Accounting of firms and households: In the new model, because of the climate change pressure, the additional environmental cost m_f is subtracted from firms' net deposits managed by the government as a fiscal instrument. The same amount of the additional income of households will be saved, which corresponds to the welfare from the government (Eqs. 3.8 and 3.9).

Bank accounting: In the balance sheet of the banking system, the additional environmental cost m_f will transfer this negative value to the firm's deposits. For obeying the money conservation of the new model, an equal amount of money is added to the household part.

To sum up, the firm's life cycle in the new model is a combination of the life cycle of the two former models. Firms purchase energy from its local area, consuming energy to produce goods and sell them to households, at the same time, hiring or firing employees according to the relationship between *output* and demand. Profitable firms return a proportion of their profit to households, and firms that are either financially or energetically unhealthy may collapse, waiting for revival with probability at each time step.

The validity of the coupled model: For the coupled models, the economic cycle state of the model when the energy is sufficient is the same as in the literature (see the four phases) [24] (when the dynamics on the LCT side are not considered). At the same time, when economic fluctuations are not considered, the phase diagram obtained by the model is consistent with the LCT model (see Figure 3.6) [1].

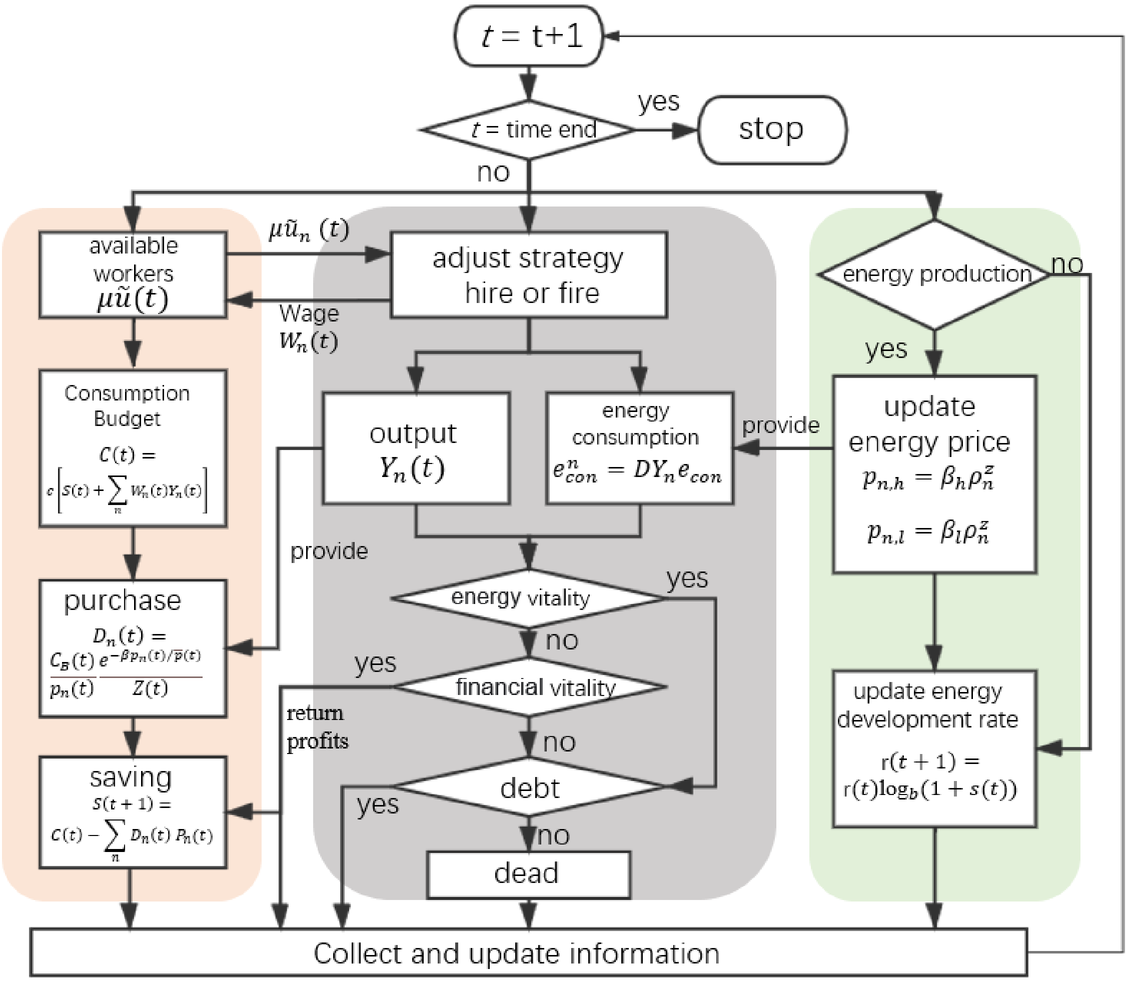
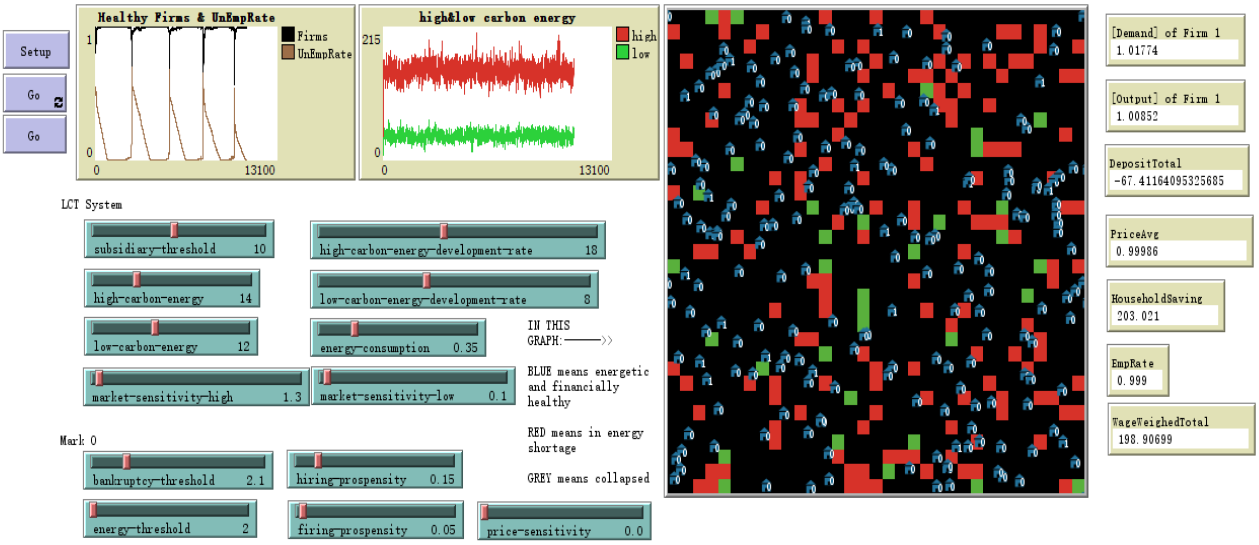


Fig. 3.3. Flowchart of the behaviors of node *n*.

3.3 Timing of policy interventions

The coupled model is based on Netlogo simulation platform [28], and the Netlogo user interface with the coupled model is shown in Figure 3.4. The three buttons on the left-up control operation of the model. The “setup” button is used to initialize the model, and after initialization one can click on the “go” button to begin the simulation. If one would like to watch the subtle changes between time steps, the “go once” button can be used to run the simulation one step at a time. The monitor on top is used to observe several crucial parameters as they change over time steps, the left one displays the situation of the economic system with the number of firms and the unemployment rate, and the right one shows the amount of high- and LC energy in the simulation space, reflecting the structure of energy market. The slider on left controls the value of the coefficients, which can be modified during the simulation. On the right side is the central landscape. Note that firms (house symbol) are divided into three groups: a blue house stands for healthy firms, a red house for firms with an energy shortage, and a gray house stands for collapsed firms. The red and green squares in the landscape represent high- and LC energy, respectively. The entire simulation space is a regular two-dimensional (2D) lattice $N = L \times L (L = 33)$ with periodic boundary conditions.



LCT System

subsidiary-threshold 10
high-carbon-energy-development-rate 18
high-carbon-energy 14
low-carbon-energy-development-rate 8
low-carbon-energy 12
energy-consumption 0.35
market-sensitivity-high 1.3
market-sensitivity-low 0.1

IN THIS GRAPH: ——>>

BLUE means energetic and financially healthy

RED means in energy shortage

GREY means collapsed

Mark 0

bankruptcy-threshold 2.1
hiring-prospensity 0.15
energy-threshold 2
firing-prospensity 0.05
price-sensitivity 0.0

[Demand] of Firm 1
1.01774

[Output] of Firm 1
1.00852

DepositTotal
-67.41164095325685

PriceAvg
0.99986

HouseholdSaving
203.021

EmpRate
0.999

WageWeighedTotal
198.90699

Fig. 3.4. Netlogo user interface with the coupled model.

Table 3.1 Commodity market parameter settings with initial values

Parameter	Description	Initial values
c	The coefficient of consumption budget	0.5
β	Market sensitivity coefficient	2.0
η_+	Hiring propensity	0.15
η_-	Firing propensity	0.05
δ	Dividend’s ratio	0.02
ϕ	Revival probability	0.1
γ_p	Price changing efficiency	0.05
Θ	Financial bankruptcy threshold	2.0
dep_n	Firm’s deposit	
$hh_{n,s}$	Household saving	

The initial value of the commodity market shown in Table 3.1 has been modified to create the same economic cycles as in the Mark 0 model. In the entire simulation, these parameters are fixed, because economic cyclical laws will not change in a short time.

Most of the initial values are based on the LCT model described in Chapter 2 for the energy market, as shown in Table 3.2. However, some parameters, such as the market sensitivity coefficient, energy capacity, and energy consumption, may be changed to view the state of the system under various conditions. Note that the bankruptcy threshold for energy is 2.0, while the life span of energy-deficient companies is 2.0, which indicates that energy-deficient companies are relatively intolerant. In subsequent simulations, unless otherwise specified, all parameters will be set to the default values in the table.

Table 3.2 Energy market parameter settings with initial values

Parameter	Description	Initial values
$E(t)$	Initial amount of energy a firm holds	Random integer within [1,8]
$r_h(t)$	High carbon energy development rate	18%
$r_l(t)$	Low carbon energy development rate	8%
i_h	High carbon energy capacity	9
i_l	Low carbon energy capacity	4
β_h	Market sensitivity coefficient for high-carbon energy	0.1
β_l	Market sensitivity coefficient for low-carbon energy	0.1
e_{con}	The amount of firm's energy consumption	1.0
Θ'	Bankruptcy threshold for energy	2.0
t_b	Life of firms in energy shortage	2
E_n	Energy obtained by firm *n*	
m_f	Environmental cost	

In order to ensure that the sample mean of partial results is getting closer to the mean of the overall sample, a sufficient number of samples are taken to ensure a lower standard error when calculating the results, so that the mean obtained is representative and the reliability is improved.

3.3.1 Four typical phases

In the simulation, as mentioned above, to study the impact of the economic cycle on the LCT process, the new model will keep the economic part's parameter settings unchanged in all scenarios to create a market environment in which periodic economic crises occur. Conversely, different parameters are set on the energy market part, since they are vital to the simulation results and reflect the different bases and strengths of LCT in different countries and regions. Except for the market sensitivity ratio of the high- and LC energy β_h/β_l, energy capacity i_h (i_l), and energy consumption e_{con}, the new model keeps all of the other parameters fixed. β_h/β_l is a parameter that controls the equilibrium of high- and LC energy in an energy system and can also measure the government's bias in market regulation. Energy capacity i_h (i_l) represents the sufficient or insufficient state of energy in the energy market, and it reflects the level of technology for the energy supply. e_{con}, which is a parameter to determine the vitality of firms in the energy market, is related to energy efficiency technology.

By changing the values of the main parameters, four typical phases are seen, as shown in Figure 3.5 (a)–(d). The scenario settings are shown in Table 3.3.

In case P1, e_{con} is 0.2, i_h (i_l) is 14 (10), and β_h/β_l is 20 to reflect the fact that energy consumption is low and HC energy does not have much more market sensitivity than LC energy under the condition of a relatively sufficient energy state. In case P2, β_h/β_l has been increased to 120 and e_{con} is increased to 0.7. The striking rise in the market sensitivity coefficient for HC energy means that the price of HC energy is far more sensitive to the competition between local firms, and that high energy consumption will push firms into an energy shortage. In case P3, the energy consumption of industrial firms is reduced from 0.7 to 0.2, implying greater energy efficiency, and the capacity of low- and HC energy is low, reflecting an energy shortage. In case P4, e_{con} is 0.2, i_h (i_l) is 14 (10), and β_h/β_l is 120 to represent a system that is restoring HC energy, and supplying enough energy with LC energy consumption.

Table 3.3 Simulation scenarios with parameter settings

Parameter	P1	P2	P3	P4
e_{con}	0.2	0.7	0.2	0.2
β_h/β_l	20	120	120	120
ih	14	14	9	14
il	10	10	4	10

In P1, the results show that a periodic economic crisis occurs when high- and LC energy sources coexist. This is mainly because in this scenario, almost all of the firms have enough cheap energy to supply themselves, therefore the energy market may not significantly impact the economic cycle. In this case, the Mark 0 mechanism works, since the new model modifies the Mark 0 parameter for the endogenous crisis phase such that at a certain time step, the economic system will experience a catastrophic collapse of many firms and a rise in unemployment. This state is called a HC economy (i.e., a brown economy).

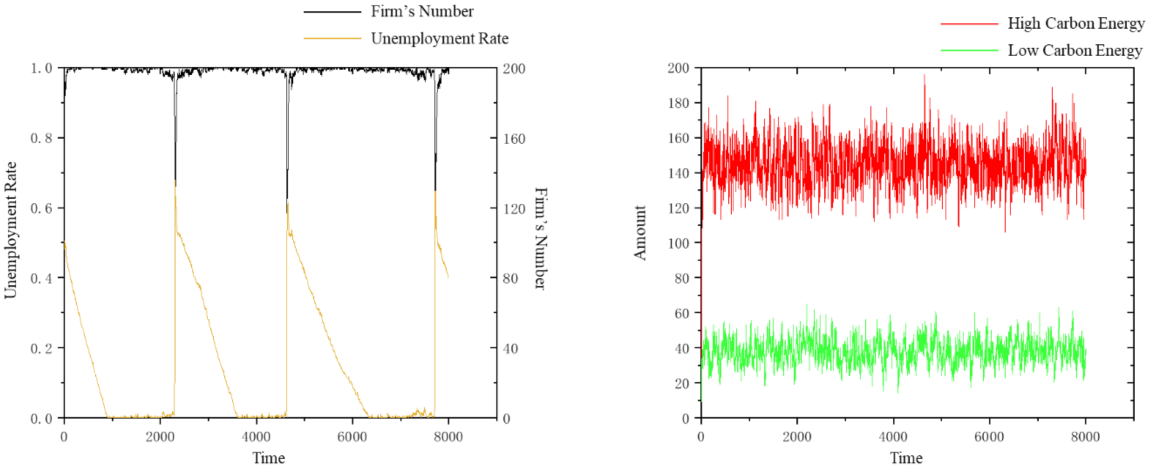


Fig. 3.5. (a) The time evolution of scenario P1: A high-carbon economy (brown economy).

In P2, both economic and energy systems are stable, with a relatively high rate of unemployment and few healthy firms consuming high- and LC energy coexisting. In this case, the periodic economic crisis disappears and is replaced by a long-run economic recession. Now, the market sensitivity coefficient for HC energy is relatively greater; firms that buy HC energy will obtain not enough effective energy to survive due to the additional environmental costs. Only firms that are lucky enough to continuously obtain LC energy or large enough to carry more energy debt can survive for a relatively long time. This phenomenon will lead to a major recession, which is a potent manifestation of the energy system's counter-reaction to the economic system. Now, the entire economy–ecosystem is driven by the energy part. This state is called a HC recession (i.e., a brown recession).

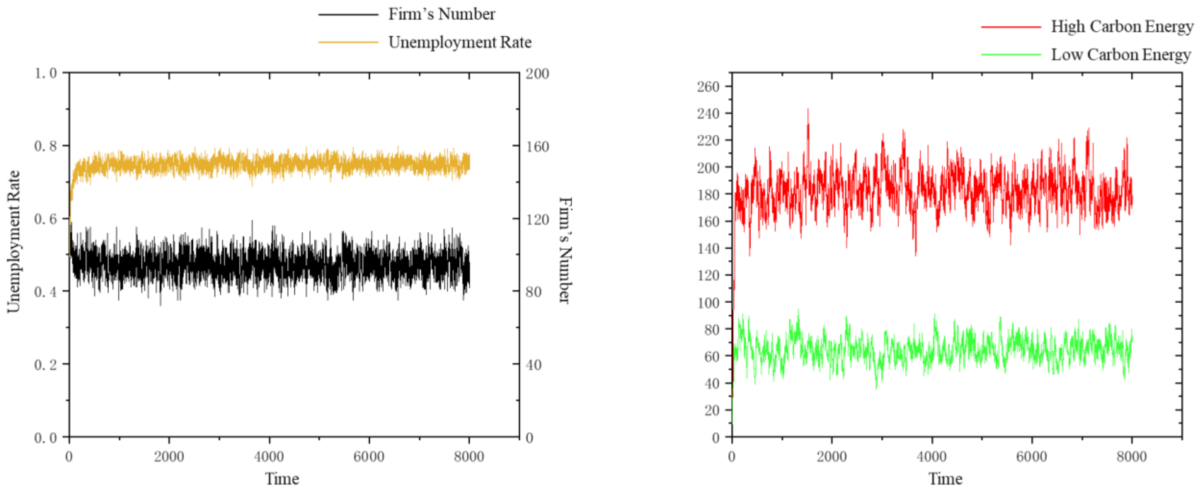


Fig. 3.5. (b) The time evolution of scenario P2: high-carbon recession (brown recession).

In P3, both economic and energy systems are stable: relatively high rate of unemployment and few health firms with only LC energy exist. In this case, the periodic economy crisis disappears and is replaced by long-run economic recession. In this situation, low energy consumption and high environmental pressure make the system transition to a LC state [1]. However, LC energy capacity is too low to support adequate energy to the firm even at the relatively low level of energy consumption in LC state. This phenomenon will drive system into economic recession, which is a potent manifestation of the energy system's counter-reaction to the economy system. Now the whole economy–ecosystem is also driven by the energy part. This state is called as LC recession (green recession).

