Applied Energy 110 (2013) 17–28

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

The impacts of carbon tax on energy intensity and economic growth – A dynamic evolution analysis on the case of China

Guochang Fang [a,b], Lixin Tian [a,*], Min Fu [a], Mei Sun [a]

[a] Center for Energy Development and Environmental Protection, Jiangsu University, Zhenjiang, Jiangsu 212013, PR China
[b] Department of Basic Courses, Yancheng Institute of Technology, Yancheng, Jiangsu 224051, PR China

HIGHLIGHTS

- Use non-linear dynamical method to model the ESER system with carbon tax constraints.
- The energy-saving and emission-reduction attractor with carbon tax constraints is obtained.
- The concept of turning point of energy intensity is put forward for the first time.
- The impacts of carbon tax on energy intensity and economic growth are described vividly.
- The best time to levy carbon tax in China is found within the framework of the four-dimensional system.

ARTICLE INFO

Article history:
Received 4 September 2012
Received in revised form 5 April 2013
Accepted 12 April 2013
Available online 9 May 2013

Keywords:
Carbon tax
Energy intensity
Economic growth
Energy-saving and emission-reduction

ABSTRACT

This paper examines the impacts of carbon tax on energy intensity and economic growth in a novel four-dimensional energy-saving and emission-reduction system with carbon tax constraints. Based on Lyapunov exponents and bifurcation diagrams, the dynamic behavior of the system is analyzed. The quantitative coefficients of the actual system are identified by artificial neural network. A scenario study is undertaken by observing the dynamic evolution behavior of energy intensity and economic growth in reality. The concept of turning point of energy intensity in the four-dimensional dynamic system is put forward for the first time. By adjusting the correlation coefficients of the four-dimensional system, more effective methods being performed to steadily and diligently reduce energy intensity. Take for instance the situation in China, the problem of when and how to introduce carbon tax are settled within the framework of the four-dimensional dynamic system. The results show that, as the tax levy point of carbon tax grows larger, the energy intensity of the four-dimensional system could be controlled better. It is both important and necessary to note the inhibition effect of these changes on economic growth. The best time to levy carbon tax and the best tax levy point are achieved after a comprehensive analysis within the framework of the four-dimensional dynamic system. The more appropriate time carbon tax is started, the higher growth rate of carbon tax is adopted, the better corresponding policies and laws are made, the easier the carbon emissions could be controlled and the more energy intensity could be declined, so as to achieve the goal of reducing the carbon dioxide emissions and keeping proper energy intensity. Numerical simulations are carried out to demonstrate the results.

1. Introduction

Energy-saving and emission-reduction is one of the most effective ways to control carbon emissions. How to find the sensitive variables of reducing carbon emissions in the energy-saving and emission-reduction system, and promote energy-saving and emission-reduction is becoming a hot topic of relative academic researches. The problems of how to harmonize the relationship between energy consumption, economic growth and carbon emissions at a national level [1,2] and how to coordinate the relationship between the electrification of transportation, the conservation of energy in building, the introduction of renewable energies, efficient energy recovery from wastes and carbon emissions at a city level [3] have attracted wide attention among scholars around the world.

Among the variables affecting carbon emissions, carbon tax as one of the most effective economic measures of controlling carbon emissions has become an area of academic interest. Levying carbon tax timely and appropriately and dealing with the relation between energy-saving and emission-reduction, energy intensity and economic growth appropriately will reduce carbon

* Corresponding author. Tel.: +86 511 88797671; fax: +86 511 88791467.
E-mail addresses: fgchang79@163.com (G. Fang), tianlx@ujs.edu.cn (L. Tian).

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http://dx.doi.org/10.1016/j.apenergy.2013.04.041

Nomenclature

a_1	development coefficient of $x(t)$
a_2	influence coefficient of $y(t)$ to $x(t)$
a_3	influence coefficient of $z(t)$ to $x(t)$
a_4	influence coefficient of $w(t)$ to $x(t)$
b_1	influence coefficient of $x(t)$ to $y(t)$
b_2	development coefficient of $y(t)$
b_3	influence coefficient of $z(t)$ to $y(t)$
b_4	influence coefficient of $w(t)$ to $y(t)$
c_1	influence coefficient of $x(t)$ to $z(t)$
c_2	influence coefficient of $y(t)$ to $z(t)$
c_3	influence coefficient of the impact of investment to $x(t)$ on $z(t)$
c_4	influence coefficient of $w(t)$ to $z(t)$
$c_4'w$	inhibition effects of $w(t)$ on diverse economic variables
$c_4''w$	positive effects of $w(t)$ on diverse economic variables
C	peak value of $y(t)$
d_1	development coefficient of $w(t)$
E	peak value of $z(t)$
k_0	emission coefficient of the standard coal
M	inflexion of $y(t)$ to $x(t)$
N	inflexion of $x(t)$ to $z(t)$
S_i	equilibrium point
T	inflexion of $y(t)$ to $w(t)$
$U(t)$	time-dependent energy intensity
$\omega(t)$	time-dependent total amount of carbon tax
$x(t)$	time-dependent variable of energy-saving and emission-reduction
$y(t)$	time-dependent variable of carbon emissions
$z(t)$	time-dependent variable of economic growth

Abbreviations

BP	back propagation
ESER	energy-saving and emission-reduction
GDP	gross domestic product
SDRC	State Development and Reform Commission

Subscript

i, j	component labels

emissions and energy intensity to a great extent [4–9], so that the objectives of protecting the environment [10] and a global warming limit of 2 °C or below [11] can be achieved, which are conducive to the sustainable development of ecological economy and global economy [12].

Growing attention has been focused on carbon tax. Hammar and Sjöström [5] described evolution behavior of carbon tax in Sweden. The authors found that carbon tax is not only a path to boost taxes, but also a policy tool to reduce carbon emissions. Bureau [13] investigated the distributional effects of carbon tax on car fuels in France. Barua et al. [14] explored the effects of carbon payments and income taxes on protecting tropical forests, and found that carbon payments would curb tropical forest loss effectively. Lin and Li [15] analyzed the effects of carbon tax on per capita carbon emissions, and researched the similarities and dissimilarities of the effect of carbon tax on per capita carbon emissions in Sweden, Finland, Denmark, Norway and Netherlands. Wang et al. [16] analyzed short-term impacts of carbon tax on China's industrial competitiveness, the authors divided China's economy into 36 sectors, and gave a detailed analysis of the impacts left by high or low rate of carbon tax on different sectors of economy. Lu et al. [17] did a research on the effects of carbon tax on Chinese economy. The results showed that the negative impacts of carbon tax on economy could be minimized by complementary policies. Liang and Wei [18] analyzed the effects of carbon tax on mitigating carbon, narrowing urban–rural gap and improving people's living standard based on the China Energy and Environmental Policy Analysis model.

Among the researches of carbon tax, the time to levy carbon tax and the tax levy point have caused extensive concern and strong interest of some scholars. The Nordic countries are the first countries to levy carbon tax. Finland and Netherlands levied carbon tax in 1990; Norway and Sweden in 1991; Denmark in 1992. The Nordic countries had made some attempts on the objects of carbon tax and the tax levy point, incorporating more and more departments in the scope of taxation gradually and appropriately adjusting the tax levy point. Callan et al. [19] examined the effects on different households when the tax levy point is 20€/ton CO_2 in Ireland, and brought forward the corresponding solutions. Lee et al. [20] studied the effects of carbon taxes on different industries in Taiwan, and pointed out that the best time to levy carbon tax in Taiwan is 2011, introducing the idea that the tax levy point should increase year by year. Su et al. [21] made a questionnaire survey about the best time to levy carbon tax and the best tax levy point in China among the experts in the fields of finance, environment and energy. As for the best time to levy carbon tax, the questionnaire survey showed 53.5% of the experts argued the time is before 2015; 37.2% of the experts argued the time is between 2015 and 2020; and 7.0% of the experts argued the time is after 2020. As for the best tax levy point, some experts argued the tax levy point should lower than 10 ¥/ton CO_2, while some argued the point should between 10¥/ton CO_2 and 20 ¥/ton CO_2 or 20–30 ¥/ton CO_2.

These researches provide a lot of inspirations for this research in terms of perspectives and ideas.