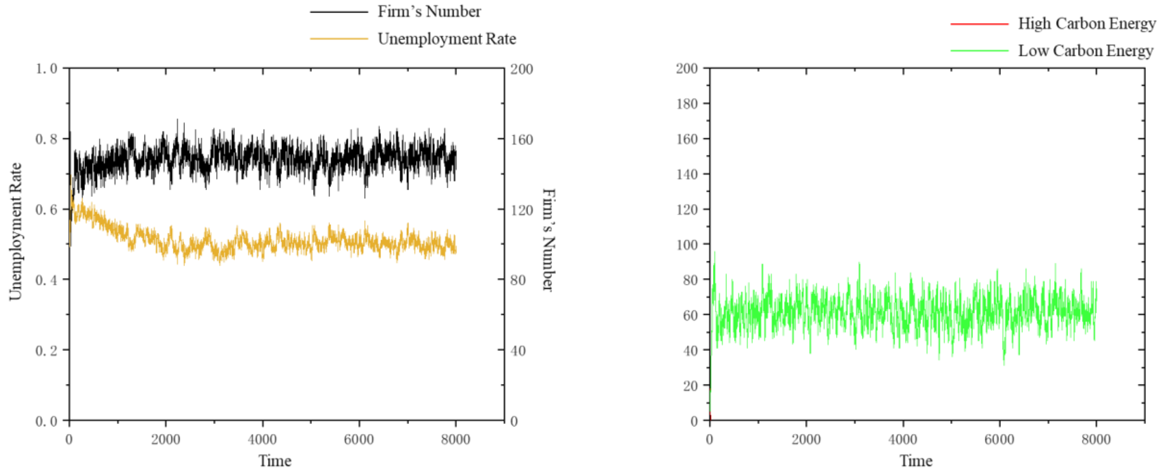


Fig.3.5. (c) The time evolution of scenario P3: low-carbon recession (green recession).

In P4, the result shows that the periodic economy crisis occurs while the system reached LC state. The same mechanism of LCT process as the P3, low energy consumption and high environmental pressure make the system transition to a LC state [1]. However, different from P3, since the energy market is rather peaceful in this situation (LC energy capacity is high enough under the relatively low energy consumption), periodic economy crisis reappears normally in LC economy. This state is called as LC economy (green economy), which is exactly what we want to achieve.

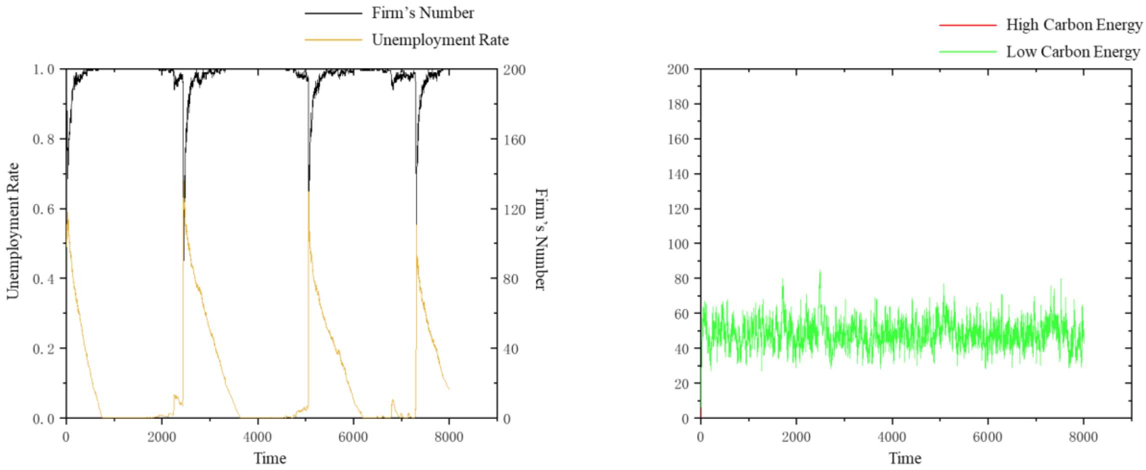


Fig. 3.5. (d) The time evolution of scenario P4: low-carbon economy (green economy).

3.3.2 Phase diagrams

This section shows the phase diagrams of the system. Two distinct phase diagrams were obtained with Regime1 (i_h = 9, i_l = 4) and Regime 2 (i_h = 14, i_l = 10) shown as in Figure 3.6 (a) and (b). In both phase diagrams, the abscissa is energy consumption (e_{con}), and the ordinate is the market regulation ratio β_h/β_l. Energy consumption e_{con} impacts the survival of the firms. The market regulation ratio β_h/β_l reflects the degree to which system administrators restrict LC energy and HC energy. In addition, there are four typical phases described as previous section: HC economy (brown economy), HC recession (brown recession or recession), low-carbon-recession (green recession), and LC economy (green economy).

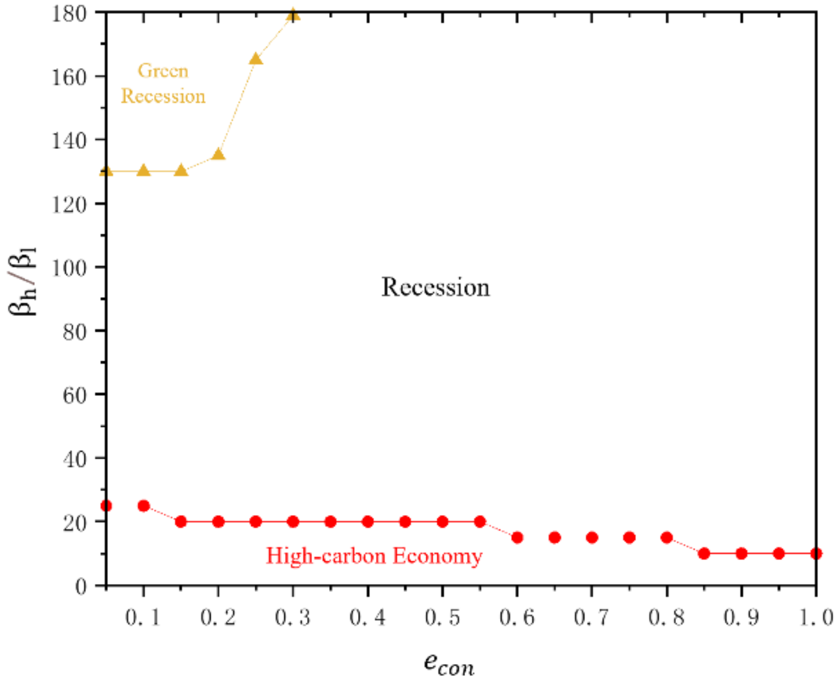


Fig. 3.6. (a) Phase diagrams for Regime 1.

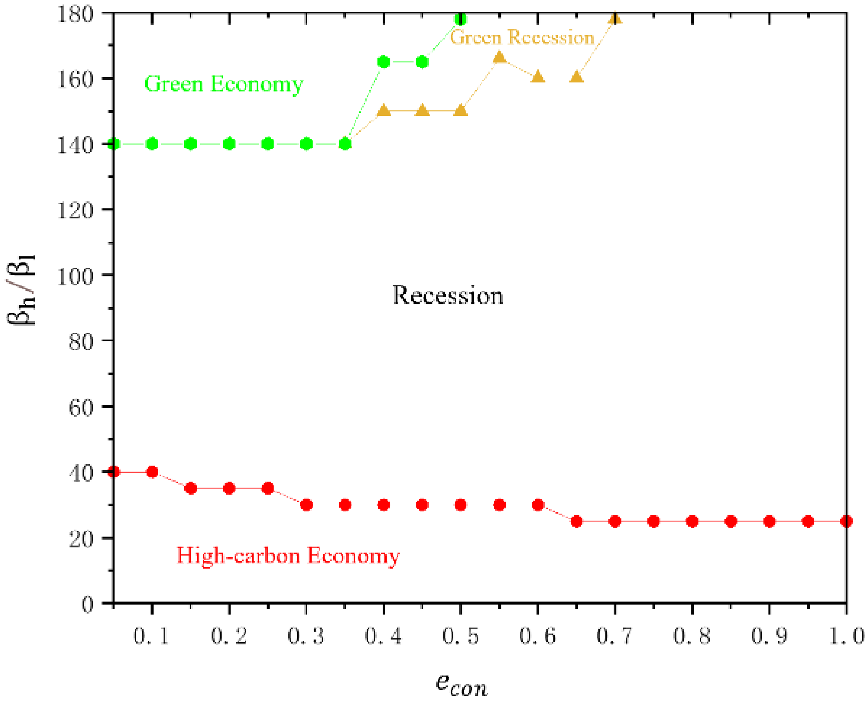


Fig. 3.6. (a) Phase diagrams for Regime 1.

3.3.2.1 Regime 1

In this regime (Figure 3.6 (a)), the LC energy capacities are lower as i_l = 4. In this case, there is no normal LC state part existing in the phase diagram, which means that there is no possible path for the system to transform into LC energy dominance while maintaining a healthy economy. Moreover, the HC economic state is not adjacent to the LC phase, and there is a recession phase between the two, indicating that a recession is inevitable in any LCT process.

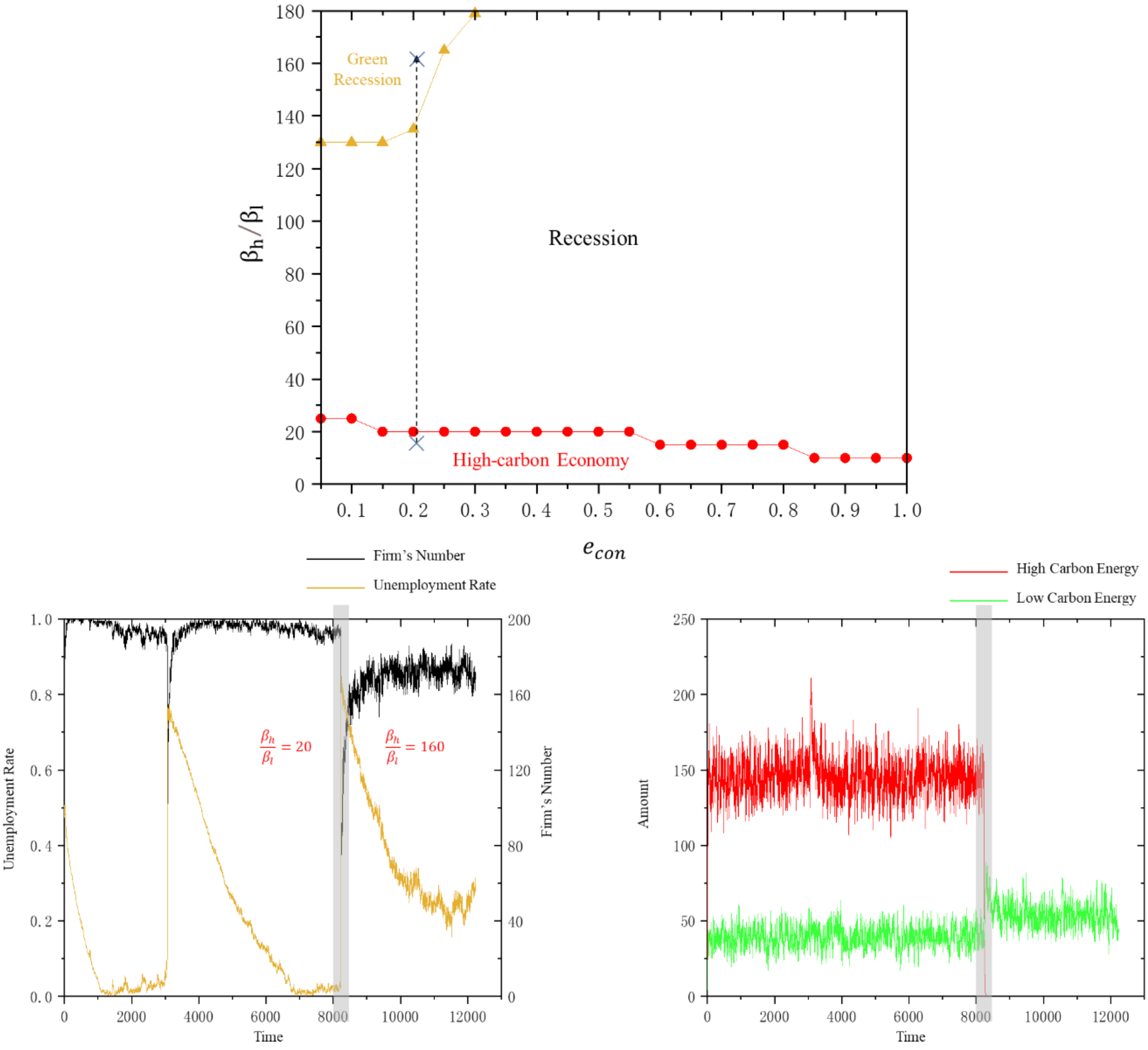


Fig.3.7. Phase diagram when the initial energy capacity value is taken with a transition in scenery.

To make it clearer, a virtual experiment was conducted to observe the evolution of the system taking a HC economy at the bottom of the phase diagram as the starting point and then increasing the market regulation ratio. The two star-shaped points in the phase diagram in Figure 3.7 represent the HC economy state and a green recession, respectively. The e_{con} of these three points is all 0.2, and the market regulation ratio is 20 and 160 (adjusted to the stable stage of the economic cycle). A move from a HC economy to a green recession can simulate an attempt to conduct LCT in a contemporary regime. Figure 3.7 shows that when the market regulation ratio β_h/β_l is increased from 20 to 160 as the government makes a preliminary effort to conduct an LCT, although the HC energy will finally be fully replaced by LC energy, it will lead to a major recession. Firms collapse because of an energy shortage and the unemployment rate increases sharply. Furthermore, the economic recession will only stabilize over time, rather than return to a healthy condition.

So, one can observe that in Regime 1, LCT regulation is stronger as the market regulation ratio β_h/β_l is increased from 20 to 160 during a stable stage of the economic cycle. The regulations that the government implements to crack down on HC energy drives the system to a recovery and a lower unemployment rate.

3.3.2.2 Regime 2

In distributed energy systems, with the development of energy technology, both high- and LC energy capacity can increase. A phase diagram depicting when the energy capacity of high- and LC energy is increased from 9 and 4 to 14 and 10, respectively, in biased proportion, as shown in Figure 3.8. Compared with phase diagram for Regime 1, in this case, one can see that with the development of biased LC energy technology, a new phase (that is, the P4 case introduced previously) emerges. This means that it is possible to complete the transition to a LC society with a healthy economic state while accelerating LC innovation. However, the HC economic state is still not adjacent to the LC phase, and there is a recession phase between the two, leading to an inevitable recession in any LCT process. This means that if we want to achieve LCT by increasing β_h/β_l, we may achieve results, but it will significantly impact the economy.

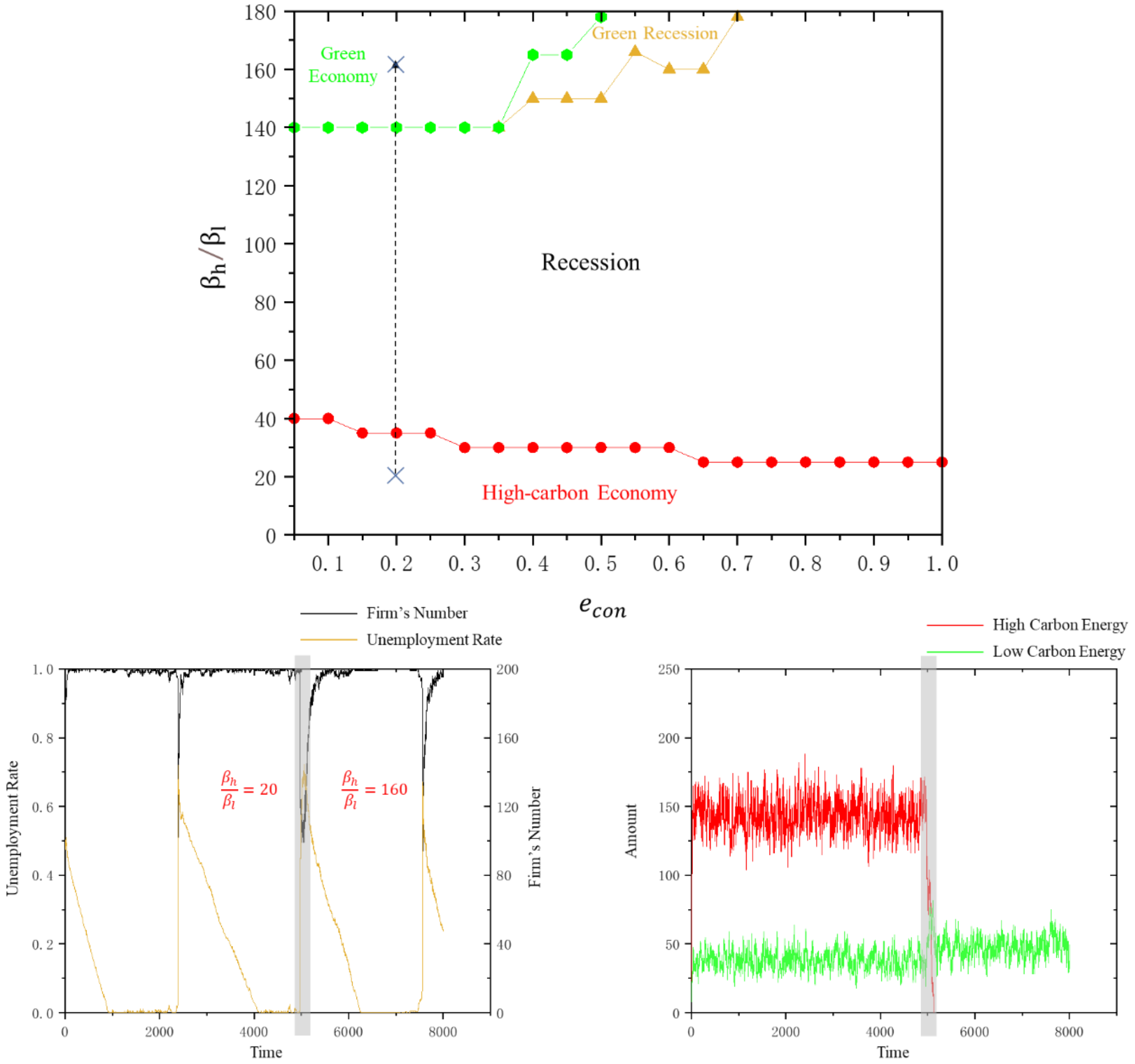


Fig. 3.8. Phase diagram when a higher energy capacity is taken with a transition scenery.