In addition, we have conducted chaos analysis and have found extensive applications its applications in dynamical systems [22,23]; Tian and Jin [24] introduced a carbon emissions dynamic evolutionary system, predicting carbon emissions of China in 2020, 2030, 2050 by non-linear predictive function and control function; Fang and Tian [25] proposed a novel three-dimensional energy-saving and emission-reduction chaotic system, and presented a series of results in perfect agreement with actual situation, which provide sound theoretical basis for the present study.

This paper introduces carbon tax into the three-dimensional dynamics system [25], which seeks to establish a four-dimensional non-linear dynamics system with carbon tax constraints. Carbon tax is firstly introduced into the non-linear dynamic evolution energy-saving and emission-reduction system. By observing the dynamic evolution behavior of the energy intensity, we achieved the effects of carbon tax on evolutionary tendency of the energy-saving and emission-reduction system. The turning point of energy intensity is initiated. The coefficients which affect the peak value, turning point and stable value are discussed systemically. The best time to levy carbon tax and the best tax levy point are achieved by dynamic evolution analysis within the framework of the four-dimensional dynamic system. The way to better develop carbon tax is investigated further. All of these have not yet been reported in present literatures.

We explore the dynamic evolution behavior of the system with China's status quo as a case study. The effect of carbon tax on energy intensity and economic growth is probed further and instructive suggestions are presented.

The rest of this paper is organized as follows. Section 2 provides a brief description of the model developed for this study. Section 3 is about a scenario study of the actual system based on China's statistical data. Conclusions are presented in Section 4. Further work required to improve the current study is discussed in Section 5.

2. Establishment of the model

In recent years, the debate on carbon tax has grown only more polarized. Introducing carbon tax into the energy-saving and emission-reduction system has become a consensus gradually, and some useful conclusions and practical advice are given [10,11,13–18]. Carbon tax may influence the development speed of carbon emissions and economic growth to a certain extent. Part of carbon tax revenue needs to be invested in the research and development of new technology of energy-saving and emission-reduction, which may promote the development of energy-saving and emission-reduction, forming a virtuous circle. This paper intends to set up a non-linear dynamic model to display the relationship between these variables, studying the impacts of carbon tax on energy intensity, economic growth and other variables.

Introducing carbon tax into the three-dimensional dynamic evolution system is further investigation of the relative previous researches [24,25]. The novel four-dimensional energy-saving and emission-reduction dynamic evolution system with carbon tax constraints is more close to actual situation, which meets the trend of development of energy-saving and emission-reduction. The dynamic evolution system with carbon tax constraints can be described by the following differential equations:

$$\begin{cases} \dot{x} = a_1x(y/M - 1) - a_2y + a_3z + a_4w \\ \dot{y} = -b_1x + b_2y(1 - y/C) + b_3z(1 - z/E) - b_4w \\ \dot{z} = c_1x(x/N - 1) - c_2y - c_3z - c_4w \\ \dot{w} = d_1w(y - T) \end{cases} \quad (1)$$

where $x(t)$ is the time-dependent variable of energy-saving and emission-reduction, $y(t)$ is the time-dependent variable of carbon emissions, $z(t)$ is the time-dependent variable of economic growth (GDP), $\omega(t)$ is the time-dependent total amount of carbon tax (for the explanation of other variables, see [25]. Take C for example, parameter C is the peak value of $y(t)$ during a given economic period. Generally speaking, the value of C is bigger than the maximum of various energy agency or forecasters all over the world. So parameter C should be a constant during a given economic period. The given economic period this paper refers to is from the past to the year of 2050. Of course, parameter C will change as economic period changing.). a_4, b_4, d_1, T are positive constants. The unit of T can be transformed into tons of standard coal. a_4 is the influence coefficient of $w(t)$ to $x(t)$; b_4 is the influence coefficient of $w(t)$ to $y(t)$; d_1 is the development coefficient of $w(t)$; T is the inflexion of $y(t)$ to $w(t)$.

Energy-saving and emission-reduction (ESER) $x(t)$ consists of two technical fields: energy-saving and emission-reduction. In a broad sense, ESER concerns economizing on material resources and energy resources, decreasing the discharge of waste and environmental pollutants; in a narrow sense, ESER includes saving energy and reducing emissions of environmental pollutants. Energy-saving and emission-reduction are two different but closely related variables. Broadly speaking, energy-saving will lead to emission-reduction, but emission-reduction not necessarily brings about energy-saving. So the emission-reduction projects should intensify the applications of energy-saving technology to avoid the shot-up of energy consumption, which may be caused by the sided pursuit of emission-reduction results. More attention should be paid to the balance of social and environmental interests. The two variables of energy-saving and emission-reduction should be integrated into one, which is the variable we call "energy-saving and emission-reduction". China officially put forward the slogan of ESER in the "Eleventh Five-Year" Plan for the first time, and the Chinese scientific researchers tend to combine energy-saving with emission-reduction to collectively call ESER. This paper sets up a novel non-linear dynamics system, in which the dynamic evolution behavior of the variables in the ESER system with carbon tax constraints are studied and the impacts of carbon tax on energy intensity and economic growth are discussed. During the evolution process of the ESER system, $y(t)$, $z(t)$, $w(t)$ all have an effect on energy-saving and emission-reduction. The practice of combining the two variables together and taking them as one variable proved to be reasonable, not affecting the evolution analysis of the ESER system and having little effect on the research and conclusions of this paper.

GDP is one of the most primary indexes which estimates macro economy, and is one of the most-watched indexes with higher integration among the macroeconomic data. It is related to economic growth rate, inflation rate, unemployment rate, credit, growth rate of investment and other economic variables. Only the dynamic system with four variables is considered based on these comprehensive relationships in this paper. The impacts of other economic variables are represented synthetically into the variables and the coefficients of the variables of Eq. (1). For example, $c_1x(x/N-1)$ in the third formula $\dot{z} = c_1x(x/N-1) - c_2y - c_3z - c_4w$ of Eq. (1), the change rate of time-dependent $\dot{z}(t)$ is associated with the influential coefficient of $x(t)$ to $z(t)$ and the share of $z(t)$ potential $(x/N-1)$ simultaneously. The effects of $x(t)$ on diverse economic variables and the relations among them are represented synthetically into the coefficient c_1 and the share of $z(t)$ potential $(x/N-1)$.

In Eq. (1), the impacts of carbon tax on carbon emissions and energy-saving and emission-reduction are considered. Introducing carbon tax will have positive effects on the low-carbon businesses or individuals, and will have negative effects on the high-carbon businesses or individuals. In general terms, introducing carbon tax will have inhibition effects on economic growth in the early stage of the dynamic system presented in Eq. (1). a_4w indicates that carbon tax will promote the development of energy-saving and emission-reduction. $-b_4w$ indicates that carbon tax inevitably influences the development speed of carbon emissions to a certain extent. $-c_4w$ represents the effect of carbon tax on economic variables. Carbon tax exerts impact on various economic variables such as GDP, import and export, domestic products price index, and index of average goods price. The impact is represented synthetically by the coefficient c_4. $c_4 = c_4' - c_4''$, where $c_4'w$ is the inhibition effects of carbon tax on diverse economic variables, $c_4''w$ is the positive effects of carbon tax on diverse economic variables. $c_4'w = \sum_i c_{4i}'w, i = 1, 2, 3, \cdots$, where $c_{4i}'w$ is the inhibition effect of carbon tax on a certain economic variable, similarly, $c_4''w = \sum_j c_{4j}''w, j = 1, 2, 3, \cdots$, $c_{4j}''w$ is the positive effect of carbon tax on a certain economic variable. According to China's economic development and industrial structure, the inhibition effects of carbon tax will surpass the recycling of the carbon tax revenues into the economy during the early implementation of carbon tax, and this stage will continue for a long time, i.e. $c_4' > c_4''$, $c_4w = (c_4' - c_4'')w$ represents the inhibition effects of carbon tax on economy synthetically. As carbon tax developed, depending on the multiplicative effects of the recycling of the carbon tax revenues into the economy, $c_4'' > c_4'$, i.e. $c_4 = c_4' - c_4'' < 0$, the impacts of carbon taxes on economy will turn to be positive.

The fourth formula in Eq. (1) indicates that: the change rate of time-dependent carbon tax $d\omega(t)/dt$ is associated with carbon tax $\omega(t)$ and the share of carbon tax potential $(y - T)$ simultaneously.

When $y < T$, the development speed of $\omega(t)$ is slow; when $y > T$, the development trend of $\omega(t)$ gets fast.

When $\omega(t) = 0$ in Eq. (1), i.e. there is no carbon tax, Eq. (1) changes into the three-dimensional energy-saving and emission-reduction system in Ref. [25]. Due to limitations on space, for the explanation of the three-dimensional energy-saving and emission-reduction system and other variables, please refer Ref. [25].

Eq. (1) is a continuous dynamic evolution system. The changing of each variable will bring about a change of the whole system. Introducing carbon tax into the three-dimensional dynamic evolution system is meant to analyze the dynamic evolution behavior of the system with carbon tax constraints, and to find the effects of carbon tax on energy-saving and emission-reduction system, i.e. the effects on energy intensity and economic growth. After an analysis of the dynamic evolution system, the following problems are proposed: Whether the introducing of carbon tax into energy-saving and emission-reduction system is necessary? When is the best time to levy carbon tax? What is the best tax levy point? How to improve effects of carbon tax properly in the energy-saving and emission-reduction system?

From Eq. (1), the energy consumption and the GDP at time t during a given period could be deduced as $y^*(t) = \phi_1(x, ky, z, w, t)$, $z(t) = \phi_2(x, y, z, w, t)$. The time-dependent energy intensity can be depicted as follows [25]:

$$U(t) = \phi_1(x, ky, z, w, t)/\phi_2(x, y, z, w, t) \tag{2}$$

where k_0 is the emission coefficient of the standard coal; $k = 1/k_0$.

In the rest of this paper (see Section 3.2), based on the dynamic evolution diagram of $U(t)$, with the turning point and stable value of energy intensity as index components, the effects of carbon tax on energy-saving and emission-reduction system are analyzed, and a series of instructive suggestions are presented.

2.1. Basic properties analysis of the energy-saving and emission-reduction system with carbon tax constraints

When the parameters of Eq. (1) are given different values, the system presented in Eq. (1) will show different dynamic behavior. On the basis of the three-dimensional energy-saving and emission-reduction system [25] combing the effects of carbon tax on the four-dimensional system, after a mass of debugging and numerical simulation, it is found that when the parameters of Eq. (1) are given in Eq. (4). Eq. (1) will display some very interesting dynamic evolution behavior as chaotic attractor (refer to Section 2.2 of this paper).

$$\begin{aligned}
&a_1 = 0.09,\ a_2 = 0.003,\ a_3 = 0.012,\ a_4 = 0.042,\\
&b_1 = 0.412,\ b_2 = 0.096,\ b_3 = 0.8,\ b_4 = 0.06,\ c_1 = 0.035,\\
&c_2 = 0.0062,\ c_3 = 0.08,\ c_4 = 0.0024,\ d_1 = 0.02,\ M = 0.9,\\
&C = 1.6,\ E = 2.7,\ N = 0.35,\ T = 0.755
\end{aligned} \tag{3}$$

Eq. (1) has real eight equilibrium points: $S_0(0, 0, 0, 0)$, $S_1(0.0574, 1.3453, 0.7750, 1.6135)$ $S_2(0.0623, -0.0186, 0.7550, -0.0518)$, $S_3(-1.4415, -1.4941, 0.7750, 3.4287)$, $S_4(0.2090, 0.8840, 0.7750, 0.5253)$, $S_5(0, -1.4931, 1.1463, 3.3510)$, $S_6(0, 0.8594, 0.8631, 0.4804)$, $S_7(0, 1.3492, 0.7726, 1.6254)$.

Calculate the corresponding characteristic equation of Jacobian matrix of Eq. (1). $S_0, S_1, S_2, S_3, S_4, S_5, S_6, S_7$ are all saddle points [25].

$$\begin{aligned}
\nabla V &= \frac{\partial \dot{x}}{\partial x} + \frac{\partial \dot{y}}{\partial y} + \frac{\partial \dot{z}}{\partial z} + \frac{\partial \dot{w}}{\partial w}\\
&= a_1\left(\frac{y}{M} - 1\right) + b_2\left(1 - \frac{2y}{C}\right) - c_3 + d_1(y - T)\\
&= \left(\frac{a_1}{M} - \frac{2b_2}{C} + d_1\right)y + b_2 - a_1 - c_3 - d_1 T
\end{aligned} \tag{4}$$

The dynamic system presented in Eq. (1) is a dissipative system if $\frac{a_1}{M} + d_1 = \frac{2b_2}{C}$ and $b_2 - a_1 - c_3 - d_1 T < 0$.

2.2. Energy-saving and emission-reduction attractor with carbon tax constraints

When the parameters of Eq. (1) are given in Eq. (4) and initials are given [0.015, 0.758, 1.83, 0.01], a chaotic attractor could be observed as shown in Fig. 1a and the corresponding time series of $x(t)$, $y(t)$, $z(t)$, $\omega(t)$ as shown in Fig. 1b.

The Lyapunov exponent spectrum of parameter c_3 is shown in Fig. 2.

The corresponding bifurcation diagram of state variable y with respect to parameter c_3 is shown in Fig. 3.

In comparison to the previous chaotic system (Lorenz system, Chen system, Lü system and Energy resources demand–supply system), the chaotic system presented in Eq. (1) has different equilibrium points and different linear and non-linear parts. When the four-dimensional chaotic systems with carbon tax constraints is decomposed into linear part $[a_{ij}]$ and non-linear part, we find that there are plenty of differences between the four-dimensional chaotic systems with carbon tax constraints and the previous chaotic system: the value of $a_{12}a_{21}$ is different, the previous chaotic system satisfy $a_{23}a_{32} = 0$, $a_{31} = a_{32} = 0$, while the four-dimensional chaotic

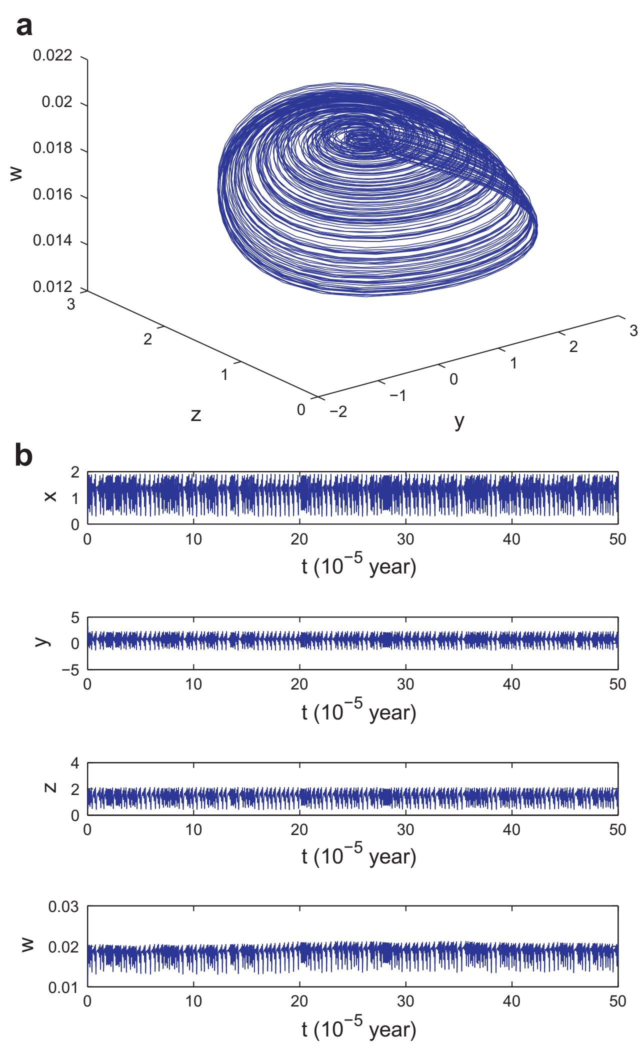

Fig. 1. (a) Attractor with carbon tax constraints (y–z–w). (b) The time series of $x(t)$, $y(t)$, $z(t)$, $w(t)$.