To verify the conclusion obtained from the phase diagram 2, a virtual experiment was carried out, and the results are shown in Figure 3.8. This simulation's starting point is in the lower-left corner of the phase diagram; e_{con} is 0.2 and β_h/β_l is 20. First, we let the system go through an economic crisis to prove that it is a typical HC economy. Then, we increase the market regulation ratio β_h/β_l from 20 to 160 during a stable stage of the economic cycle in a stable economic state (see Figure 3.8). When government regulation on HC energy comes into operation, the amount of HC energy soon drops to zero, and LC energy dominates the energy market [1]. Conversely, the regulations to push the system toward an LCT during an economically stable stage will first trigger a new economic crisis, and after a short-term recession, then the system will return to a stable state. This is because the price of HC energy surges as the regulation ratio increases. The effective energy firms' gains may be negative when industrial firms purchase HC energy and therefore, they will probably collapse due to a severe energy shortage with additional environmental costs. By the mechanisms of the LCT system, since only the energetically healthy firms are included in the counting of the energy demand, the demand for HC energy vanishes in dozens of time steps, and so the production of HC energy also ceases. Therefore, this simulation result is consistent with what we see in phase diagram 2: when the LC energy capacity i_l is high enough, the system can complete the transition to a LC society by increasing β_h/β_l when $e_{con}$is low. However, from the model, for policymakers, the system can complete an LCT with an inevitable or unassuming "will soon disappear" recession (Regime 2). However, is this an acceptable or appropriate path? In fact, it is believed that no one wants to make this choice.

3.3.3 Mechanism analysis and methods to avoid recession

From the previous results, when the government wants to promote LCT, it will experience an economic recession, even if the LC technology has been improved (Regime 2). Therefore, in this section, the mechanism causing the gap (recession) in Regime 2 will be investigated in terms of the economic (financial state) and energy (energy state) perspective to find a way to transition to a LC state without experiencing a recession.

3.3.3.1 How does a firm's financial status affect LCT

In the new model, the system's bias toward energy types will impact a firm's financial fragility leverage (Eq. 3.10). Different levels of the market regulation ratio β_h/β_l can reflect the degree of environmental cost effects on financial fragility, which can be represented by the distribution of an individual firm's indebtedness level. Therefore, to analyze firms' economic situation in the new model, the statistical distribution of an individual firm's financial fragility with a constant initial indebtedness level Φ_n set to 2.1 and the market sensitivity coefficient β_h/β_l is set to 20 in different economic cycles (from S1 to S4, as shown in Figure 3.9) is provided in Figure 3.10. In Figure 3.10, the indebtedness level is marked as a blue line.

The different stages of the economic cycle—S1, S2, S3, and S4—with the distribution of the indebtedness level can be explained as follows:

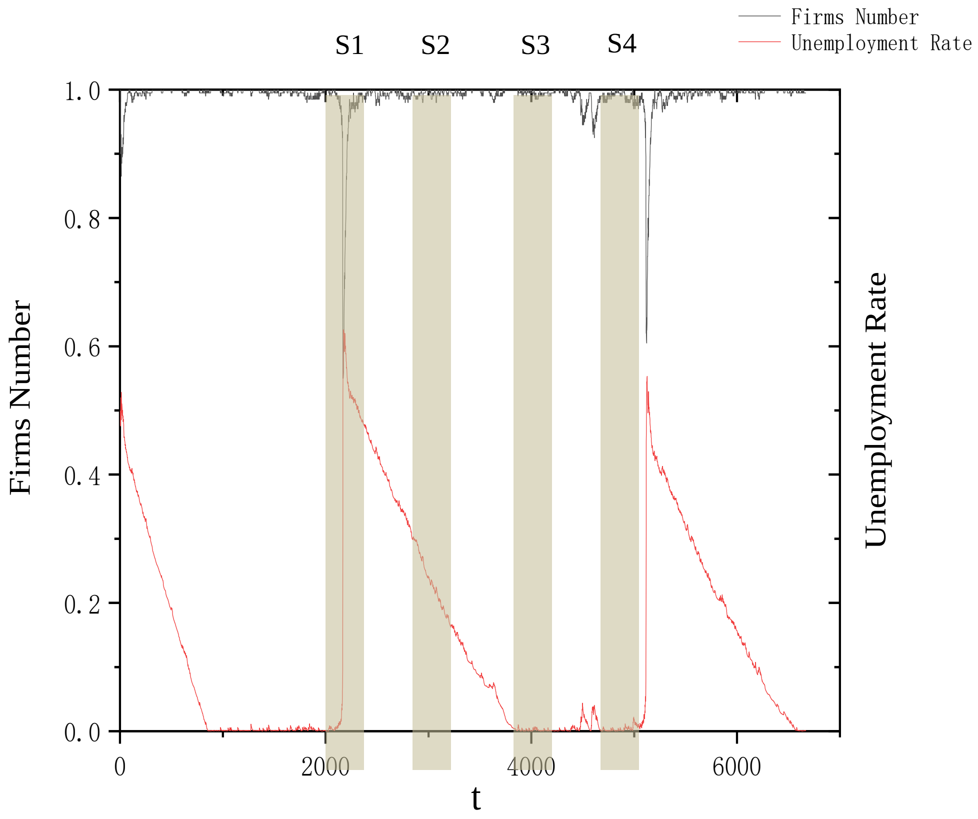


Fig. 3.9. Different stages of the economic cycle.

In crisis (Stage 1, S1): The beginning of the crisis. At this time, most firms go bankrupt, and their indebtedness level is recorded as zero. Only a small number of firms in good financial condition can survive.

Recovery (Stage 2, S2): The commodity market is in recovery, and new firms begin to appear in the market with profitable balance sheets. Because there is still a high unemployment rate, they can easily hire many people to expand their scale. Therefore, it can be seen from Figure 3.10 that the firm's distribution shifts to the left at this time.

Stable (Stage 3, S3): The unemployment rate is always close to a low level in this stage. The profit situation of companies begins to become differentiated. Therefore, most firms' debt begins to increase, and the distribution of the individual firm's leverage begins to move to the right (danger line) gradually. At this stage, if the debt volatility is high enough (i.e., the environmental burden is high), the system can easily evolve into a new crisis.

Dangerous (Stage 4, S4): The system has been stable for a long time. Competition among companies is fierce, and most are on the verge of bankruptcy, except for a few firms that can maintain a good financial condition. At this time, if there is a greater fluctuation, the system will quickly enter the economic crisis state.

The system experiences a complete cycle periodically. Now, we can analyze the impact of the energy part on the economic system.

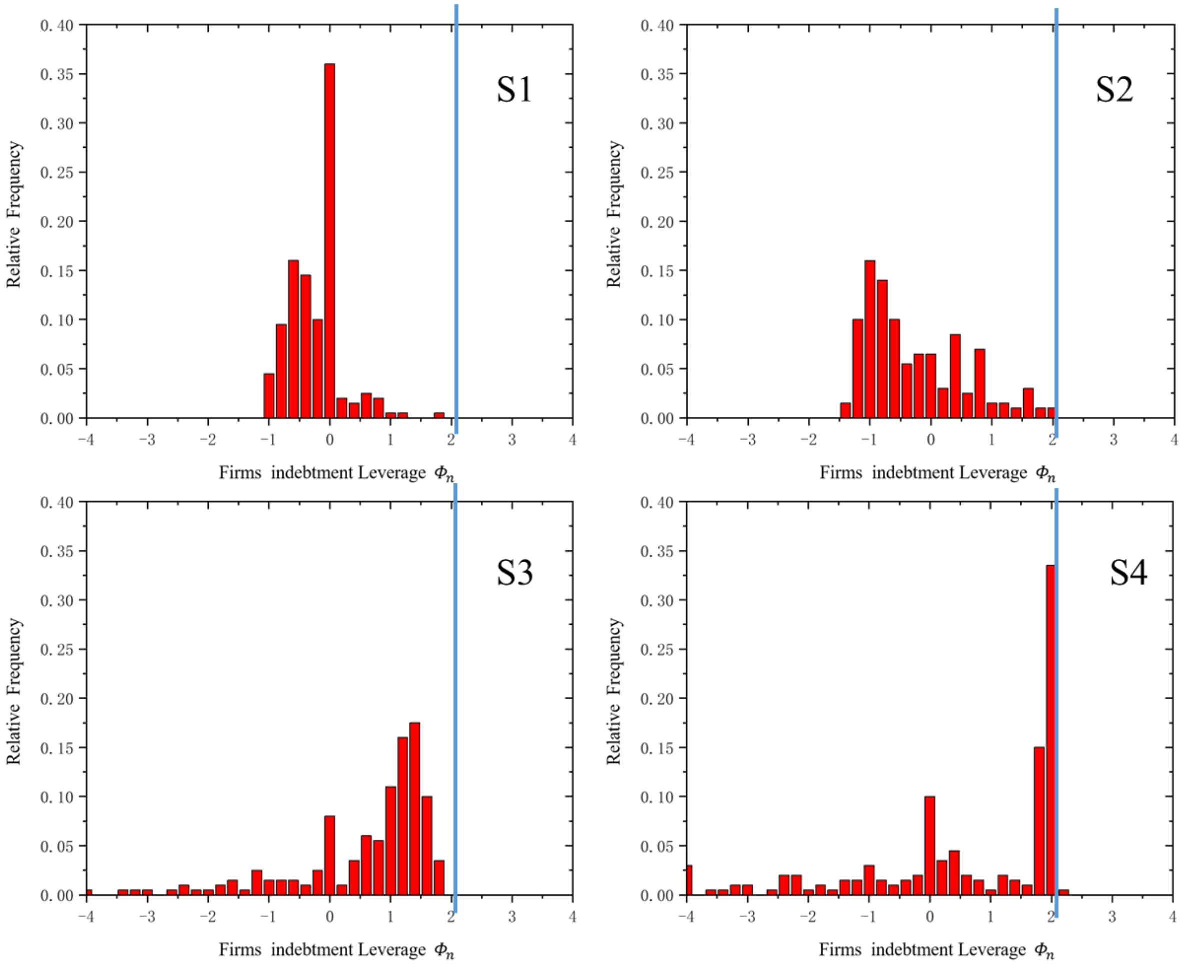


Fig. 3.10. Financial debt distribution with modest environmental costs at different stages of the economic cycle.

In Eq. (3.10), the system's bias toward energy types will impact the firm's financial fragility leverage. When the market regulation ratio β_h/β_l is low, the system is not too restrictive to HC energy, which will not have a significant effect on the distribution of individual firms' indebtedness level. However, when β_h/β_l increases, firms that purchase HC energy will be subject to a heavy fine, which will impact their business condition. So, from Eq. (3.10), one can understand that a firm's financial fragility leverage can be seen as the "Bankruptcy critical threshold blue line" moving to the left (the value of the bankruptcy threshold is initially set to 2.1, namely, Φ_n is set to 2.1, which is marked by a blue line). As a result, some firms in the safe zone may enter the danger zone and go bankrupt earlier because of increasing environmental pressure. Although the fine value is different for each firm that buys HC energy, when β_h/β_l is adjusted to a fixed value (with modest environmental costs like β_h/β_l = 20), the distance of the blue line to the left fluctuates in a small range and we can regard it as a fixed value.

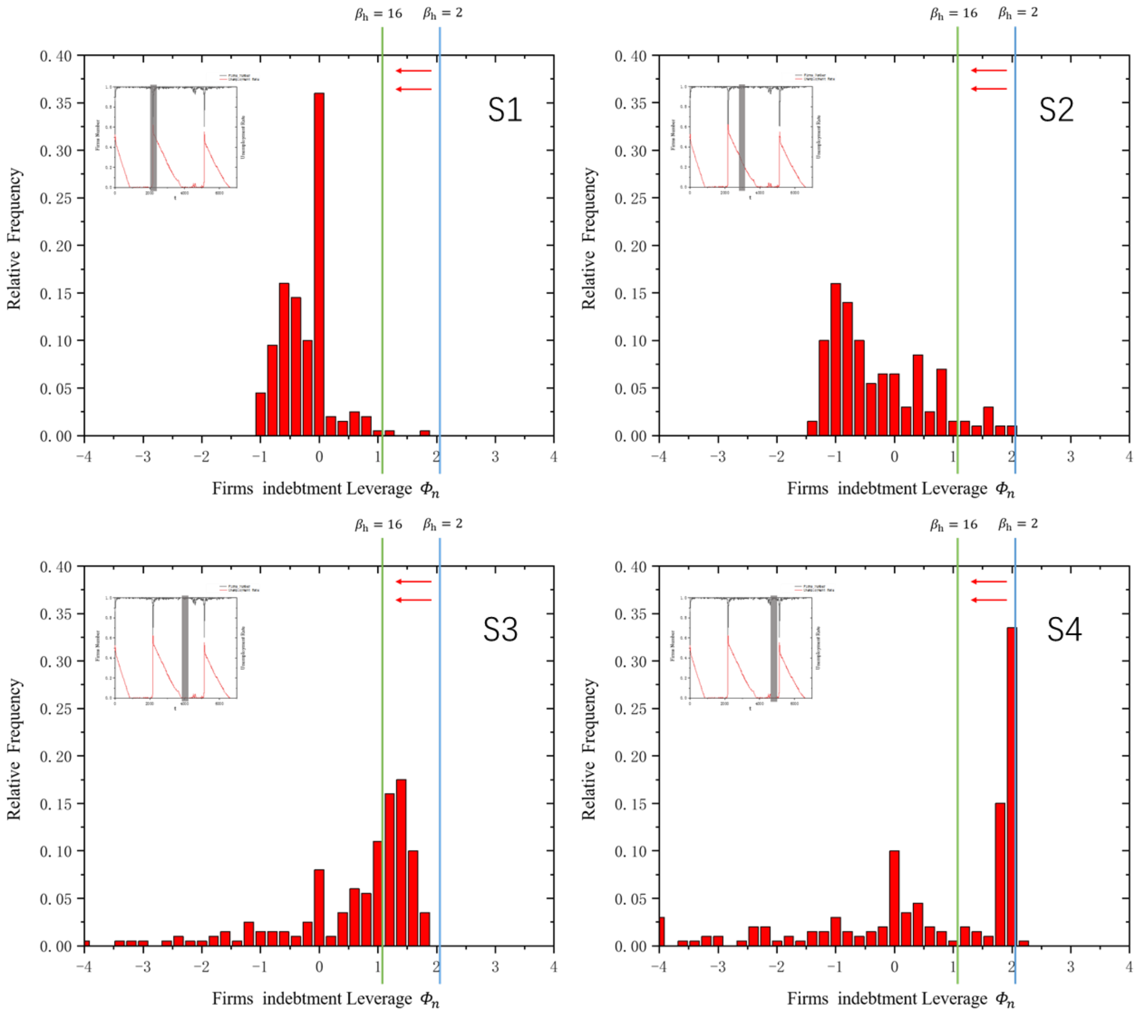


Fig. 3.11. Financial debt distribution with aggressive environmental costs at different stages of the economic cycle.

However, if we assume that the system needs severe pressure for LCT to increase β_h/β_l to the same value from a modest to a heavy level at different economic cycles, the number of firms affected will be different. Two different critical threshold lines exist under distinct environmental pressure levels (modest β_h/β_l = 20 and heavy β_h/β_l = 120); they are marked in the financial fragility distribution at different stages of the economic cycle as shown in Figure 3.11.

One can see that in Stages 1 and 2, if we adjust β_h/β_l from 20 to 120, only a few firms suffer the extra burden and there is almost no impact on the system as a whole; the system is in a safe state. However, when the system is in Stages 3 and 4, if we increase β_h/β_l, it will cause many companies to cross the critical line from a safe zone simultaneously, which could cause them to go bankrupt and trigger an environmental triggered crisis [54].

In the phase diagram of Regime 2, there is an area of economic recession. To reduce the economic harm in the transitional process by adopting extra environmental pressure, one subconsciously thinks or suggests that performing political interventions during the economically stable stage (like during most normal boom times (S3 and S4)), we may suppose the robustness of the environmental pressure may also be greater. However, from our analysis, adjusting the environmental cost (β_h/β_l) in accustomed economic cycles of crisis and recovery stages (S1 and S2) is more reasonable.

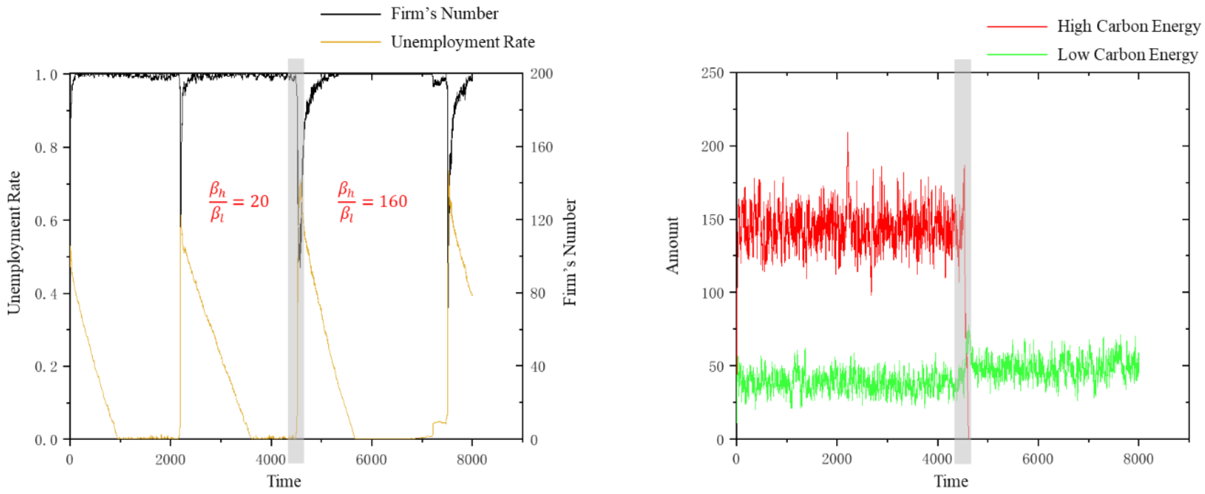


Fig. 3.12. LCT after an economic crisis.