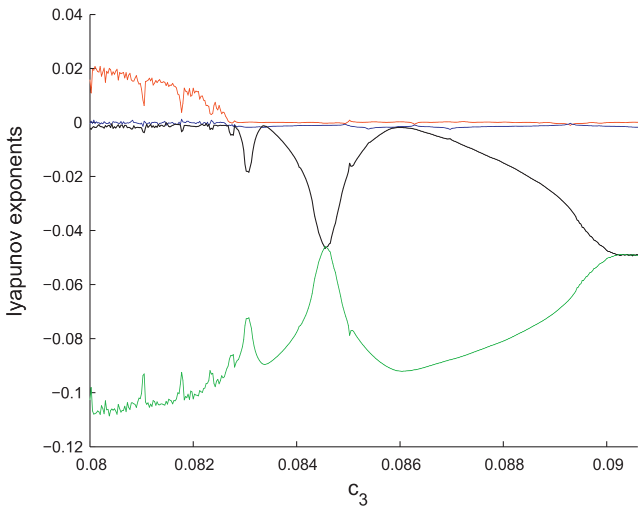

Fig. 2. Lyapunov exponent spectrum.

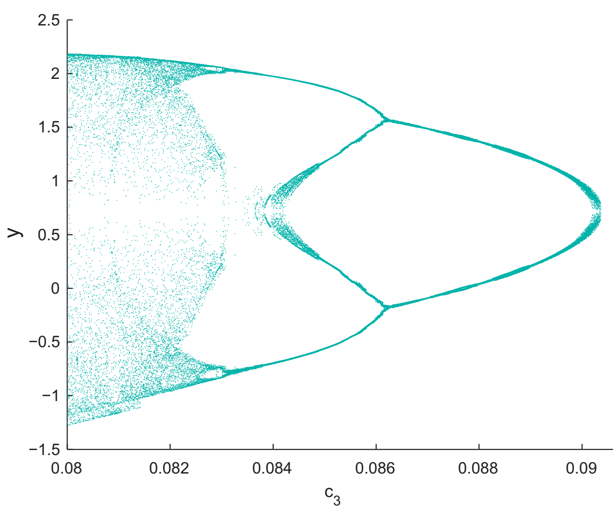

Fig. 3. Bifurcation diagram of *y*.

systems with carbon tax constraints satisfies $a_{23}a_{32} \neq 0$, $a_{31} \neq 0$, $a_{32} \neq 0$. The foregoing analysis indicates that the chaotic system presented in Eq. (1) is different from the previous chaotic system. Furthermore, the phase diagram, Lyapunov exponent spectrum and bifurcation diagram of Eq. (1) all have decided the difference. The chaotic attractor in Fig. 1a is a new chaotic attractor, because this chaotic attractor is obtained under the restraint of carbon tax (such as a_4w, b_4w, and $d_1w(y-T)$), so we call it the energy-saving and emission-reduction chaotic attractor with carbon tax constraints.

Based on Lyapunov exponent spectrum and bifurcation diagram, the existence of chaotic attractor could be verified in the sense of numeral simulation. Šilnikov theorem (see [26,27]) could be used to prove Eq. (1) has Smale horseshoes and horseshoes chaos, and the existence of chaotic attractor could be verified in the sense of theoretical proof.

3. Parameter identification and scenario analysis

3.1. Parameter identification

Calculation of $x(t)$ is mainly referred to the algorithm in Ref. [28]. The data of $x(t)$, $y(t)$ and $z(t)$ come from Ref. [25]. There is no carbon tax in China at present. In order to collect more data for dynamic evolution analysis, the initial levy amount of carbon tax could be given, and the levy rate of carbon tax is improved with the increasing carbon emissions. When it goes up to a peak value (the peak value of carbon emissions), the levy rate of carbon tax could be decreased gradually. By observing the dynamic evolution behavior of the four-dimensional system (the four-dimensional energy-saving and emission-reduction system with carbon tax constraints is a continuous dynamic evolution system), the best point to levy carbon tax can be found. The time period when this point appears is the best time to levy carbon tax, and the value this point reflects is the best tax levy point of carbon tax.

Based on the ideas from the countries which had introduced carbon tax and the correlative research [19,29,30], combined with the correlative research of carbon tax in China and China reality [21], we present four protocols of carbon tax, i.e. given the levy amount of carbon tax as 10 ¥/ton CO_2, 15 ¥/ton CO_2, 20 ¥/ton CO_2 and 25 ¥/ton CO_2 in the year of 2000, the levy amount gradually increasing at an annual average rate of about 0.2 ¥/year. The four situations are taken as initial values in the four-dimensional system to make a concrete analysis, and the best-case scenario under the sense of responsible trading carbon emission credits will be obtained after comparing the advantages and disadvantages of the four situations.

Since there is no carbon tax in China at present, in the following scenario analysis, we try to deduce the future dynamic evolution results of the four-dimensional system by available published data. Select a single year as the year to levy carbon tax and the corresponding value as the tax levy point. From this initial value, the dynamic evolution behavior of the four-dimensional system is studied, and integrated dissections are carried out. The data in scenario analysis is from 2000 to 2009, so the year of 2000 is selected as the year to levy carbon tax. Select the data of 2000 as the initial value, carbon tax comes into play gradually with the dynamic development of four-dimensional system, and the dynamic diagram of energy intensity is observed. When the energy intensity of the four-dimensional system with carbon tax constraints is lower than that of the three-dimensional system [25], the data that this situation displays is the exact data we are looking for. Because the four-dimensional energy-saving and emission-reduction system with carbon tax constraints is a continuous dynamic evolution system, let the year when this situation displays as the year to levy carbon tax, the corresponding data as the tax levy point, when the four-dimensional system runs in this situation, carbon tax will work well so as to achieve the goal of reducing the carbon dioxide emissions and keeping proper energy intensity. Based on the correlative researches of carbon tax in China, we give the tax levy point a broader range: 10–25 ¥/ton CO_2, and make an assumption for levy amount gradually increasing at an annual average rate of 0.2 ¥/year. All these assumptions fit China's current actual situation.

Take the situation of 15 ¥/ton CO_2 for example. The data of carbon tax could be obtained from the carbon emissions date in Ref. [25] and the corresponding carbon tax rate, the data of carbon tax of China of the years 2000–2009 can be shown in Table 1.

The data in Table 1 is the calm base development speed.

Combining with statistical data of China in Ref. [25], the parameters of the actual system which are derived by the BP algorithm of artificial neural network [22,25,31,32] are shown in Table 2.

Fix the parameters of Eq. (1) shown in Table 2. Select the data of 2000 as the initial condition. The corresponding phase diagrams of the actual system are observed as shown in Fig. 4a and b. The phase diagrams in Fig. 4 are limit cycles, indicating that the actual system is steady, which meets the actual situation.

The levy amount of carbon tax in the year of 2000 is a hypothetical value, the purpose of which is to get the parameters of the

Table 1
The data of carbon tax of China (2000–2009, 1999 is the base).

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
w	1.1211	1.0646	1.1847	1.4165	1.6658	1.9589	2.0694	2.2586	2.5087	2.6709

Table 2
The parameters of the actual system (1).

a_1	a_2	a_3	a_4	b_1	b_2	b_3	b_4	c_1
0.1352	0.2295	0.1873	0.4263	0.1812	0.4273	0.3782	0.6216	0.4341
c_2	c_3	c_4	d_1	M	C	E	N	T
0.3317	0.5673	0.0852	0.2541	0.6152	0.5749	0.6483	0.5524	0.5521

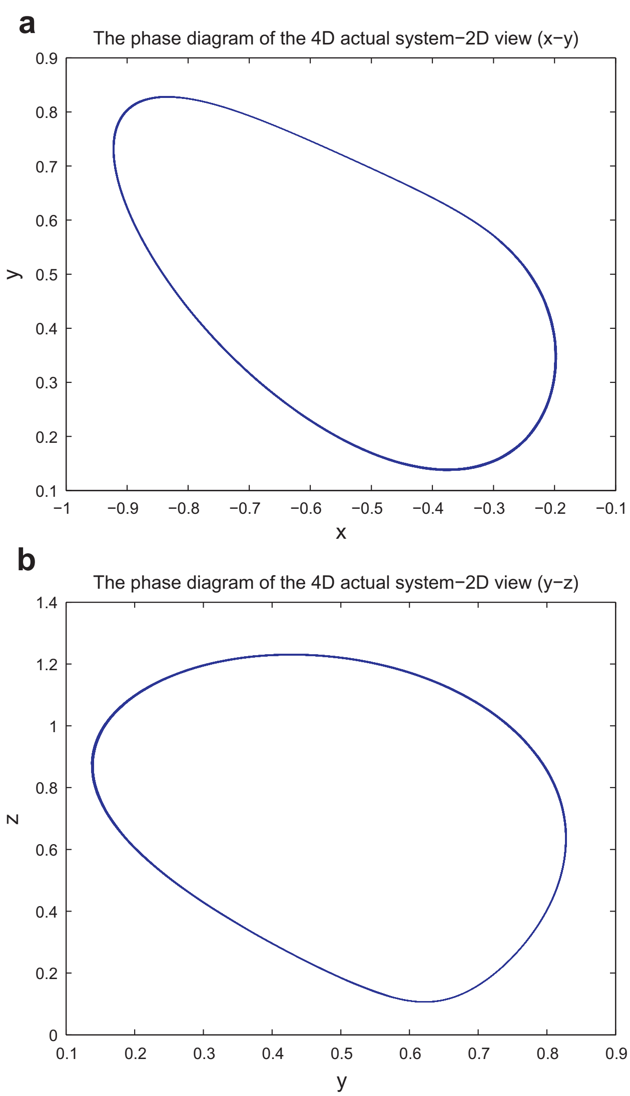

Fig. 4. (a) The phase diagram of the 4D actual system (2*Dx*–*y*). (b) The phase diagram of the 4D actual system (2*Dy*–*z*).

actual system and the initial value of the actual system by artificial neural network, and analyze the dynamic evolution behavior of the actual system. With the levy amount of carbon tax in the year of 2000 changing, the parameters of the actual system and the initial value of the actual system will change accordingly. Of course, the actual system also has different dynamic evolution behavior.

3.2. A scenario analysis

Carbon tax has strong impact on the overall variables of the system and the system as a whole. During the process of energy-saving and emission-reduction research, we find that energy intensity constraint plays a more effective role than overall emissions constraint in the reduction of greenhouse gas emission, economic growth should be taken into account in the progress of energy-saving and emission-reduction, so this paper mainly focuses on its impact on energy intensity and economic growth.

In the study of introducing carbon tax into the energy-saving and emission-reduction system, what time to introduce and how to develop carbon tax are the two critical problems for a better energy-saving and emission-reduction system. The previous researches concerning the above two problems did some aggressive studies, but the models they established are simple, or they only use a questionnaire to survey people's attitudes to these two problems. So the conclusions they reached lack theoretical basis, and are not vivid enough. This section of the research starts - with dynamic evolution behavior of the actual system. The formula of energy intensity is diagramed. By observing the turning point and evolution tendency of energy intensity, dynamic evolution behavior of economic growth and a series of results in perfect agreement with China's actual situation are presented.

3.2.1. The best time to levy carbon tax

First of all, we should take into considerations of the relative merits of the three-dimensional system and four-dimensional system with carbon tax constraints. Fix the parameters as shown in Table 2, select the datum of 15 ¥/ton CO_2 as the initial condition. The parameter C is the peak value of carbon emissions during a given period, which marks the overall emissions and the progress of energy-saving and emission-reduction. Fig. 5 shows the energy intensity of the two actual systems when C is the same. The [1]red curve in Fig. 5 is the energy intensity of the actual three-dimensional system [25], and the blue curve in Fig. 5 is the energy intensity of the actual four-dimensional system with carbon tax constraints. Contrasting the red curve with the blue one, the four-dimensional dynamic evolution system with carbon tax constraints is superior to the three-dimensional dynamic evolution system on the whole, and easier to control. The turning point appears after a stable period, and the final stable value is far smaller than the former one.

With the development of energy-saving and emission-reduction, carbon tax is introduced and goes to work gradually. Each variable of the actual system has corresponding change. The energy intensity of the actual system displays various dynamic evolution behavior. Fig. 6 shows the energy intensity of the actual system

[1] Stable value1 (red curve) corresponds to the three-dimensional system, stable value 2 (blue curve) corresponds to the four-dimensional system.

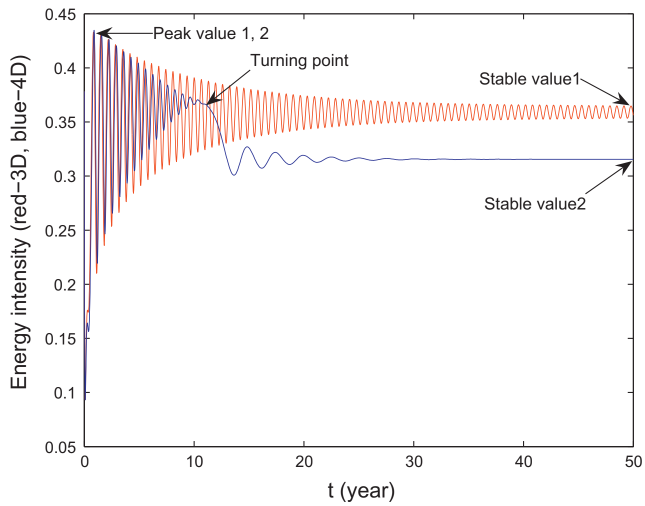

Fig. 5. Energy intensity of the actual system.

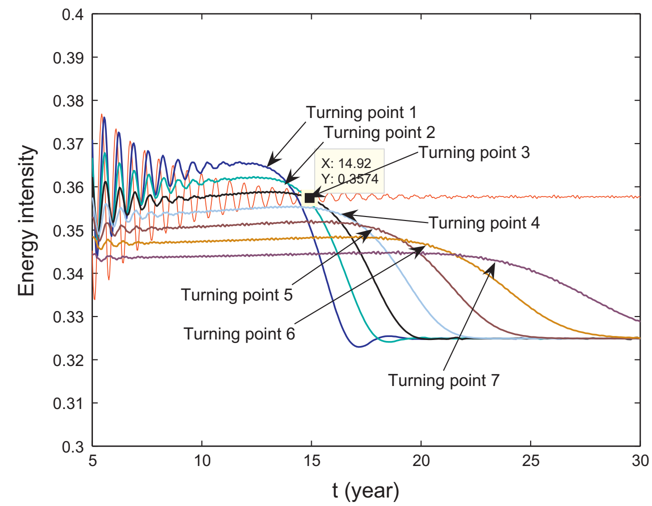

Fig. 7. Energy intensity when the tax levy point is 10 ¥/ton CO_2.

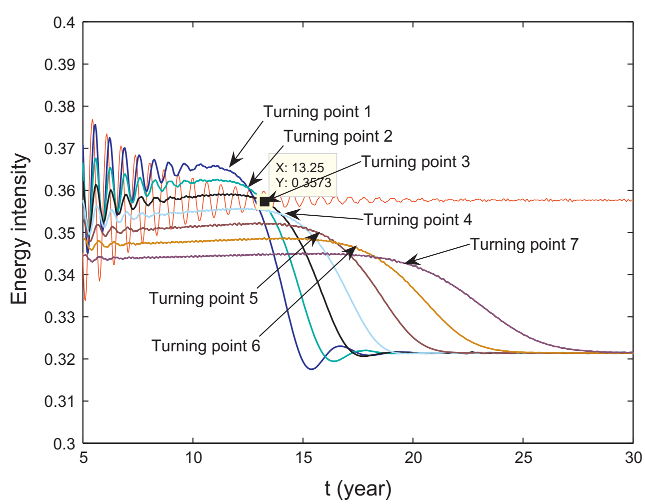

Fig. 6. Energy intensity when the tax levy point is 15 ¥/ton CO_2.