To verify this result, as shown in Figure 3.12, a virtual experiment is performed to adjust β_h/β_l from 20 to 160 under the same parameter settings as the experiment conducted in Section 3.3.2.2 for Regime 2, and one of difference is that starting to adjust β_h/β_l when the system experiences an economic crisis (S1) or a recovery (S2). First, the system is run through two complete cycles in a HC state, then when the next crisis happens, β_h/β_l is changed from 20 to 160. The results of the simulation are consistent with our expectations. As can be seen from the left part of Figure 3.12, with the economic recovery and the market's preference for LC energy, LC energy naturally dominates the market and avoids the environmental regulation-triggered economic crisis. This result is obviously different from the result that causes a new crisis when adjusting in a stable stage (S3 and S4), such as the LCT adjustment in Regime 2 (Figure 3.8).

3.3.3.2 How does retained energy affect the economic cycle?

Referring to the variable in the Mark 0 model used to measure the debt level, the model sets the variable $\emptyset_n$ to measure the firm's energy reserves (Eq. 3.5). In this section, we statistically analyze the energy debt distribution of the firms.

Based on all of the simulation results in the phase diagram, it is found that there are only two energy debt distributions for the system's energy readiness: it is either sufficient or insufficient.

1) **Sufficient**: In the excessive energy supply state (as shown in Figure 3.13), e_{con} is 0.2, β_h/β_l is 20, and $i_h(i_l)$ is 14 (10). In this state, energy supply and demand are well-balanced to support flexible LCT intervention, there are no issues related to energy shortages, and there are no excessively high energy prices due to environmental costs. In this case, the LCT part will have no impact on the Mark 0 part, like in P1 and P4.

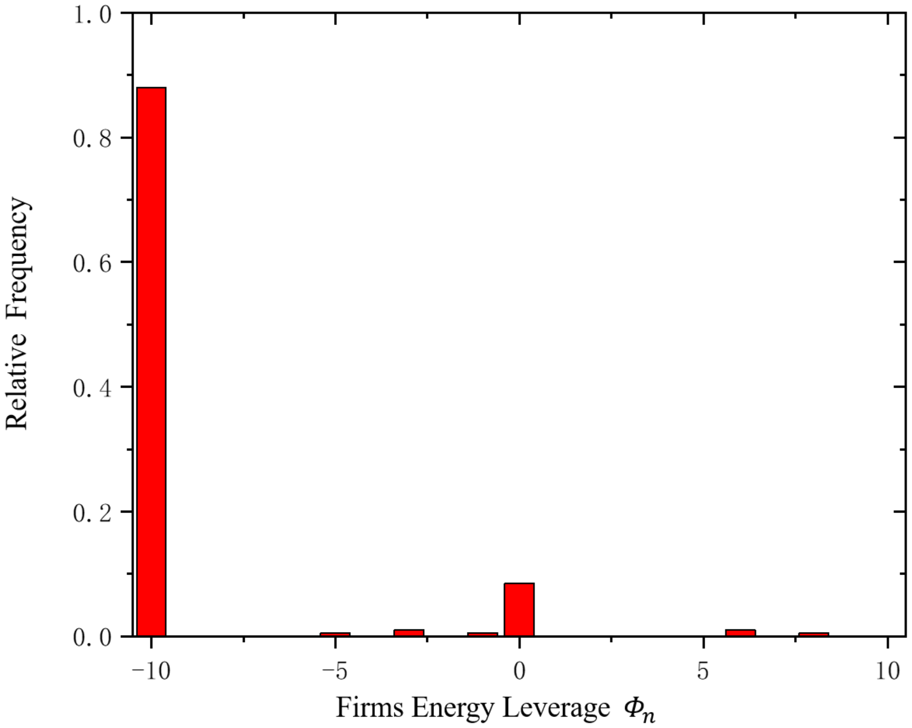


Fig. 3.13. Energy debt distribution: Sufficient.

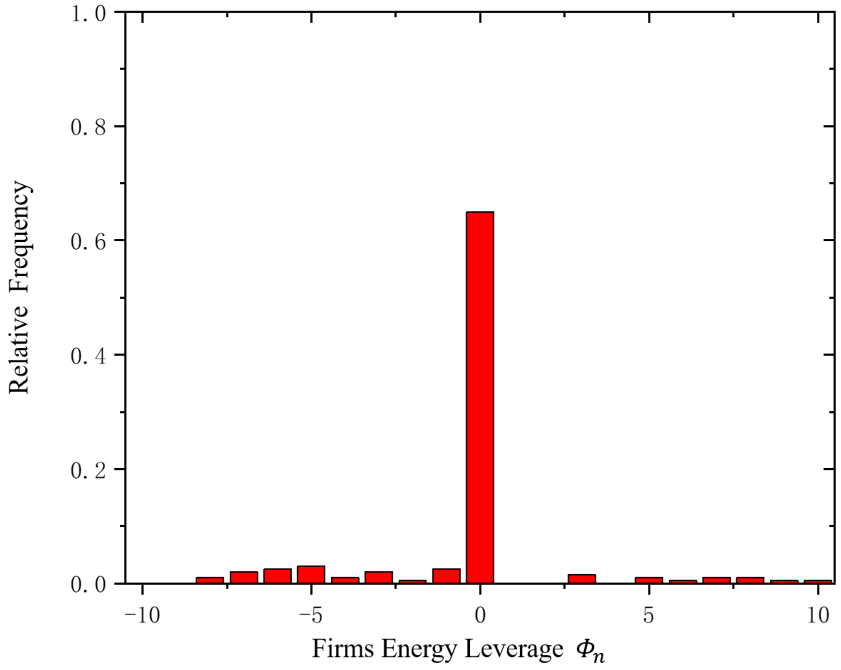


Fig. 3.14. Energy debt distribution: Insufficient.

2) **Insufficient**: In this state, most firms are experiencing an energy shortage (as shown in Figure 3.14), e_{con} is 0.5, β_h/β_l is 100, and $i_h(i_l)$ is 9 (4). First, if firms do not find enough cheap energy and increase their energy efficiency, they will not operate in the areas in which there is a lower demand density with a supply of relatively high energy capacity, and they will increase their technology to reduce energy consumption, or they will soon die for a lack of sufficient energy. Second, if the system suffers from a high level of environmental pressure, the energy bill will become too high to accelerate firms not having enough money to hire staff and then they will fall into an operational crisis. In this case, the energy shortage from the LCT part will result in an economic recession, like in P2 and P3.

To our surprise, in the system, the energy state in the energy market is only two extreme opposite distributions, and there is no intermediate state. The same phenomenon can be observed in reality. After marketization, life and production necessities with a high price sensitivity, such as food and energy, are likely to exhibit two extreme situations—sufficient or insufficient.

In short, as long as the supply of energy does not significantly exceed demand, even if the theoretical energy output meets consumption, the economic part will still fall into crisis. Moreover, the stable economic system's operation can only be achieved when the energy supply is much greater than the energy consumption.

3.4 Empirical evidence

The next step is to structurally verify the new model. According to the structural verification in Chapter 2, one can observe that only the Mark 0 model is adopted by adding a new parameter to reflect regime details (economic crisis and cycle) driven by landscape impact as described by MLP (such as Θ represents the financial bankruptcy threshold, η_+ and η_- are considered as the hiring and firing propensity, etc.) [2, 93,128].

For corresponding empirical examples or behavioral validation, one can observe the economic indicators of the Danish stock market index during two economic crises in 2008 and 2020. An analysis of the interaction between the economic system and the energy system corresponds with reality.

Figure 3.15 shows the Danish OMC index with two economic crises occurred in 2008 and 2020 at the same time many other countries such as the United States are also seeing the same trend in the evolution of financial indicators [130]. As the result of long-term technological and policy efforts, the share of LC energy in Denmark in 2020 is almost double than in 2008 (see Chapter 2). In addition, the Danish carbon tax (environmental cost) in 2020 is nearly double that in 2008 (see Chapter 2). Thus, in Denmark, where environmental pressures have persisted for a long time, three qualitative correspondences exist between the different scenarios, and the model results can be seen in Figure 3.15.

1) After the 2008 crisis, it entered a long-term economic depression or recession due to the dual effects of an energy shortage and environmental pressure, as in the results for P2 in the model.

2) As the share of LC energy increases, even if environmental pressure doubles, during the 2020 crisis, Denmark was able to escape from a deep crisis due to an energy shortage and environmental stress (the same as the results as P4).

3) As suggested in the model, strong environmental protection interventions are recommended during economic crisis and recovery (S1 and S2 in the model). In reality, when the Danish government implemented a green recovery policy, a huge index increase can be observed in Figure 3.15 in the post-crisis and recovery period after the 2020 crisis.

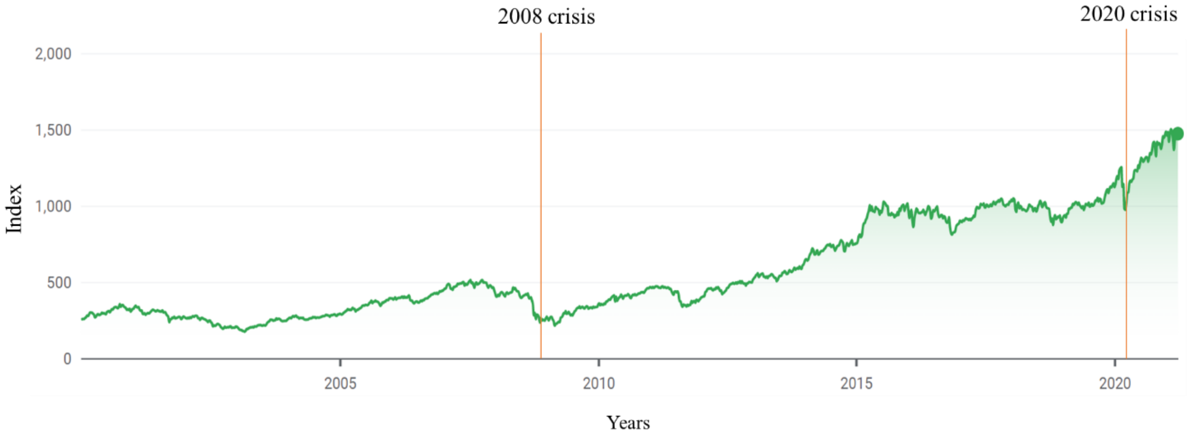


Fig. 3.15. Danish OMC index with two economic crises occurring in 2008 and 2020[133]

For other empirical examples, the following points are given to correspond with reality as follows:

1) The Polish economy cannot afford strong environmental interventions due to its high dependence on HC energy sources, so it has been opposed to the speed and intensity of the reduction of carbon allowance when LC technologies (energy consumption and energy capacity) have not reached an advance level.

2) Due to the energy shortage in Texas, it is easy to destroy the economy and fall into depression [131].

3) If energy consumption is located at a relatively high level, such as in China, it is necessary to limit energy consumption (such as power restrictions) because the environmental cost can easily cause a crisis (Regime 1 and 2) [132].

3.5 Summary of Chapter 3

In Chapter 3, to investigate the influence of economic cycles on LCT at the regime level, the Mark 0 minimal macroeconomic model and the LCT model are combined based on an ABM approach.

Four different typical system states are observed: a HC economy (brown economy), a HC recession (brown recession), a LC recession (green recession), and a LC economy (green economy). The results show that LCT policy intervention in stable (S3) and dangerous (S4) states can trigger a new economic crisis due to heavy environmental fines, and promoting LCT in the early crisis (S1) and recovery stages (S2) of the business cycle is recommended. Moreover, the results show that an energy shortage will lead to an economic recession (P2 and P3).

Therefore, the conclusions are as follows:

1) The new crisis will be triggered by the implementation of LCT policy intervention during economic booms or recessions (S3 and S4).

2) The reasonable time for LCT policy intervention is when the economy is in a state of economic crisis (S1) or economic recovery (S2).

3) Biased energy capacity, that is, accelerating LC technology to avoid additional environmental costs, while balancing the energy supply and demand (sufficient energy capacity and relatively low energy consumption) can achieve a smooth LCT without an economic recession (P2 and P3).

Chapter 4 The impact of technological evolution on LCT

4.1 Background

The challenge of analyzing innovation of LC technologies at the niche level is a mix of political intervention used to support the development of new technology and the diffusion of LC energy technologies that replace the fossil-based energy regime. The main issues for policymakers are as follows: 1) how to manage the interventions to guarantee learning effects and market returns (cumulative effect) can obtain radical niche innovation (spontaneous transition), especially under the condition where the basic performance of LC technology is less than that of HC technology; 2) how political intervention like distinct technology subsidies (fixed and biased) can be used to protect discontinuous niche innovation to obtain a tipping point (punctuation of radical or disruptive innovation); and 3) how to properly manage technological development (combination strategy driven by LC technology performance ceiling, degree of protection for cultivating a suitable punctuation time) to guide reasonable transition pathways. Unfortunately, these topics remain as a solution and only MLP conceptually provides some historical evidence [8,133]. Moreover, niches are usually not described clearly and the detailed impact of innovation on LCT is rarely addressed.

In addition, LC technological development and the MLP theory of technological development have common features as follows: 1) technological evolution tends to be characterized by discontinuous and radical innovations (the diffusion of radical innovations often has discontinuous and disruptive effects); 2) technological evolution is accompanied by both technological accumulation and market share accumulation, as well as the combined effect of both for technological development. Meanwhile, the PE models can represent these features in detail.

In this chapter, using ABM, the LCT model is reformed by considering the PE evolutionary technological transition model to enrich the baseline model. With this model, technological development at the niche level can be properly represented. Spontaneous LCT driven by the LC technological evolutionary learning process is investigated.

4.2 Model

Recently, the study of technological evolutionary and energy systems has been introduced separately. For instance, the PE model is an evolutionary model of technological diffusion in which a new and an old technology are available, both of which improve their performance incrementally over time. The PE behavior, that is, the system switching from one stable equilibrium to another because of performance uncertainty, can be observed in the model. The PE model can be used to characterize technological evolutionary discontinuities caused by small sub-groups of innovators becoming isolated, developing a significant new trait, and then displacing an old technology in a very short period (radical or disruptive innovation). In addition, in the field of energy and environment research, an LCT model with local energy markets is proposed to show the relationship between energy capacity, energy consumption, and market regulation, and the model results can provide insights about transition policy [1].

Thus, by coupling the PE and LCT baseline models, a combination technological evolutionary model is combined with the LCT model to find the various interactions between technological evolution and the LCT process, and to provide insights regarding a suitable transition strategy for policymakers.

In the following, the two models are briefly described, and the coupling of the PE model and the LCT model is presented.

4.2.1 The LCT model

As introduced in Chapter 2, a baseline LCT model is built with several groups of agents (i.e., firms, energy industries, etc.), all of which display complex behaviors by using some sub models such as energy production, the local energy market and a firm's life cycle. As formerly discussed, the baseline LCT model allows one to investigate crucial interactions and diverse behaviors between agents. These agents usually follow a relatively simple operations logic, but when they interact, complex phenomena appear. Firms can move around the system, purchase, and consume energy, and they will die if energy is insufficient. The energy industry generates either HC or LC energy. The supply and prices of these two kinds of energy will change with the environmental pressure and the intensity of competition in the local market. The energy industry will respond to the purchases of firms and increase the production quantity of the more popular type of energy based on positive feedback between supply and demand. By setting different parameters, the LCT model simulates the evolution of the system under different energy technologies and environmental pressures. Through the observation of these agent evolution results and the analysis of agent behavior, we can usually obtain some useful transition strategies.

4.2.2 Punctuated equilibrium (PE) technology diffusion model

The PE model originates in biology [134] and was then introduced to management science [135-136]. In 1999, Christoph H. Loch and Bernardo A. Huberman established a model to describe the PE phenomenon in technological diffusion. Different from other models that use an S-curve to describe technological diffusion, with new technology gradually replacing the old, the PE model describes another process. New technology will go through a long-term stage of not being selected but, as time goes by and the development of new technology and its market share slowly increases, it will quickly occupy the whole market when its market share reaches a critical mass.

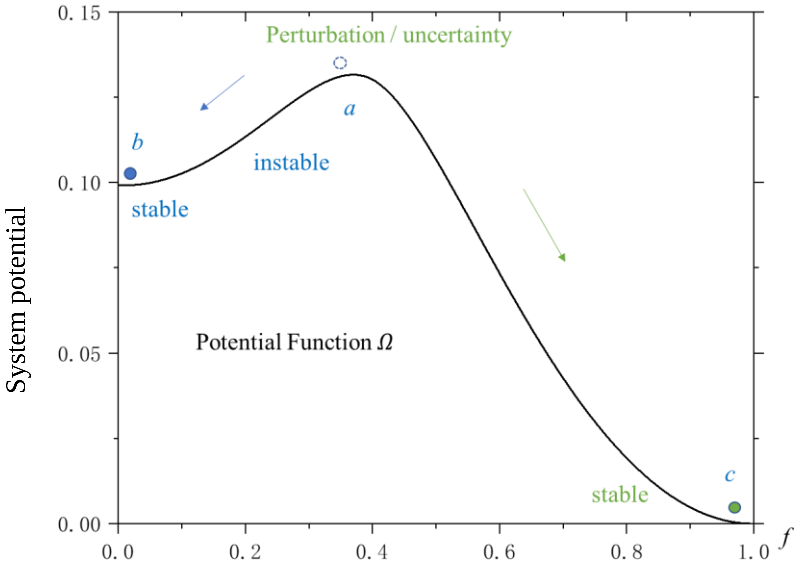


Fig. 4.1. Numerical example of the potential function.

In the PE model, consider a firm selecting new technology based on total performance, which is determined by inherent (basic) performance *p*, externality *b*, and uncertainty performance of new technology. The fixed, basic performance of both technologies is considered for the simplest analytical explanation in this section. (An incremental basic performance increase of both technologies over time will be adopted in the next section).

1) There are two technologies competing in the market (*f* old is the share of the old technology, *f* new is the share of the new technology), and the sum of their market shares is 100%.

2) Each technology has a total performance G (the basic performance of the two technologies is constant over time).

3) The firm evaluates the performance G of each technology and decides whether to change their previous technology.