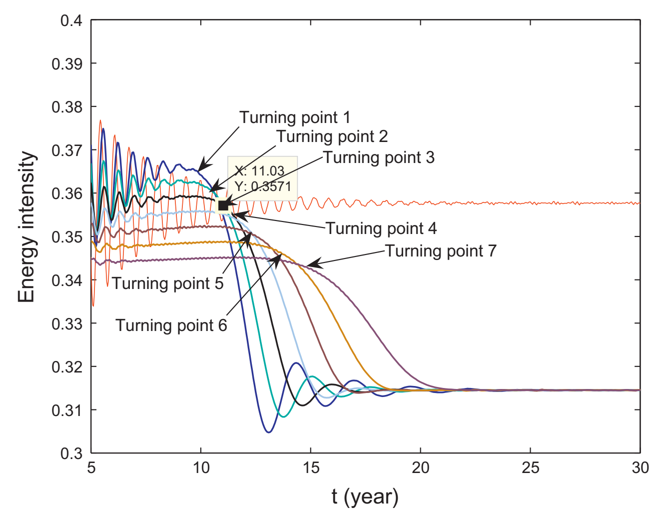

Fig. 8. Energy intensity when the tax levy point is 20 ¥/ton CO_2.

when the initial value is 15 ¥/ton CO_2. The red curve is the energy intensity of the actual three-dimensional system. Turning points 1–7 correspond to the dynamic evolution curve of parameter *C* (different value of *C* corresponds to different stage of development). Comparative observations of the curves in Fig. 6 show that the turning point of energy intensity arrives later and later. The energy intensity of the actual system is bigger than that of the there-dimensional system ([25]) before turning point 1 and turning point 2. It remains basically the same at turning point 3, and is smaller than the there-dimensional system after turning point 3. Based on an overall consideration of various factors, the turning point 3 is the most ideal choice, whose energy intensity is less than or equal to that of the three-dimensional system (the red curve). The turning point of energy intensity arrives not very late. The time when turning point 3 refers to is the year before 2015, i.e. the best time to levy carbon tax in China is 2013–2014, and the best tax levy point is 17.6–17.8 ¥/ton CO_2. Introduce carbon tax into the energy-saving and emission-reduction system at this time, energy intensity could be controlled to an ideal value in a short time.

Fig. 6 shows the diagram of energy intensity formula (2) which is derived from Eq. (1) (the same is Figs. 5–9 and 11). The evolution tendency of energy intensity is demonstrated dynamically and

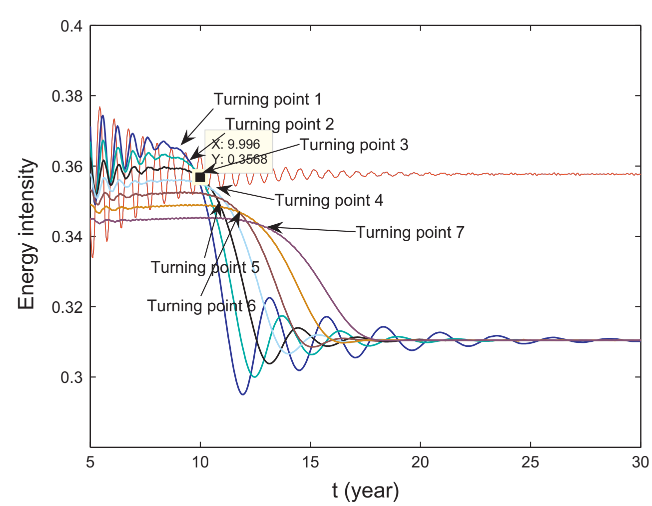

Fig. 9. Energy intensity when the tax levy point is 25 ¥/ton CO_2.

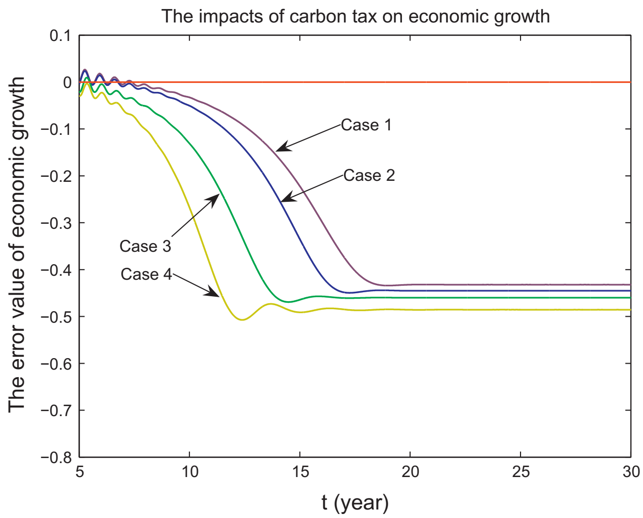

Fig. 10. The error value of economic growth.

intuitionally. When the levy sum of carbon tax is the other three values, the parameters of the actual system and corresponding initial value could be obtained by the methods described above, and we can have the similar dynamic evolution analysis.

Fig. 7 shows the energy intensity's dynamic evolution diagram when the levy sum of carbon tax is 10 ¥/ton O_2. Fig. 8 shows the energy intensity's dynamic evolution diagram when the levy sum of carbon tax is 20 ¥/ton CO_2. Fig. 9 shows the energy intensity's dynamic evolution diagram when the levy sum of carbon tax is 25 ¥/ton CO_2.

Comparative observations of Figs. 6–9 demonstrate the corresponding turning point of energy intensity arrives earlier and earlier with the levy sum of carbon tax increasing gradually. Turning point 3 in each figure is the most ideal choice. The time of turning point 3 in Fig. 7 refers to the year of 2015, and the tax levy point is 13 ¥/ton CO_2; that in Fig. 6 refers to the year of 2013, and the tax levy point is 17.6 ¥/ton CO_2. The time of turning point 3 in Figs. 8 and 9 refer to all before the year of 2012. Fig. 8 refers to the year of 2011, and the tax levy point is 22.2 ¥/ton CO_2; Fig. 9 refers to the year of 2010, and the tax levy point is 27 ¥/ ton CO_2.

From the above findings, the bigger levy sum of carbon tax is, the better energy intensity could be controlled. The inhibitory impacts of carbon tax on economic growth should be considered in the process of controlling energy intensity, and changes in levy sum of carbon tax will affect energy intensity in different ways.

Fig. 10 shows the impacts of carbon tax on economic growth when levy sum of carbon tax changes. Case 1 is the curve when the levy sum of carbon tax is 10 ¥/ton CO_2; case 2 is the curve when the levy sum of carbon tax is 15 ¥/ton CO_2; case 3 is the curve when the levy sum of carbon tax is 20 ¥/ton CO_2; case 4 is the curve when the levy amount of carbon tax is 25 ¥/ton CO_2.

Comparative observations of the curves in Fig. 10 indicate that carbon tax has inhibitory impacts on economic growth. The four curves are all under the curve of zero. The inhibitory impacts increases with the levy sum of carbon tax increasing. When the levy sum of carbon tax increases with the same range, the impacts of carbon tax on economic growth enlarges, i.e. the spacing between the four curves become larger and larger.

Comparative observations of the curves in Figs. 6–10 show that turning point 3 in Fig. 6 has the best controlling effect, whose energy intensity is less than or equal to that of the there-dimensional system, which indicates that carbon tax works well in the energy-saving and emission-reduction system. If the turning point of energy intensity arrives earlier, energy intensity could be controlled to an ideal value as soon as possible. The inhibitory impact on economic growth is not very big. Therefore, it can be concluded that the best time to levy carbon tax in China is the year 2013–2014, and the best tax levy point is 17.6–17.8 ¥/ton CO_2.

Levying carbon tax in China could relieve the international community's pressure on China's emission-reduction. China's overall emissions have overtaken the US becoming number one, with the emissions of average per capita having exceeded the world average level. The fears of China's sharp rise in emissions have converted to the pressure on China's emission-reduction in reality. The policies, such as "carbon tariff" and "import requirements of carbon emission credit" prompt China to take appropriate actions. Levying carbon tax in China could accumulate experience of taking part in redesigning international rules in green economy era. During the green economy times, world order is redefined, the redesign of production, circulation and consumption rules have been launched. China should comply with this trend actively to gain the right of speech in the process of designing future world rules. Levying carbon tax could promote the green reform of China's taxation system. With the help of taxation adjusting, resource and environmental price system could be reconstructed, and the rational utilization of resources could be guaranteed. Levying carbon tax in China could promote the transformation of development patterns too. Taking carbon tax as the base, the green reform of China's taxation system will help promote China's development patterns change from extensive growth pattern to intensive growth pattern.

T is the inflexion of $y(t)$ to $w(t)$; the value of T determines the time to levy carbon tax. Fig. 11 shows the dynamic evolution diagram of energy intensity when T takes different values. The red curve shows the energy intensity of the three-dimensional ESER system without carbon tax; the blue curve shows the energy intensity when $T = 0.5521$; the green curve shows the energy intensity when $T = 0.6021$. Comparative observations of the three curves confirm that when T becomes larger gradually, the stable value of energy intensity is very close to that of the ESER system which has no carbon tax; while the stable value of the blue curve is much smaller than the one of the green curve. When T becomes larger, i.e. the time to levy carbon tax in the ESER system goes later, the more difficult energy intensity could be controlled in the ESER system, at the moment carbon tax has lost its control force with energy intensity. An interesting phenomenon could also be found in Fig. 11, which shows the blue curve is higher than the green one in the brown circle. In contrast with levying carbon tax later

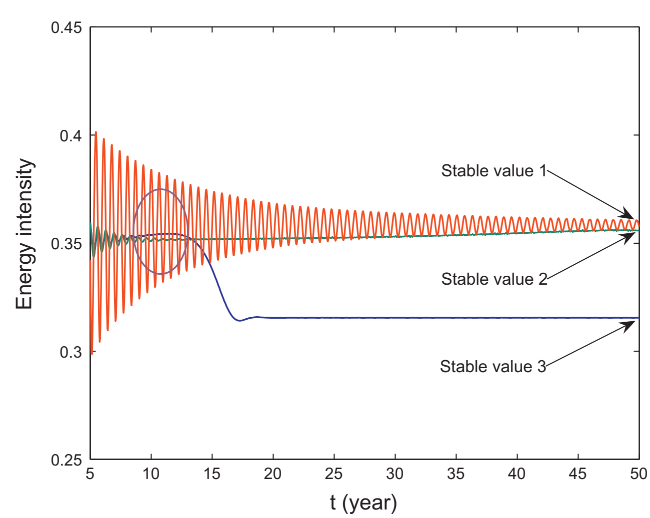

Fig. 11. Energy intensity when T changing.

(now the variables in the ESER system become mature), levying carbon tax earlier will make the value of energy intensity bigger in the early stage of evolution, but the stable value of energy intensity is much smaller than the former one after a short fluctuation. However, this fluctuation problem could be solved by the development of carbon tax (see the following discussion about d_1). To sum up, carbon tax should be levied timely.

The time to levy carbon tax and the tax levy point should suit China's basic conditions. The Ministry of Finance and State Development and Reform Commission (SDRC) issued the report of *China's carbon tax taxation system frame design* (Report for short) in June 2010. The report presented the road map of levying carbon tax in China, and the time to levy carbon tax is about 2012. China implemented refined oil products reform in 2009. The resource tax reform was predicted to implement in 2009–2010, so the initial proposals of levying carbon tax was identified later 1 or 3 years than the resource tax reform (2012–2013). The resource tax reform had been delayed, and the time to levy carbon tax should be postponed correspondingly. This report gave the tax levy point 10–20 ¥/ton CO_2.

Take European 200–300 ¥/ton CO_2 for example, by converting, the cost of every ton of coal rises about 400–600 ¥. If take European tax rate at early stage, China's economic growth and national industry structure will be thwarted noticeably, to which China cannot afford. Considering the impact on economy and the adaptability of enterprises, the tax levy point was expected to be 10–20 ¥/ton CO_2, and the tax rate could gradually increase according to the adaptability of enterprises.

This paper sets up the ESER system with carbon tax constraints, starting with dynamics, evolution tendency of energy intensity and economic growth as measurable indicators. By discussing the dynamic evolution behavior of carbon tax in the ESER system, the best time to levy carbon tax and the right tax levy point are achieved within the framework of the four-dimensional dynamic system: the right time to levy carbon tax in China is 2013–2014, and the best tax levy point is 17.6–17.8 ¥/ton CO_2.

The results are recorded after the evolution analysis of the actual power system and data. By comparing with the results of the Report (the time to levy carbon tax is about 2012, the tax levy point is 10–20 ¥/ton CO_2), the two results is close to each other, but there are also differences between them. Up till now, there have not been enough researches about the time to levy carbon tax and the tax levy point in China. Some studies did present the time to levy carbon tax and the tax levy point, but the results were gained based on very simple linear models, simple contrastive analysis or questionnaire survey. Compared with previous studies, the conclusions drawn in this paper have more theoretic foundation.

Of course, the best time to levy carbon tax is related to technology innovation, existing social, economic and political systems and some other factors such as the extent of public acceptance. This paper makes a new attempt to study the problem from quantitative approach, in view of which only four major correlate factors are considered. The dynamic system which contains more variables will be analyzed in further research.

3.2.2. How to improve effects of carbon tax properly in the energy-saving and emission-reduction system

In the previous section, the problems of the best time to levy carbon tax and the best tax levy point are discussed. The method to improve the effects of carbon tax properly in the energy-saving and emission-reduction system will be discussed in this section, which could decline energy intensity steadily and rapidly, and control carbon emissions within the ideal range. The case of 15 ¥/ton CO_2 is analyzed in this section. d_1 is the development coefficient of carbon tax, which indicates development level of carbon tax, the variation of which will have a great influence on the actual system. Fix the parameters as shown in Table 2, with parameter d_1 being varied. Fig. 12 shows the energy intensity when d_1 becomes larger gradually (Fig. 12 only shows the evolution tendency of energy intensity when d_1 becomes larger. The time which the curves refer to have no definite meanings, the curves are magnified properly so that they could be observed clearly). The red curve shows the energy intensity when $d_1 = 0.3541$; the blue curve shows the energy intensity when $d_1 = 0.5541$; the yellow curve shows the energy intensity when $d_1 = 0.7541$; the green curve shows the energy intensity when $d_1 = 0.9541$. Comparative observations of the four curves confirm that when d_1 becomes larger gradually, the corresponding turning point arrives earlier and earlier, and the values in their curves decline slightly.

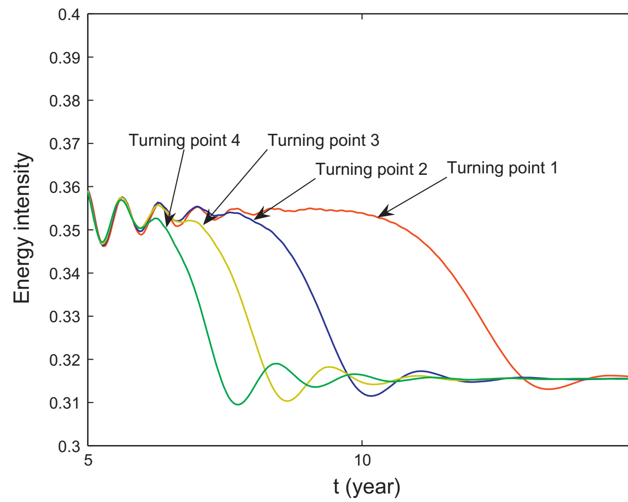

Fig. 12. Energy intensity when d_1 becomes larger gradually.

Fig. 13 shows the impacts of carbon tax on economic growth when d_1 takes the above values. Case 1–4 correspond to the conditions when d_1 becomes larger gradually. Comparative observations of the four curves in Fig. 13 show there are some inhibitory impacts on economic growth when d_1 becomes larger gradually. The four curves are all under the curve of zero. In spite of this, the spacing between the four curves are not very big; when d_1 increases by the same value, the spacing becomes smaller and smaller.

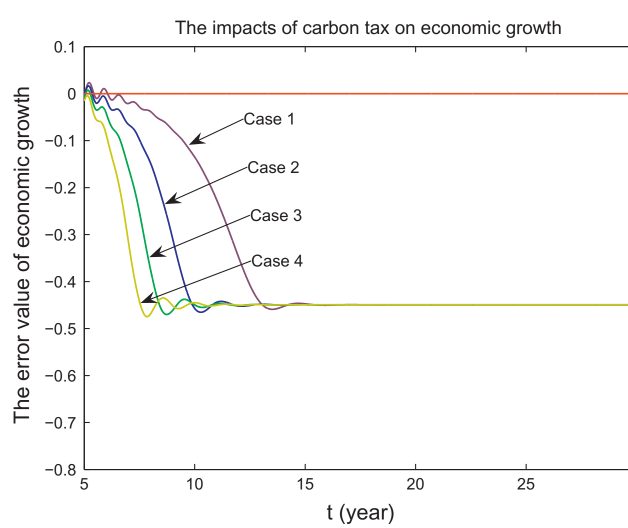

Fig. 13. The error value of economic growth.