Technology adopters make repeated choices between the established and new technologies based on their perceived performance, which is subject to uncertainty. From a numerical example of the potential function obtained from the new technology market share state evolution function $\Omega(f)$, as shown in Figure 4.1 [94], the dynamic new technology adoption behavior can be summarized as follows. First, if the system is not in equilibrium (between state a and b), it will move (expectedly) toward the next (in a "downhill" direction in Ω) local minimum of Ω (state b). However, with a very low probability, random fluctuations (uncertainty in basic performance of new technology) may be sufficient to push adoption to the other side of the maximum of Ω (state a). If this happens, the new technology adoption system will flip, and the adoption will stabilize in another equilibrium state (state c). This is the PE behavior of sudden technological adoption.

4.2.3 Combination of the PE model and the LCT model

In this section, the combination of the technology evolution PE model with the LCT baseline model will be introduced considering an incremental basic performance increase of both high- and LC technologies over time and demonstrate the different adoption regimes in the coupled model.

The basic framework of this new model is inherited from the LCT model, creating a two-dimensional 33 × 33 regular lattice, in which there are two types of agents—firms and energy industries. Energy industries will supply or generate high- or LC energy, and firms can purchase or consume the energy.

In the new model, the industry firm's lifetime mechanism remains the same as in the LCT model. However, for the mechanism of the energy industries, the original fixed energy capacity parameters is changed in the new model in which the energy technology capacity will increase over time. The market share of these high- and LC technologies will not only be obtained from market feedback, but also be determined through the judgment of the energy industries themselves based on PE technological development.

4.2.3.1 A firm's life cycle

- A firm's life cycle:

At every time step n, all firms randomly walk to a neighboring node, dissipating an amount of energy e_{con} as consumption at the same time. If the firm is on a node covered by one kind of energy, it will purchase the energy with the price $p_{n,h}$ (or $p_{n,l}$) (see Eqs. 4.3 and 4.4), gaining effective energy $i_{n,h}^{eff}$ (or $i_{n,l}^{eff}$) as follows:

$$i_{n,h}^{eff} = i_h - c_h p_{n,h} \tag{4.1}$$

$$i_{n,l}^{eff} = i_l - c_l p_{n,l} \tag{4.2}$$

where i_h and i_l are the energy capacity of high- and LC energy, as explained in Chapter 2. If the firms prosper or decline is fully determined by the energy it obtains, E. If the firm does not have adequate energy ($E < 0$) to support its operation after the move, the firm will collapse due to an energy shortage. If the firm holds an amount of energy greater than the subsidiary threshold e_{sub}, it will split into two subsidiary firms at the same node, each of them carrying one-half of the energy of the original firm.

- Local energy market:

The energy price is formulated by the local firm number,

$$p_{n,h} = \beta_h \rho_n^z \tag{4.3}$$

$$p_{n,l} = \beta_l \rho_n^z \tag{4.4}$$

where β_h and β_l are the coefficients describing the market sensitivity of high- and LC energy, respectively. The number of local firms ρ_n^z is counted in a neighboring area 3×3 of the node.

4.2.3.2 Energy supply

In the new model, the LCT baseline model was greatly changed. In the original LCT model, all of the energy industries (i.e., patches) would be regarded as a whole. They would summarize and give feedback to the overall demands of the system, and then generate energy randomly on the patches with statistical productivity. However, in the new model, we regard each patch/energy supplier as an independent individual that has its own technology accumulation and that will decide whether to produce and what kind of energy they will produce in each round according to its own situation.

The mechanism for energy suppliers determining energy production is as follows. It is assumed that there are two types of energy technologies on the market—traditional HC energy and new LC energy. Each technology has its own total performance G, which consists of basic technology performance P and an externality benefit b. The formula is as follows:

$$G = P + fb \tag{4.5}$$

where f represents the market share of the technology ($f_h$is the HC technology market share, and $f_l$is the LC technology market share), if $f = 1$, it means that the technology completely occupies the market. fb represents a benefit other than the technology itself, which is brought by additional adopters, where b measures the size of additional benefits brought by adopters. P represents the basic performance of the technology (P_h is HC technology performance, P_l is LC technology performance), which is the evaluation parameter of the technology for whether it is reliable or can improve efficiency.

With technological development, P will increase gradually over time, but the increase is not infinite. It will reach a saturation state as the maximum value ($\overline{P}$) represents the upper limit of what this technique can achieve. The formula for the growth of P over time is as follows:

$$P_i(t+1) = P_i(t) + c_i f_i(t) P_I(t) \frac{\overline{P_l} - P_i(t)}{\overline{P_l}} \tag{4.6}$$

where c_i indicates the learning characteristics of the technology, such as the competence of its developers or its complexity, and c_i determines how fast a technology advances toward its performance ceiling.

Compared with traditional HC energy, the technical performance G of low-carbon energy will have an additional uncertain part ξ. ξ is a random integer within [0,4]. This is because in the process of the development and popularization of the new technology, some uncertain part will often appear. This uncertain part may bring unexpected benefits to the company, but can also cause losses to the firms in some conditions.

$$G_l = P_l + f_l b_l + \xi \tag{4.7}$$

For each patch, their technological reserve is different. Normally, each patch will compare the technological reserve of its own high- and LC energy and select the one with the highest performance G.

$$Energy\ Type = max\{G_h, G_l\} \tag{4.8}$$

This does not mean that each patch will be fixed in terms of the type of technology that they develop. In fact, some will evaluate the market prospects of the technology to determine which energy they choose to produce.

Firstly, they will calculate the gap between the two technologies, *D*, according to their own technology development rate as follows:

$$D(f) = G_l - G_h \tag{4.9}$$

Then through the judgment function η_{hl}, they will decide whether to change their previous choice, which was decided in Eq. 4.10.

$$\eta_{hl}\,(f_h, f_l) = \begin{cases} \frac{1}{2} e^{\beta D(f_h, f_l)} & if\ G_h > G_l, \\ 1 - \frac{1}{2} e^{-\beta D(f_h, f_l)} & if\ G_l > G_h, \end{cases} \tag{4.10}$$

η_{hl}, refers to the probability of switching from high carbon technique to low carbon technique, as shown in Figure 4.2 (the parameter settings are P_h and P_l are set to 3 and 3; b_l is set to 2, b_h is set to 3; and β is set to 2).

One can see that as the *P* of new technology gradually catches up with or even surpasses the old technology, the energy industry choosing to produce the high carbon energy will have a greater probability to replace it by generate low carbon energy. The purpose of using an S-curve is to ensure that even though the new technology may not perform as well as the old technology, there will still be some people who switch to the new technology because they are more optimistic about its future development.

η_{hl}, refers to the probability of switching from low carbon technique to high carbon technique, as shown in Figure 4.2. The probability is η_{hl} and $\eta_{lh} = 1 - \eta_{hl}$. However, each energy industry, will not evaluate (execute) technologies continuously; but according to a Passion process with rate α. In other words, only some energy industries will evaluate the technology in the system.

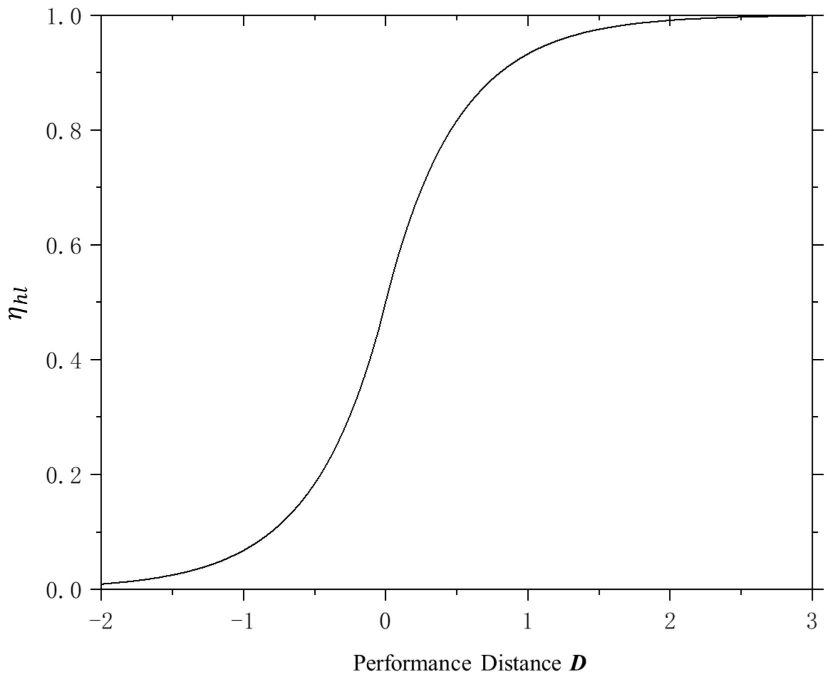


Fig. 4.2. The relationship between total performance gap *D* and switching probability η_{hl}

In the LCT model, a parameter β (market sensitive parameter) is considered as a policy instrument for market adjustment that acts as an additional price for firms to purchase energy in the local market to regulate the market. This parameter acts mainly on the firm side. Different values of β reflect different market environments and policy pressures, and by increasing β, we can test the results of the market shifts under different environmental pressures. In the new model, since we want to discuss the impact of energy technology development (energy industry) on LCT, and β is a control variable acting at the firms' end, we fix the value of β to avoid an impact on the results.

However, similar to β, we use another parameter α to reflect different market environments and policy pressures, such as subsidies for LC technologies to represent protection for LC research or innovation. The original definition of α in the PE model is evaluate the rate, because "A firm does not evaluate technologies continuously, but according to a Poisson process with rate α," and, at a certain point in time, only some firms in the market will make this choice. At this point the state function is as follows:

$$\frac{df_l}{dt} = \alpha g(f_l) = \alpha[(1 - f_l)\eta_{hl}(f_l) - f_l\eta_{lh}(f_l)] \tag{4.11}$$

where α is an intrinsic property of energy industry firms, and the value of α should be the same for all energy industry firms. The probability of both going "switching from choosing LC technologies to choosing HC technologies" and "switching from choosing HC technologies to choosing LC technologies" are the same evaluation (execution) behaviors, and the probability of both should be α with no outside interference (i.e., when the value of $\alpha_{hl}$is equal to the value of α_{lh}), the technical policy is unbiased.

However, if outside interference is taken into account (such as LC subsidy for protection LC innovation, etc.), then the values of the evaluation or execution (α) of the two choices "switching from choosing LC technologies to choosing HC technologies" and "switching from choosing HC technologies to choosing LC technologies" can be considered two independent variables that change with policy adjustments. For example, if the government policy encourages energy industry firms to switch to LC technology by providing subsidies for generating LC energy, then firms will have higher expectations for the future of LC technology, and more energy industry firms will consider switching to LC technologies, resulting in a higher value of α_{hl} than before. If the government increases the restrictions on carbon emissions, then more energy industry firms than usual will consider reducing their investment in HC technologies, leading to a lower value of α_{lh}. Therefore, the mechanism of supporting subsidies for protecting LC technologies and suppressing the development of HC technologies gives the parameter α a biased property (i.e., the policy is biased in favor of LC technologies when α_{hl} is greater than α_{lh}).

In the new mechanism, α changes from an inherent technology assessment attribute of an energy industry firm to a variable that is subject to regulatory influences such as policies to protect LC technologies, so that the current system's state function will take the following forms:

$$\frac{df_l}{dt} = \alpha_{hl} f_h \eta_{hl}(f_l) - \alpha_{lh} f_l \eta_{lh}(f_l) \tag{4.12}$$

$$\frac{df_h}{dt} = \alpha_{lh} f_l \eta_{lh}(f_h) - \alpha_{hl} f_h \eta_{hl}(f_h) \tag{4.13}$$

By setting different α_{hl} and α_{lh} to obtain different biases for LC technology protection and support, the impact of protection policy on energy industry firms and LCT can be investigated.

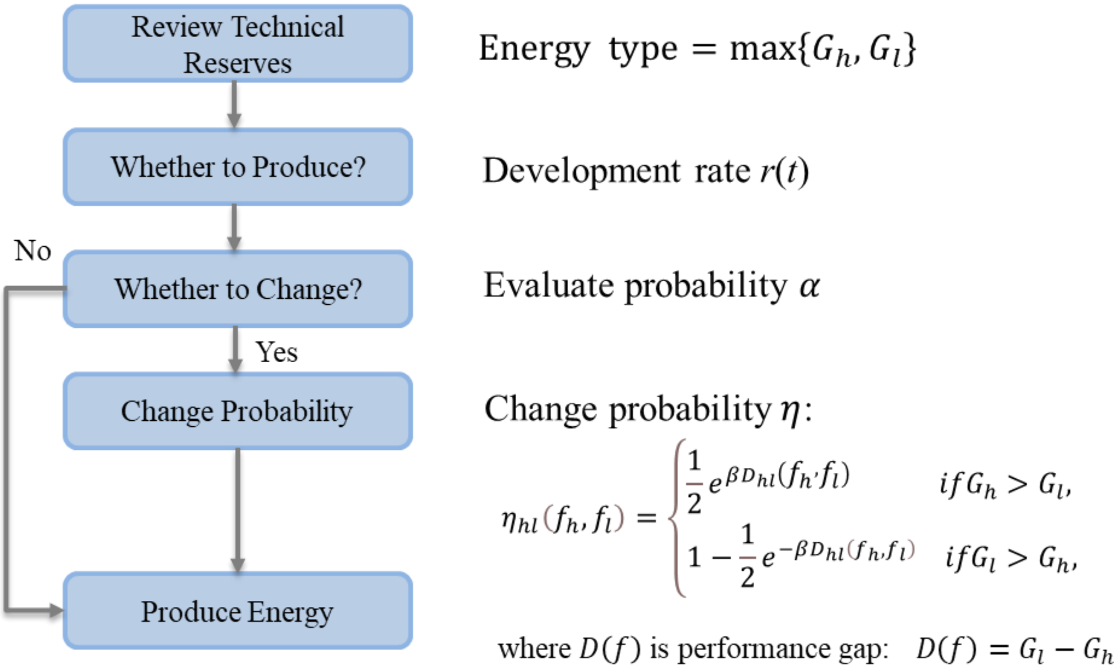


Fig. 4.3. Flowchart of the energy production mechanism

Most energy companies first determine the type of energy (HC or LC) to produce by comparing *G*, and then deciding whether to produce the selected type of energy with productivity r_h or r_l, and finally, the decision to evaluate or not to follow the above mechanism is based on α. In other words, most energy companies will evaluate the decision-making of technology selection (according to the *G* value) and the production rate (r_h or r_l) with a probability of α, and η_{hl} affects the action after the assessment of technology selection (according to the *G* value) and the production rate (r_h or r_l) (i.e., whether to produce an energy according to the type of superior technology and the productivity of such technology with the evaluation probability as α). Therefore, after the new technology outperforms the old technology, not all people will rush to the new technology. There will still be a small number of people who stick to the old technology for various reasons. The new model not only allows the energy company to transform from a HC energy technology to a LC energy technology, but also allows the companies that have already transformed to supply LC energy to return to supply HC energy (Shown as in Figure 4.3). The flowchart of these behaviors is provided in Figure 4.4.

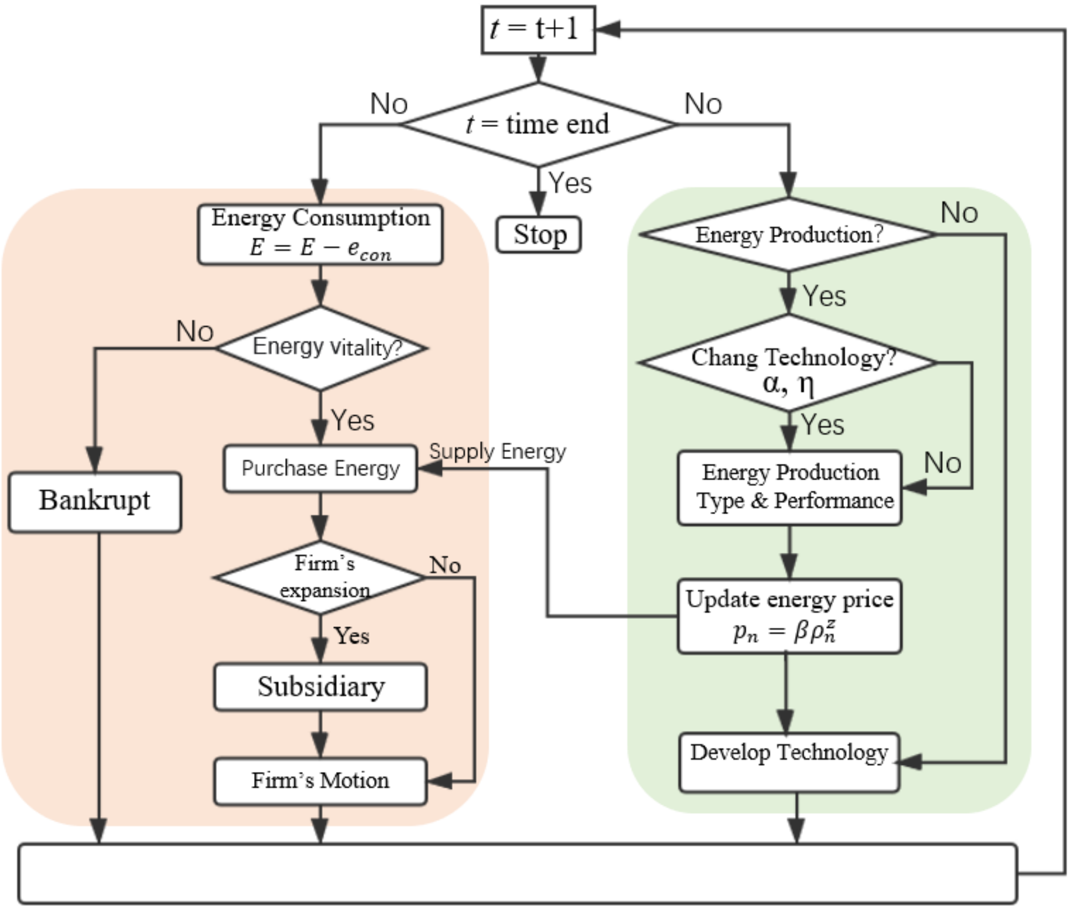
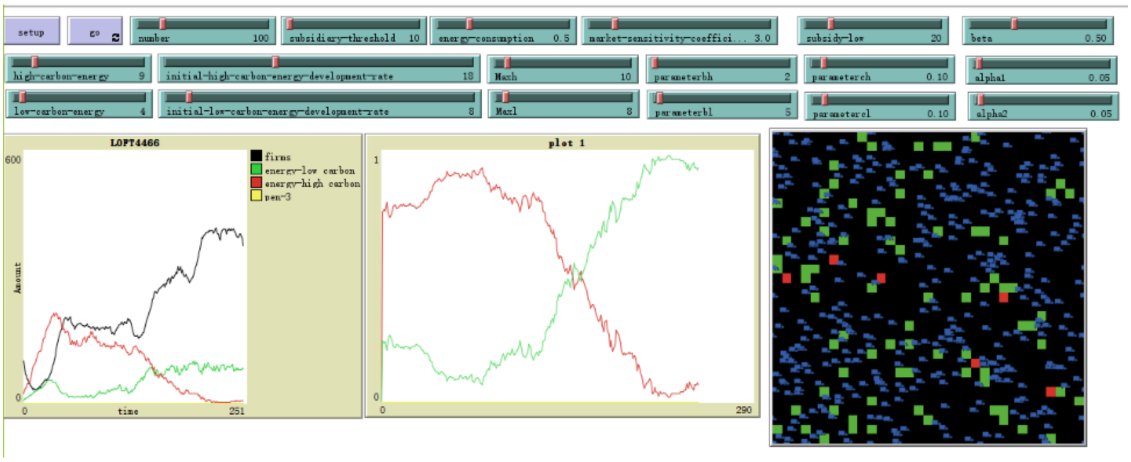


Fig. 4.4. Flowchart of the behaviors at node *n*.

The coupled model is based on the Netlogo simulation platform, and the Netlogo user interface with the coupled model is shown in Figure 4.5. The buttons on the top control the operation of the model. The “setup” button initializes the model, and after initialization, one can click the “go” button to begin the simulation. The monitors on top are used to observe several crucial parameters as they change over time steps, to the left the situation of LC energy penetration is displayed, reflecting the LCT process. The sliders on top are used to control the value of coefficients, which can be modified during the simulation. On the bottom right is the central landscape. The model is populated with firms (houses) and energy supply companies (green and red patches), where the black patch represents empty sites. At the beginning, all industry firms randomly obtain their energy from the grid (green for LC energy, red for HC energy). The energy industry (patch) can then choose to switch to generating green energy (LC energy like solar or wind) or red energy (HC energy like micro-combined heat and power sources or other fossil-based energy). To eliminate the edge effects, the model has periodic boundary conditions, and the whole simulation space is a 2D regular lattice $N = L \times L (L = 33)$.

Most of the initial values are based on the LCT model described in Chapter 2 for the energy market, as shown in Table 4.1. However, some parameters such as energy capacity are changed from the original constants to the variables to view the state of the PE mechanism. Note that the value of e_{con} is set to 0.2 because according to the conclusion of Chapter 2 [1], the system can only successfully transition when energy consumption is small enough. The market sensitivity coefficient ratio is set to 20 because the system will remain a HC energy-dominated state under this parameter setting, which is what the coupled model wants to do: put the system in the HC state first and then investigate whether the technological evolution will impact the energy market without adjusting the market sensitivity.

The initial value of technology development (as shown in Table 4.2) has been modified to create the evolutionary technology transition as the PE model. In the entire simulation, these parameters are carefully matched with the setting in the relevant section for investigating the PE phenomenon in the LCT process.



number 100
subsidiary-threshold 10
energy-consumption 0.5
market-sensitivity-coeffici... 3.0
subsidy-low 20
beta 0.50
high-carbon-energy 9
initial-high-carbon-energy-development-rate 18
Maxh 10
parameterbh 2
parameterch 0.10
alpha1 0.05
low-carbon-energy 4
initial-low-carbon-energy-development-rate 8
Maxl 8
parameterbl 5
parametercl 0.10
alpha2 0.05

Fig. 4.5. Netlogo user interface with technological evolution, coupled with the LCT model.

Table 4.1. Energy market parameter settings with initial values.

Variable	Description	Initial value
$E(t)$	Amount of energy that a firm has retained	Random integer within [1,8]
$r_h(t)$	Rate of high-carbon energy's development	18%
$r_l(t)$	Rate of low-carbon energy's development	8%
$i_{n,h}^{eff}(t)$	Effective high-carbon energy capacity for the firms at node *n*	
$i_{n,l}^{eff}(t)$	Effective low-carbon energy capacity for the firms at node *n*	
$s_h(t)$	Number of firms that purchase high-carbon energy	
$s_l(t)$	Number of firms that purchase low-carbon energy	
$\rho_n^z(t)$	Local firm number within the vicinity *z* of node *n*	
i_h	The amount of energy provided by one unit of high-carbon energy	
i_l	The amount of energy provided by one unit of low-carbon energy	

Constant		Baseline value
e_{con}	The amount of industrial firm's energy consumption	0.2
e_{sub}	The threshold of firm's reproduction	10
β_h	Market sensitivity coefficient for high-carbon energy	2
β_l	Market sensitivity coefficient for low-carbon energy	0.1

Table 4.2. Technology development market parameter settings with initial values.

Variable	Description	Initial value
$f_{h,l}$	High- (low-) carbon technology adopter	
$G_{h,l}$	Total performance of the high- (low-) carbon technology	
ξ	Basic performance uncertainty of the low-carbon technology	Random integer within [0,4]
D	Total performance gap	
η_h	Probability of choosing high-carbon technology	
η_l	Probability of choosing low-carbon technology	
α	Evaluation rate	
B	Uncertainty degree of selection probability	
$\boldsymbol{\Omega}$	Potential function of the system transition	

Constant		Baseline value
$P_{h,l}$	Basic technology performance	9(4)
$b_{h,l}$	Externality benefit	2(2)
$\bar{p}_{h,l}$	Performance ceiling	10(8)
$c_{h,l}$	Learning characteristics of the technology	0.03(0.03)

4.3 Technology evolutionary driven LCT

At the beginning of the system, 100 firms will be created and randomly distributed on a 33 × 33 regular lattice. Each firm will have a random energy value that corresponds to enterprises of different sizes and reflects the heterogeneity of agents. Moreover, to ensure that the sample mean of partial results is getting closer to the mean of the overall sample, a sufficient number of samples are taken to ensure a lower standard error when calculating the results, so that the mean obtained is representative and the reliability is improved.

Many simulations have been run over the full possible range of initial parameter settings. As a result, it is found that the variation of only two parameters yield profound effects on the time evolution of the system and the corresponding fundamental dynamics. These are the energy consumption (e_{con}) and the basic performance ceiling ($\overline{P}$). The latter parameter governs the importance of PE technology evolutionary effects in the model. It is, in some senses, equivalent to the learning process. Figure 4.6 shows the four distinct diffusion trajectories that were observed in the model as characterized by these two key parameters, as well as the whole ecosystem in its equilibrium state. The time evolution of the number of nodes that stores HC energy n_h (red) or LC energy n_l (green) for the four phases are displayed in Figure 4.6 (a–d), and the amount of high- and LC energy reflects the progress of LCT.

In the case of P1, e_{con} is 0.2, i_h (i_l) is 9 (4) and $\bar{p}_h$ $(\bar{p}_l)$ is 10(5) to reflect the situation that low energy consumption easily brings economic prosperity, low carbon technology innovation is inactive. While, in P2, e_{con} is 0.5, i_h (i_l) is 9 (4) and $\bar{p}_h$ $(\bar{p}_l)$ is 10(7) to reflect the situation that low energy consumption brings economic prosperity, and low-carbon technology innovation is start active. Moreover, in P3, e_{con} is 0.3, i_h (i_l) is 9 (4) and $\bar{p}_h$ $(\bar{p}_l)$ is 10(8) to reflect the situation that low energy consumption brings economic prosperity, and low carbon technology innovation is highly active, the energy consumption of industrial firms is reduced from 0.5 to 0.2, implying a greater energy efficiency. Enlarging the $\bar{p}_l$ will accelerate punctuation time as the new technology becomes more attractive. In P4, e_{con} is 1, i_h (i_l) is 9 (4) and $\bar{p}_h$ $(\bar{p}_l)$ is 10(8) to reflect the situation that high energy consumption leads to economic depression, while low carbon technology innovation is active.

Table 4.3: Simulation scenarios with parameter settings

Parameter	P1	P2	P3	P4
e_{con}	0.2	0.5	0.3	1
$\bar{p}_h$ $(\bar{p}_l)$	10(5)	10(7)	10(8)	10(8)
ih	9	9	9	9
il	4	4	4	4

4.3.1 Four typical phases and learning processes drive spontaneous LCT

In P1 (shown as in figure 4.6 (a)), an equilibrium or stationary state is achieved. One can see that due to the extremely small $\bar{p}_l$, the energy industry merely selects LC energy to produce, and the emergence of LC energy has almost no impact on the market, while HC energy is still dominant. Moreover, because energy consumption is set to a low value, the energy supply can meet the consumption of all firms, so firms can develop and expand normally. Overall, in P1, the energy industry is resistant to adopting new technology, making LCT hard to achieve.

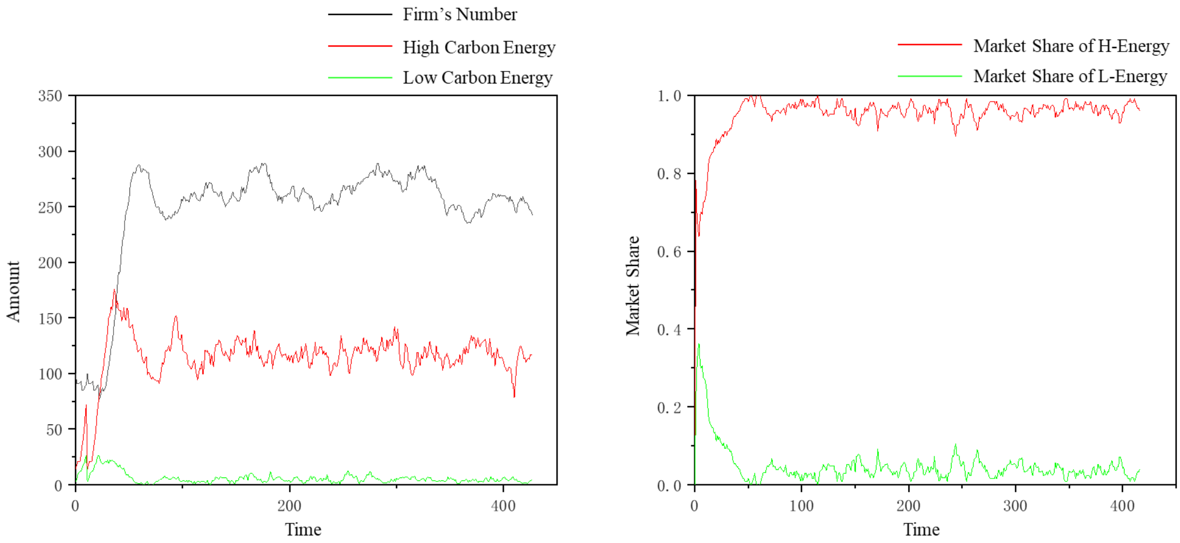


Fig. 4.6. (a) The time evolution of scenario P1.

In P2, the average technical level of LC energy gradually increases, and LC energy gradually occupies part of the market. However, similar to P1, $\bar{p}_h$ has a relatively low market performance compared to $\bar{p}_h$, so it can only weaken the dominant position of high carbon energy, but cannot complete the social transformation to low carbon energy.

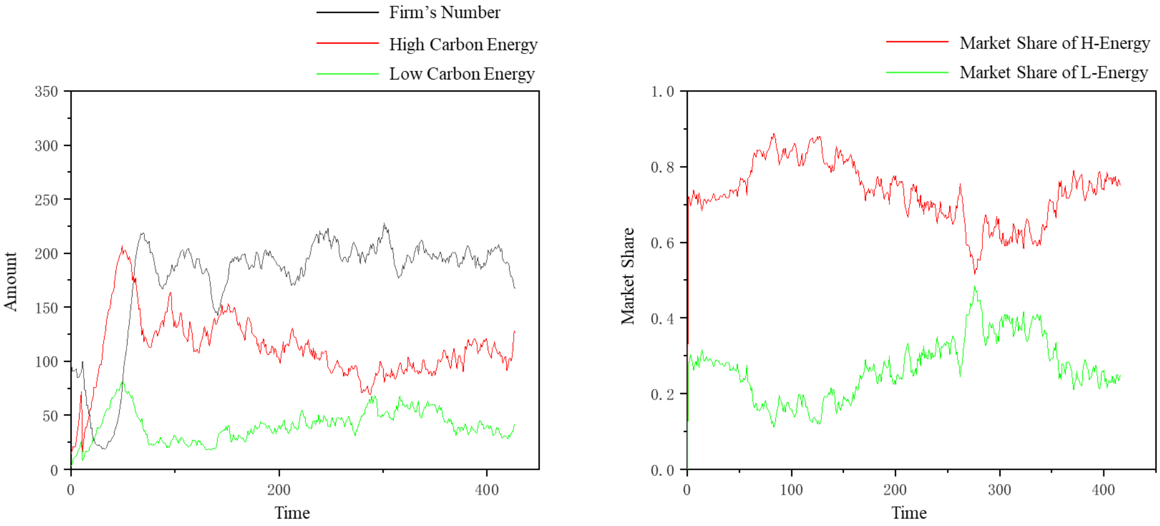


Fig. 4.6. (b) The time evolution of scenario P2.

In P3, the upper development limit of LC energy technology is at a high level, while energy consumption is low. The model starts out with HC technology being greater than LC technology in use; LC technology will reduce the performance gap over time. It is a slight evolutionary shift from the previous status.

From Figure 4.6 (c), one can see that with the development of LC energy technology, LC energy's market share first stays at a low level. When the technology accumulates to a particular stage, incremental LC technology accelerates the expected punctuation time as the new technology becomes more attractive to users, and the market share rises rapidly and finally occupies the dominant position.

This simulation result shows that the system can spontaneously complete a LCT when the basic performance ceiling of LC technology ($\bar{p}_l$) is relatively higher driven by discontinuous cumulative innovation and market share, although with the restriction that $\bar{p}_l$ does not exceed $\bar{p}_h$.

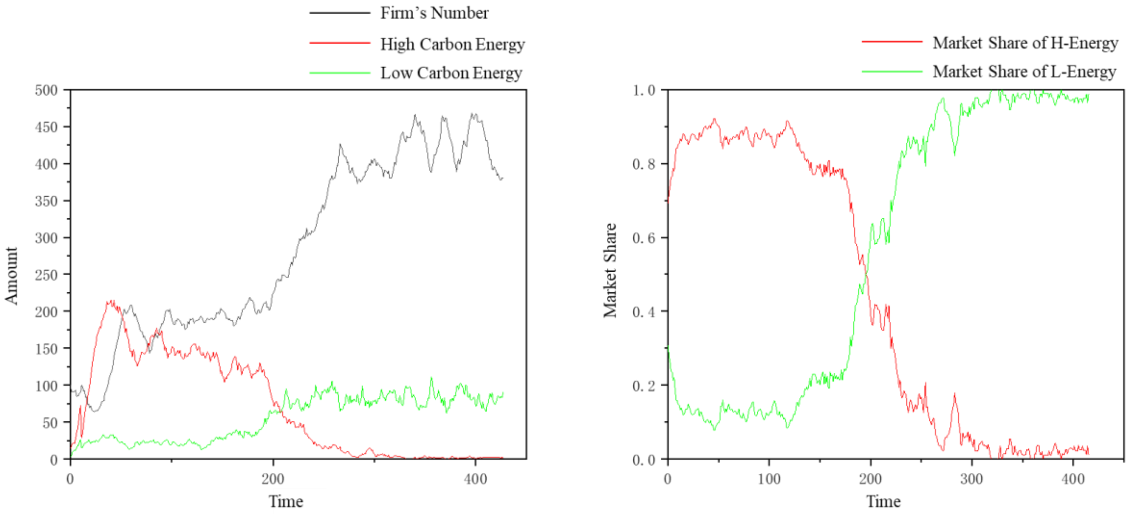


Fig. 4.6. (c) The time evolution of scenario P3.

In P4 (shown as in figure 4.6 (d)), the energy consumption is so high that the energy production of firms cannot meet their consumption. Soon all of the firms will go bankrupt due to a lack of energy.

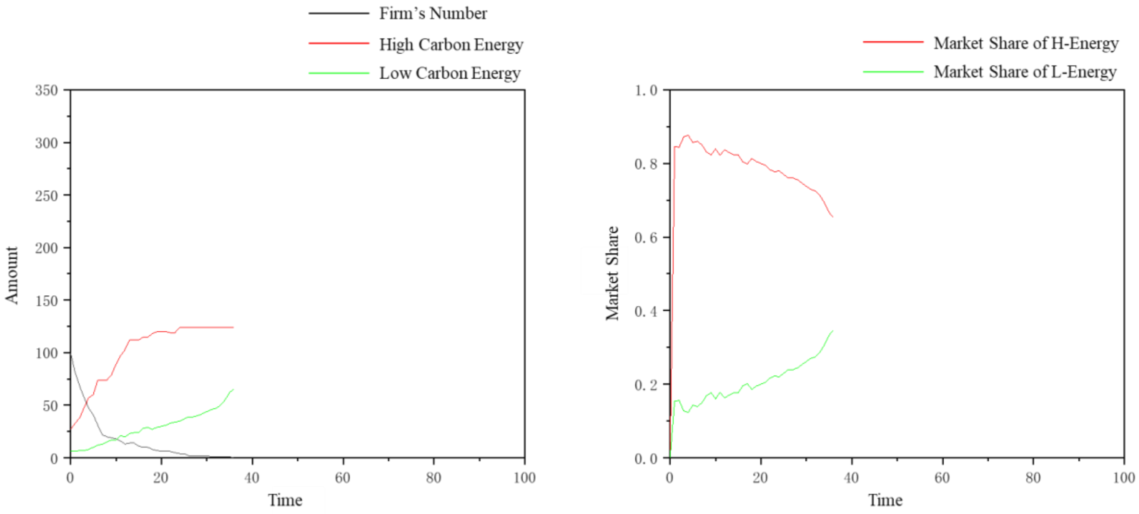
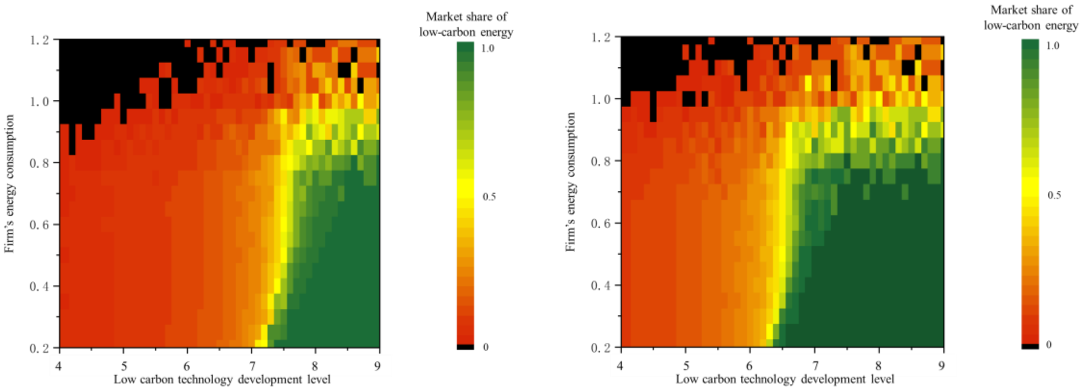


Fig. 4.6. (d) The time evolution of scenario P4.

4.3.2 Phase diagram in different protection policy bias

This section shows the phase diagrams of the system. Figure 4.7 shows the LC energy penetration (quantity of LC energy over the total amount of energy) as the order parameter of the equilibrium state, and two distinct phase diagrams with different levels of LC technology protection obtained with Regime 1 (α_{hl} = 0.05, α_{lh} = 0.05) and Regime 2 (α_{hl} = 0.5, α_{lh} = 0), as shown in Figure 4.7 (a) and (b). In both of these phase diagrams, the abscissa is the LC technology performance ceiling ($\bar{p}_l$), and the ordinate is the energy consumption e_{con}. The LC technology performance ceiling ($\bar{p}_l$) reflects the degree to which the system obtains the upper limit capacity of LC energy, and it affects the limit of the LC energy technology development level in the system. A higher $\bar{p}_l$ can make LC technology more competitive in the market, so it is easier for energy production companies to choose it. The energy consumption e_{con} impacts the survival of firms at a fixed level of energy development and supply, which will determine whether the energy consumption level will become a factor hindering the normal development of firms. There are four typical phases in the phase space of these two control parameters: HC economy (red dominant), state of coexistence (yellow dominant), LC economy (green dominant), and recession (black dominant).



Regime 1: $\alpha_{lh} = 0.05,\ \alpha_{hl} = 0.05$

Regime 2 : $\alpha_{hl} = 0.5,\ \alpha_{lh} = 0$

Fig. 4.7. Phase diagrams of Regime 1 and Regime 2.

In these phase diagrams, the transition from the HC state to the LC state is not particularly sudden or abrupt and there is a "critical value" to reveal critical phenomena.

4.3.2.1 Regime 1

In this regime (Figure 4.7, left), there is no bias at the level of LC technology protection (α_{hl} = 0.05, α_{lh} = 0.05). In this case, there is a normal LC state part that exists in the phase diagram, even if the performance ceiling value of LC technology is lower than that of HC technology.

Moreover, there is no possible path for the system to transform into a LC state when the performance ceiling value of LC technology is lower than a certain critical value ($\bar{P}_l$ < 6.5); the system still needs sufficient technical accumulation.

Finally, in conditions of high LC technological development, the system needs to meet a sufficiently low energy consumption to shift to a LC state.

4.3.2.2 Regime 2

In this regime (Figure 4.7, right), there is bias at the level of LC technology protection (α_{hl} = 0.5, α_{lh} = 0), which represents a market in which energy companies are encouraged to transition from HC to LC energy technology, while companies that choose LC energy technology will not be allowed to return to adopt HC technology.

In the case of Regime 2, even if the upper limit of LC technology performance is lower than the upper limit of HC technology performance, a normal LC state in the phase diagram still exists.

In addition, when the performance limit of LC technology is lower than some critical value ($\bar{P}_l$ < 7.5), the system has no possible path to transform to a LC state, and the system still requires sufficient technological accumulation.

Finally, under the conditions of high development of LC technology, the system needs to meet a sufficiently low energy consumption to transform into a LC state.

Conversely, compared with the phase diagram for Regime 1, one can see that with an increase in the level of protection bias of LC energy technology, the boundary (high- and LC state) moves to the left. In the middle region, after the system stabilizes, adjusting the bias of LC technology protection can make the system successfully transform; that is, from the yellow region (the LC and HC energy coexistence state) to the green region (the LC state) without changing the status of technological development. However, in the left region (red region), even if the bias of LC technology protection is increased, the transition will not be successful. These results reveal that regulating the degree of LC technology protection can facilitate the transition to a LC state under certain circumstances, but it is necessary to pay attention to the degree of technological development, otherwise it is likely to be useless. At the same time, for systems or countries with a high level of LC technology development, increasing the level of LC technology protection can effectively accelerate the transition.

To verify the conclusions obtained from the two phase diagrams, a virtual experiment is carried out, and the results are shown in Figure 4.8. This simulation was conducted to observe the evolution of the system taken when a HC economy is the starting point in the lower-left corner of the Regime 1 (α_{hl} = 0.05, α_{lh} = 0.05 and other parameters were set as in Table 4.4). Then, increasing the level of

LC technology protection (α_{hl} = 0.5, α_{lh} = 0), a move from a HC economy to a LC economy located in Regime 2.

Table 4.4: Parameter setting for S1.

Parameter	S1
e_{con}	0.3
$\bar{p}_l$	7.2
ih	9
il	4

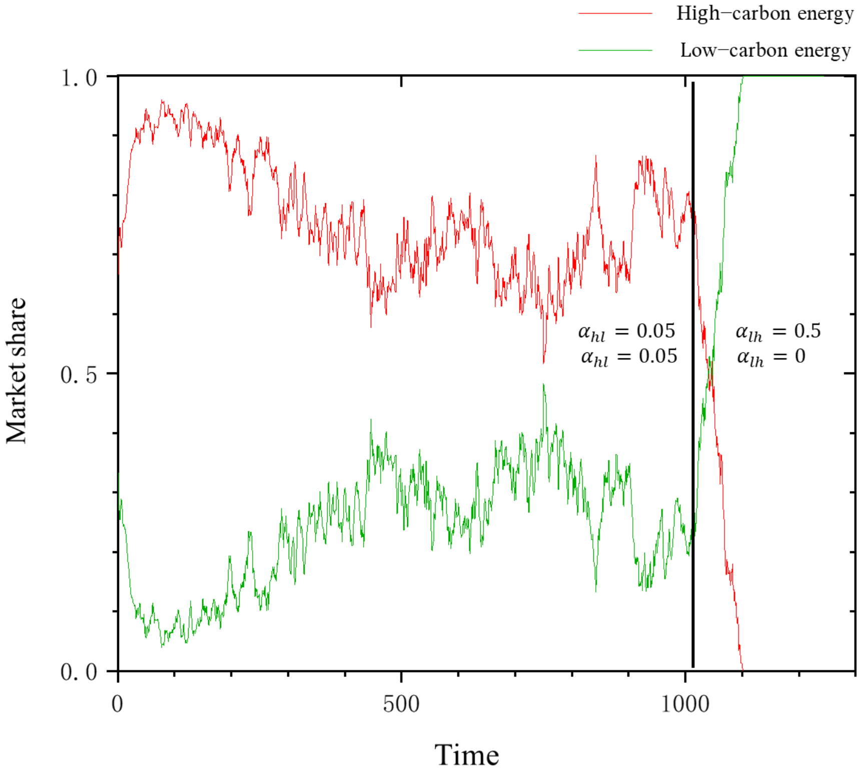


Fig. 4.8. Time evolution of examples of LCT in S1.

When the system located at the performance ceiling of LC technology $\bar{p}_2$ is less than 6 with energy consumption econ range from 0.2 to 0.8, before and after the introduction of the protection policy bias for LC technologies, the system state keeps as red state in Regimes 1 and 2, which means that the policy bias does not allow this part of the region to complete the LCT.

To clarify this, a virtual experiment was conducted, and the results are shown in Figure 4.9. The evolution of the system that taking the HC economy as the starting point is in the lower-left corner of Regime 1 (α_{hl} = 0.05, α_{lh} = 0.05 and the other parameters set as in Table 4.5). The market is completely dominated by HC energy sources in the system, and LC energy sources have only a small share (about 5%). Then, increasing the level of LC technology protection (α_{hl} = 0.5, α_{lh} = 0). However, HC energy continues to dominate the market, with only a small increase in the market share of LC energy.

Table 4.5. Parameter setting for S2.

Parameter	S2
e_{con}	0.3
$\bar{p}_l$	4.5
ih	9
il	4

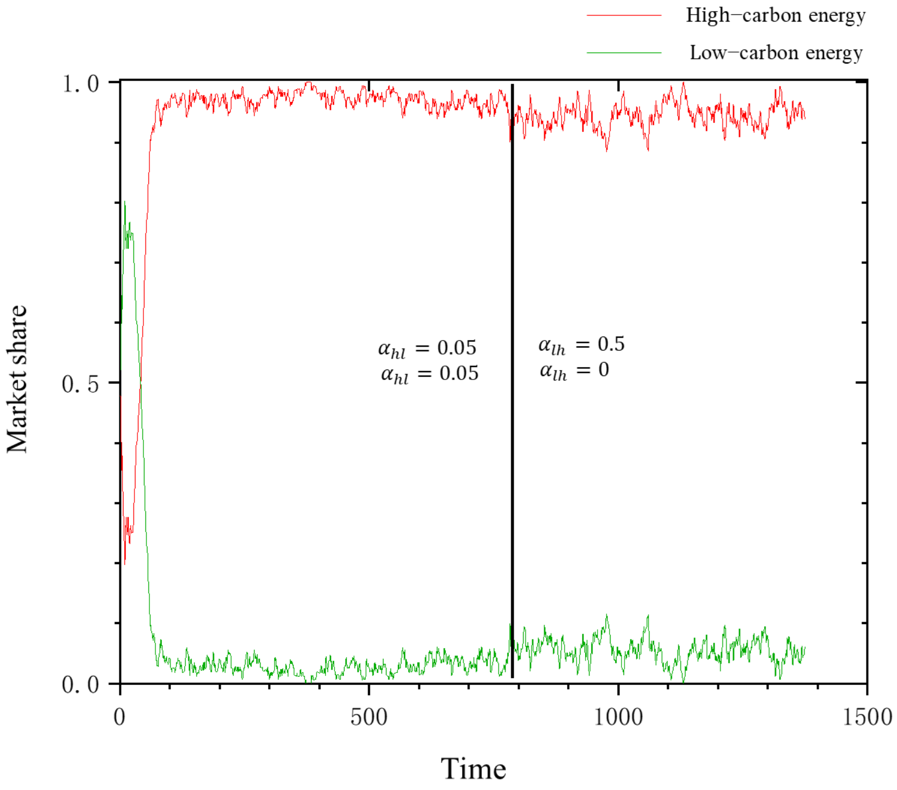


Fig. 4.9. Time evolution of examples of LCT in S2.

4.3.3 The impact of the LC technology performance ceiling on the punctuation time

Through the phase diagram analysis, we understand how far the new technology needs to go before it has the potential to replace the old technology, with or without technological protection. So, if the new technology has the potential to replace the old technology, how long does it take to complete the replacement process?

Figure 4.10 provides a plot of the relationship between the punctuation time and the performance ceiling of LC technology $\bar{P}_l$ under the condition of no LC technology protection bias. Punctuation time $P(t)$ is defined as the time when LC energy penetration reaches 90%. The other parameters are set as shown in Table 4.6. The horizontal axis is the performance ceiling of LC technology $\bar{P}_l$ and the vertical axis is the punctuation time $P(t)$.

From the figure we can learn the following:

- An increase in $\bar{P}_l$ can result in accelerating the punctuation time as LC technology becomes more attractive with use, and the efficiency of the decrease will rapidly decay.
- When the $\bar{P}_l$value is between 7.3 and 8, increasing $\bar{P}_l$ is the most effective for reducing the punctuation time.
- When the $\bar{P}_l$ value is between 8 and 10, increasing $\bar{P}_l$ is not very effective for reducing the punctuation time.

Table 4.6. Parameter settings.

Parameter	
e_{con}	0.3
$\bar{p}_h$	10
ih	9
il	4

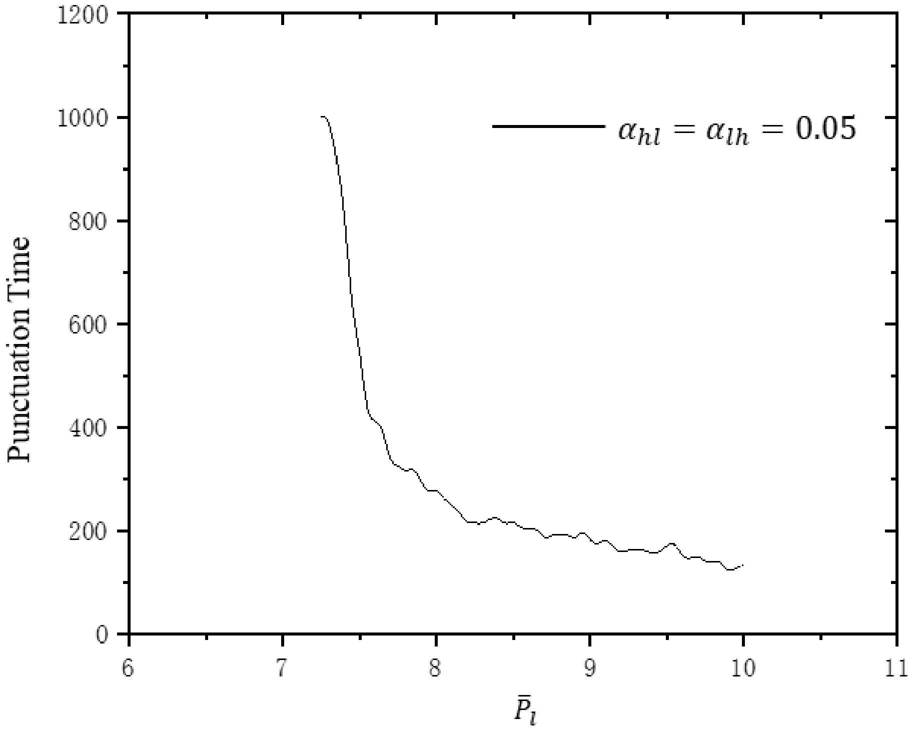


Fig. 4.10. The relationship between the punctuation time and $\bar{P}_l$ without a technical policy bias.

4.3.4 The impact of the LC technology protection policy bias on the punctuation time

Figure 4.11 gives a plot of the relationship between the punctuation time $P(t)$ and the performance ceiling of LC technology $\bar{P}_l$ under the condition of different degree of LC technology protection bias. Other parameters are set as shown in Table 4.7. The horizontal axis is the performance ceiling of LC technology $\bar{P}_l$ and the vertical axis is punctuation time $P(t)$. Gray, red, and green line represent different degree of protection bias.

From the figure, it is found that the system is highly sensitive to changes in the protection bias as follows:

- An increase in $\bar{P}_l$ can lead to accelerating the punctuation time, and the efficiency of the decrease will rapidly decay. When the $\bar{P}_l$value is between 7.3 and 8, increasing $\bar{P}_l$ is the most effective for reducing punctuation time.
- Increased protection policy bias (α_{hl} increasing from 0.05 to 0.3 or 0.6) can effectively reduce the requirements for LC technology development.
- In some cases, for example, when the system located at $\bar{P}_l$ is equal to 8 with no LC technology protection bias (gray line, $\alpha_{hl} = \alpha_{lh} = 0.05$), it is better to increase the protection policy bias (α_{hl} increase from 0.05 to 0.3 or 0.6) than to increase $\bar{P}_l$ to reduce the punctuation time for transition.

Table 4.7. Parameter setting.

Parameter	
e_{con}	0.3
$\bar{p}_h$	10
ih	9
il	4

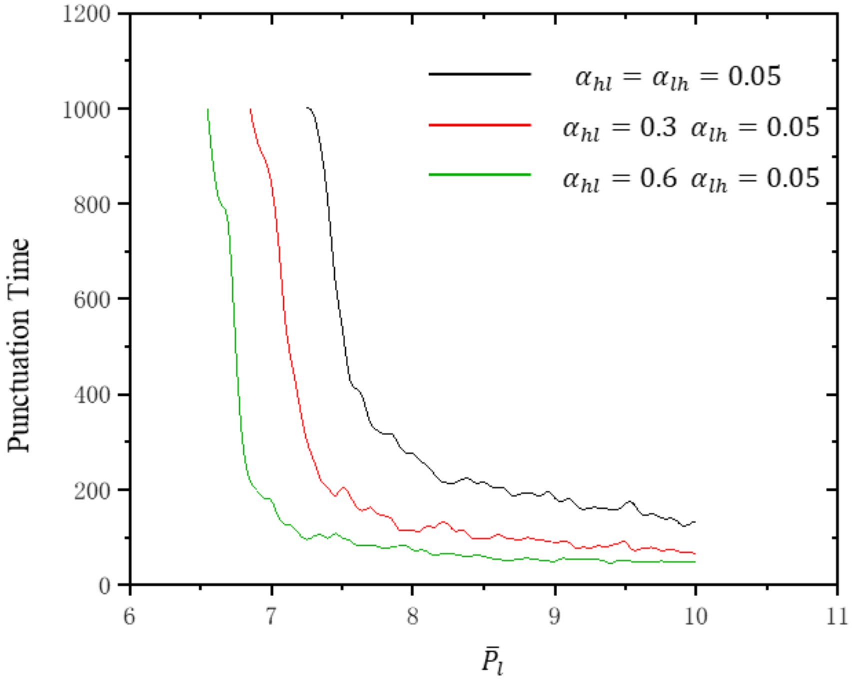


Fig. 4.11. The relationship between the punctuation time and $\bar{P}_l$ under different degrees of bias.

4.3.5 The effect of the LC technology performance ceiling and energy consumption on LCT

Figure 4.12 provides a plot of the effect of the LC technology performance ceiling $\bar{P}_l$ and energy consumption e_{con} on LCT promotion when the protection policy bias is fixed (before political intervention: $\alpha_{lh} = 0.05$, $\alpha_{hl} = 0.05$; after political intervention: $\alpha_{lh} = 0.5$, $\alpha_{hl} = 0$. The other parameters are set as shown in Table 4.8. The horizontal axis is the performance ceiling of LC technology $\bar{P}_l$ and the vertical axis is policy effectiveness. Policy effectiveness is defined as the change in the market share of LC energy before and after a policy adjustment (LCT promotion), when the change in the policy bias is fixed, which reflects the effect of the policy adjustment. Different lines respond to the policy effect changing over $\bar{P}_l$ (under different values of energy consumption e_{con})

From the figure, we can see the following:

- The effect of policy adjustment is larger with a medium value of $\bar{P}_l$ (6.3–7.8).

- When the value of $\bar{P}_l$ is less than 5.5 or greater than 8, the effect of policy adjustment is very low. This is because when the value of $\bar{P}_l$ is low, technical performance is so low that even if the policy is adjusted, the energy industry will still abandon LC technology. In addition, when the $\bar{P}_l$ value is high, the energy industry is biased to adopt low-carbon technologies because their inherent good performance leads to higher competitiveness, while the policy adjustment brings limited proportional effect at this time; therefore, the policy adjustment is less attractive than the low-carbon technology itself when the performance ceiling of low-carbon technology is high.

- The lower the energy consumption (e_{con}), the higher the policy effect (LCT promotion).

Table 4.8. Parameter setting.

Parameter	
e_{con}	0.2 -1.2
$\bar{p}_h$	10
ih	9
il	4

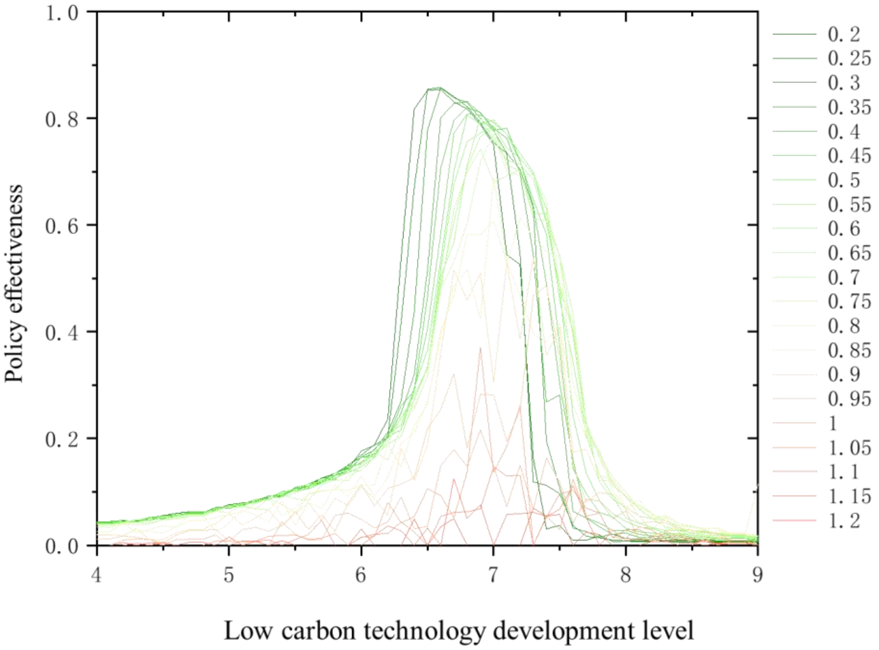


Fig. 4.12. The effect of the performance ceiling and energy consumption on LCT promotion (policy effectiveness).

4.4 Empirical evidence

First, for the structural verification of the new model, according to the structural verification in Chapter 2, one can notice that only the PE module is revised by adding the new parameter to reflect niche detail as MLP described (such as c represents the learning process and P is considered to be basic performance of technology, etc.) [2,94].

Second, for the correspondence of empirical examples or behavioral validation, the following renewable energy development are given to correspond with reality:

Figure 4.6 shows the historical development of the installed capacity of solar power in China from 2001 to 2017. With the emphasis on climate change, the output of patents and academic papers in China continues to grow [137], and, after accumulating LC innovation and market share, a radical turning point occurred in 2012 for solar power [138]. The same phenomenon can be found in P3.

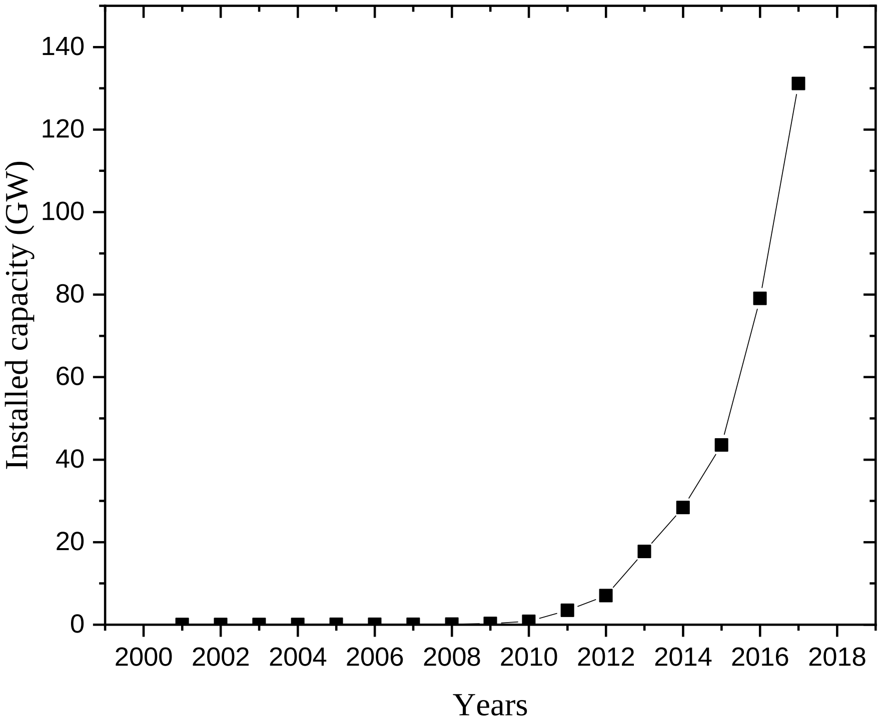


Fig. 4.6. Historical development of the installed capacity of solar power in China (2001–2017) [137].

On the other hand, there are spillover effects such as LC technology spillover and green premium effects in a realistic LC technology diffusion process.

Spillover effects refer to impacts on people or societies outside of the organization that occur when an organization carries out a certain activity, in addition to the effects expected by the activity. Spillover effects can be divided into knowledge spillover effects, technological spillover effects, and economic spillover effects [139], among other types of spillover effects.

Therefore, the following points are added to the empirical content:

a) Cross-system or cross-regional investment activities and knowledge and technological spillover effects

With the accelerating process of economic globalization, technological progress in a country (especially in developing countries) can be achieved through both independent innovation and technology importation, absorption, and reinvention, and the same phenomenon is also present across regions inside the system.

In the model, these effects can be represented by the parameters c, α, and b, etc.

1) Autonomous innovation brings regional spillover effects. There is a difference in the technology spillover within the domestic region. For China, there are large differences between the eastern, central, and western regions. The green technology spillover effect of investment activities is most significant in the central region, which would prolong the incubation period for technological diffusion (corresponding to a difference in the values of c and b in the model).

2) The introduction of technology brings cross-system spillover effects. There is a green technology spillover effect of foreign direct investment (FDI) between developing and developed countries.
    - From developed system to developing system. There is a significant green technology spillover effect of foreign research and development (R&D) contained in FDI on China's green technology progress.
    - From a developing system to a developed system. For example, the study of the reverse technology spillover effect is one of great value to developing countries. The reverse technology spillover channels obtained by developing countries through FDI can be divided into two categories—technology channels and non-technology channels.

3) The threshold effect of absorptive capacity on the technical receptors (corresponding to a difference in b values in the model): Technology absorptive capacity has threshold characteristics for green technology spillover effects.

4) Open innovation can help increase the technology spillover gap. With more specialized insights into the study of technology diffusion across systems and regions, open innovation can lead to knowledge and technology accumulation in disruptive innovation (PE model), increase the knowledge and technology spillover gap, promote technology diffusion, and accelerate the arrival of the tipping point of disruptive innovation.

b) Green technology premium

The green technology premium represents the diffusion momentum of LC technology, defined as the absolute value or proportion of the cost improvement of LC technologies over HC technologies. The key to LC technology diffusion is to reduce the green technology premium. When the cost of new green technologies shrinks compared to brown technologies, or when they are as cheap as brown technologies due to government guidelines and subsidies, then there may be opportunities for large-scale green technology diffusion.

1) The relationship between technology spillover and the green premium: Controlling the green premium intersection between high and LC technology costs by regulating green technology spillover effects.
2) The relationship between policy instruments and the green premium: Subsidizing LC technologies or suppressing HC technologies (e.g., α in the model) has a bias toward green technology spillovers and reduces green premiums.
3) Market instruments to reduce the green premium: Adjusting the prices of HC energy and LC energy in the financial market will balance the intensity of the green premium effect. Introducing new market mechanisms such as carbon markets will increase the cost of HC technologies.

c) Technology entrepreneurship management

Spillover effects (knowledge and technology spillover and premium effects) complicate the management of LC technology innovation and diffusion, which leads to higher management requirements for LC technology entrepreneurs (i.e., knowledge of technology entrepreneurship policies (patent introduction or support for original innovation, etc.) and knowledge of economic and financial aspects related to green premiums. To build a virtuous technology evolution ecology, the management of technological entrepreneurship is also a priority. For example, to identify the key dimensions in early-stage technology acquisition, technology acquisition decisions should be made by many technology-related professionals—such as senior managers in R&D, (open) innovation managers, intellectual property officers, products, business and finance managers, and lawyers—that support firms during technology transactions.

These discussions are useful for a more in-depth study of PE models, such as knowledge and technology spillovers and premium mechanisms when multiple LC technologies compete, and for applying the above relevant elements in new studies to try to give reasonable answers on how to solve the LC technology dilemma.

4.5 Summary of Chapter 4

In this chapter, a technology evolutionary model, namely, the PE model, was combined with the LCT model to investigate the impact of LC technology diffusion on LCT. The model adopted an ABM of technology diffusion where bounded rational agents are faced with uncertainty about the performance of LC technology versus HC technology as well as external benefits.

It was found that:

- the radical “PE” pattern of the LC technology adoption is emerged, the off-equilibrium adoption or diffusion trajectory of LC technology can be obtained by radical and unstable shifts within the restriction that LC technology performance ceiling ($\bar{P}_l$) is less than HC technology performance ceiling ($\bar{P}_h$),
- Four typical phases were found in the phase diagram for Regimes 1 and 2, and even if the upper limit of LC technology performance is lower than the upper limit of HC technology performance ($\bar{P}_l < \bar{P}_h$), a normal LC state in the phase diagram exists.
- Compared with phase diagram of Regime 1, in Regime 2, with an increase in the level of protection bias of LC energy technology, the boundary (high- and LC state) moves to the left to reduce the pressure of LC technology development.
- When the performance limit of LC technology is less than some critical value ($\bar{P}_l < 7.5$ for Regime 1, $\bar{P}_l < 6.5$ for Regime 2), the system has no possible path to transform to a LC state, and the system still requires sufficient technological accumulation.
- Under the conditions of high development of LC technology, the system needs to meet sufficiently low energy consumption to transform into a LC state.
- Regulating the degree of LC technology protection can facilitate the transition to a LC state under certain circumstances, but it is necessary to consider the degree of technological development, otherwise it is likely to be useless.
- An increase in $\bar{P}_l$ can result in accelerating punctuation time, and the efficiency of the decrease will decay rapidly.
- Increasing protection policy bias (α_{hl} increases from 0.05 to 0.3 or 0.6) can effectively reduce the requirements for LC technology development to reach punctuation time.
- When the system located at tipping point of the LC technology is high enough for LCT, it is better to increase in protection policy bias (α_{hl} increase from 0.05 to 0.3 or 0.6) than to increase the $\bar{P}_l$ to reduce the punctuation time for transition.
- The effect of policy adjustment of the LC technology protection bias on LCT promoting is larger with a medium value of $\bar{P}_l$ (6.3–7.8), and when the value of $\bar{P}_l$ is less than 5.5 or greater than 8, the effect of policy adjustment is very low.
- The lower the energy consumption (e_{con}), the higher the policy adjustment of the LC technology protection bias effect on LCT promotion.

Chapter 5 Conclusion

Considering the economic and technological impacts on LCT, ABMs provide insight about very important phenomena regarding the colorful pathways of the complex LCT process. Through further analysis, it is found that this co-evolutionary framework can indeed give some creative insights, which were always overlooked in mainstream LCT studies, to better understand the LCT process.

In Chapter 2, we use the ABM approach to build a distributed energy system combined with a localized energy market to capture the behavior of a group of agents (e.g., type of energy, firms, etc.), with diverse behaviors and important interactions (e.g., energy production and energy purchasing) and then obtain specific policy recommendations. Under the condition of increased energy capacity with positive feedback between supply and demand, LCT is found to be facilitated by a combination of market adjustments favoring LC energy and policy adjustments for low energy consumption. By contrast, with a low energy capacity and high energy consumption, the transition from a HC economy to a LC economy inevitably causes a catastrophic economic depression. Finally, from the baseline LCT model, the following conclusions were found for most general systems. 1) The improvement of energy capacity is a fundamental prerequisite for LCT without inducing economic catastrophe. 2) Enhancing energy saving and energy storage efficiency could increase the successful rate of safe LCTs. 3) Market regulatory bias is the "final blow" that destroys HC industry and drives the system into a LC state.

Moreover, a DS model to analyze LCT in the energy–economic system is established to verify the LCT model. In such a model, one can quickly find the equilibrium point of the system, whether it is stable or not, and the results obtained by the two methods (the LCT and DS models) can be compared to each other, thereby promoting further optimization of the two methods to make the results and the LCT model more credible.

Finally, it is argued that the combination of the MLP and ABM enables us to reach a deeper and more detailed analysis of LCT, that the MLP can contribute to the overall design of ABM, and that ABM can provide a dynamic, continuous, and quantitative description of the MLP.

In Chapter 3, to extend the baseline model considering the impact of the economic cycle on LCT, a simplified macroeconomic system combined with a distributed industry–energy ecosystem was established based on an ABM approach. Four different typical system states can be observed: HC economy (brown economy), HC recession (brown recession), LC recession (green recession), and LC economy (green economy). The results show that LCT policy intervention in stable (S3) and dangerous (S4) states can trigger a new economic crisis by heavy environmental fines and promoting LCT in the early crisis (S1) and recovery (S2) stages of the business cycle is recommended. Moreover, the results show that an energy shortage will lead to an economic recession (P2 and P3),

Therefore, the conclusions of Chapter 3 are as follows:

1) A new crisis will be triggered by the implementation of LCT policy intervention in the state of economic booms or danger (S3 and S4).

2) The reasonable time for LCT policy intervention is when an economy is in a state of economic crisis (S1) or economic recovery (S2).

3) Biased energy capacity, that is, accelerating LC technology to avoid additional environmental costs, while balancing the supply and demand for energy (sufficient energy capacity and relatively low energy consumption) can achieve a smooth LCT without an economic recession (avoid P2 and P3, struggle to reach the system conditions as P4 suggests).

In Chapter 4, to extend the baseline LCT model considering the impact of technological evolution on LCT, the PE technology evolution model is combined with the LCT model. Based on this reformed model, four different phases can be observed. It is also found that the radical “PE” pattern of LC technology adoption emerges spontaneously, driven by the fact that the learning process under the LC technology performance ceiling ($\bar{P}_l$) is less than under the HC technology performance ceiling ($\bar{P}_h$).

The conclusions of Chapter 4 are as follows:

1) When the radical “PE” pattern of LC technology adoption emerges, the off-equilibrium adoption or diffusion trajectory of LC technology can be obtained by radical and unstable shifts with the restriction that the LC technology performance ceiling ($\bar{P}_l$) is lower than the HC technology performance ceiling ($\bar{P}_h$).
2) Four typical phases were found in the phase diagram of Regimes 1 and 2, and even if the upper limit of LC technology performance is lower than the upper limit of HC technology performance ($\bar{P}_l < \bar{P}_h$), a normal LC state in the phase diagram exists.
3) Compared with the phase diagram of Regime 1, in Regime 2, with an increase in the level of protection bias of LC energy technology, the boundary (high- and LC states) moves to the left to reduce the pressure of LC technology development.
4) When the performance limit of LC technology is less than some critical value ($\bar{P}_l < 7.5$ for Regime 1, $\bar{P}_l < 6.5$ for Regime 2), the system has no possible path to transform to a LC state and the system still requires sufficient technology accumulation.
5) Under the conditions of high development of LC technology, the system needs to meet a sufficiently low energy consumption to transform into a LC state.
6) Regulating the degree of LC technology protection can facilitate the transition to a LC state under certain circumstances; however, it is necessary to pay attention to the degree of technological development, otherwise it is likely to be useless.
7) An increase in $\bar{P}_l$ can result in accelerating the punctuation time, and the efficiency of the decrease will rapidly decay.
8) Increasing protection policy bias (α_{hl} increase from 0.05 to 0.3 or 0.6) can effectively reduce the requirements for LC technology development for reaching punctuation time.

9) When the system is located at a tipping point of the LC technology high enough for LCT, it is better to increase the protection policy bias (α_{hl} increase from 0.05 to 0.3 or 0.6) than to increase $\bar{P}_l$ to reduce the punctuation time for transition.

10) The effect of policy adjustment of the LC technology protection bias on promoting LCT is greater with a medium value of $\bar{P}_l$ (6.3–7.8), and when the value of $\bar{P}_l$ is less than 5.5 or greater than 8, the effect of policy adjustment is very low.

11) The lower the energy consumption (e_{con}), the higher the policy adjustment of the LC technology protection bias effect on LCT promotion.

To conclude, through co-evolutionary study, reasonable pathways can be discovered in terms of economic and technological evolution, and suitable policy recommendations can be obtained for managing LCT.

Finally, based on this thesis, there are many potential viable and valuable issues to solve as follows:

1) A broad and profound two-way or mutually reinforcing intercommunication among LCT model, the DS model, and MLP from in terms of the political, economic, financial, social, cultural, and technical perspectives for strengthening the interdisciplinary combinations.

2) Deep and constructive interplay between the LCT model (along with the DS model and MLP) and the macroeconomic model to explore in more detail the impact of various political interventions in the economic cycle on LCT.

3) The discovery, creation, and extension of the theory of technology evolution based on the findings of combinatorial analytical methods (the LCT model along with the DS model and MLP) such as niche multi-technology development and the LC technology dilemma, etc.

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