The aim of the research is to promote the role of carbon tax in the course of developing energy-saving and emission-reduction system. Thus, it is necessary for the turning point of energy intensity arrives as early as possible, while minimizing the impacts of carbon tax on economic growth and other variables. Based on an overall consideration of various factors, the case in which turning point 4 in Fig. 12 has the best control effect of energy intensity in all the figures discussed above, which has the smallest turning point, the slightest fluctuation, and the inhibitory impacts on economic growth is not every noticeable (comparing with several other value). The results indicate that, to better perform the controlling effects of carbon tax on energy intensity, carbon tax should be further developed properly. More effective corresponding policies and laws should be set down. For example, adopt progressive tax rate. Reduce other taxes and offer subsidy while levying carbon tax. Reduce corporate and personal income tax. Grant energy-saving investment subsidies and lower income group subsidies. Impose more carbon tax on high pollution and high emissions industries, but no carbon tax on enterprises and individuals who use renewable energy, etc.

Carbon emissions could be controlled better and the more energy intensity could be declined by levying carbon tax in the ESER system. With the development of carbon tax, the evolution development of ESER system, the change of economic structure and development patterns, carbon abatement cost will witness its inflection point at some point. The lower carbon abatement cost means the bigger effect of $z(t)$ on $y(t)$, reflected in Eq. (1) is coefficient b_3 gets bigger. When b_3 gets bigger, if the carbon tax policies are unchangeable, the effect of ESER will be effected, even with a fatal impact on the ESER system. Fig. 14 shows dynamic evolution diagram of the energy intensity when $b_3 = 0.4296$. The ESER system is broken down at this moment ($b_3 \geqslant 0.4296$, the ESER system will broken fall).

The current carbon tax policies need to adjust when carbon abatement cost decreases. Within the framework of the four-dimensional dynamic system, this adjustment could be performed by reducing the carbon tax rate and increasing the recycling of the carbon tax revenues into economy, i.e. increasing $c_4''w$. Fig. 15 shows dynamic evolution diagram of the energy intensity when the carbon tax policies changing. The blue curve shows the energy intensity when $d_1 = 0.7541$; the red curve shows the energy intensity when $d_1 = 0.7541$, $b_3 = 0.3696$; the green curve shows the energy intensity when $d_1 = 0.4541$, $c_4 = -0.0452$. Comparative observations of the three curves prove that: when carbon abatement cost decreases and the current carbon tax policies are unchangeable, the fluctuation of energy intensity is relatively large, reflected in Fig. 15. The red curve oscillates more violently than the blue one, when d_1 decreases and c_4'' increases (c_4 decrease), with energy intensity being brought back to the former steady evolution tendency.

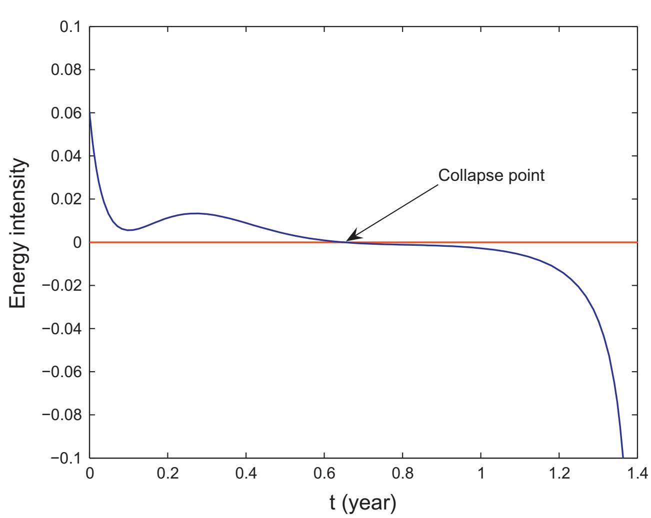

Fig. 14. Energy intensity when $b_3 = 0.4296$.

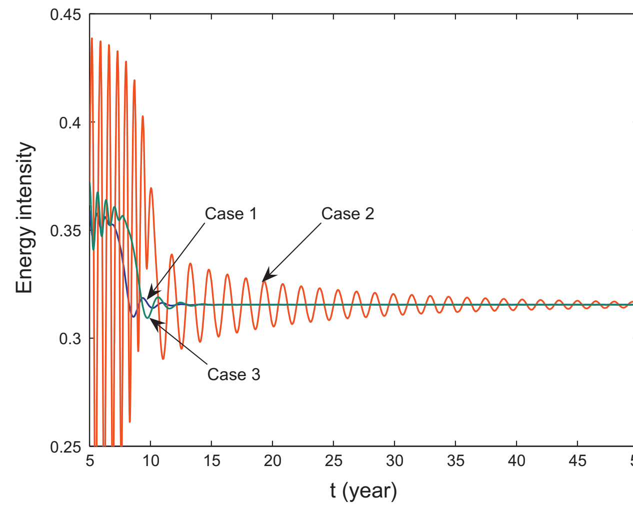

Fig. 15. Energy intensity when carbon tax policies changing.

To sum up, the four-dimensional energy-saving and emission-reduction system with carbon tax constraints is superior to the three-dimensional energy-saving and emission-reduction system in that: the energy intensity and carbon emissions could be controlled more effectively. The best time to levy carbon tax in China is 2013–2014, and the best tax levy point is 17.6–17.8 ¥/ton CO_2.

When carbon tax is further developed properly, more effective corresponding policies and laws are necessary. The impacts of carbon tax on energy-saving and emission-reduction system could play a more preferable role, in controlling the energy intensity better. The carbon tax policies need to adjust when the ESER system changes greatly (such as carbon abatement cost decreases).

3.3. Implications of the study

Previous studies mainly use some basic linear models [14], general equilibrium model [17], the gray model and input–output model [20], etc. The time to levy carbon tax and the impacts of carbon tax on economic growth and other variables were analyzed. Some researchers made innovations in model and method, such as difference-in-difference method [15], China Energy and Environmental Policy Analysis model [18], and SWITCH model [19]. The research findings are fruitful.

This paper starts with dynamics creatively, sets up four-dimensional energy-saving and emission-reduction system with carbon tax constraints and incorporates energy-saving and emission-reduction, carbon emissions, economic growth and carbon tax in a non-linear dynamics system. The time-varying energy intensity calculation formula is derived from the novel four-dimension non-linear dynamics system. The turning point of energy intensity is firstly presented as well as discovered. By observing the evolution tendency of energy intensity and the impacts of carbon tax on economic growth, the best time to levy carbon tax and the best tax levy point are achieved by numerical simulation analysis within the framework of the four-dimensional dynamic system. All of these are innovative research methods. There are not so many researches about the time to levy carbon tax and the tax levy point in China. Some studies presented the time to levy carbon tax and the tax levy point, but the results were gained based on very simple linear models or questionnaire survey, which lack validity and reliability. The conclusions drawn in this research are: the best time to levy carbon tax in China is 2013–2014, and the best tax levy point is 17.6–17.8 ¥/ton CO_2.

Compared with previous studies, both model and scenario analysis are used in this paper, with the theoretic foundation being more fully explained. The findings of the research are more coincident with that of China's reality.

4. Conclusions

Based on the time-varying energy intensity calculation formula, which is derived from the novel four-dimension non-linear dynamics model for energy-saving and emission-reduction with carbon tax constraints, this research has illustrated the impacts of carbon tax on energy intensity. The dynamic behavior of the new system is analyzed, and energy-saving and emission-reduction with carbon tax constraints attractor is achieved. There is no carbon tax in China at present. Data of carbon tax is supposed in reasonable scopes. Coefficients of the actual four-dimension system are obtained based on the artificial neural network. Taking the relative data in China as cases, we analyze the dynamic behavior of the actual four-dimensional energy-saving and emission-reduction dynamic evolution system with carbon tax constraints.

Four initial levy sum of carbon tax are postulated. The turning point of energy intensity and the fluctuation of evolution curve are made as the two main scale targets. A comparative analysis about the dynamic evolution tendency of energy intensity and its consequent influence on economic growth under four assumptions is carried out. The best time to levy carbon tax and the best tax levy point are achieved within the framework of the four-dimensional dynamic system. Moreover, the method to improve the effects of carbon tax properly in the energy-saving and emission-reduction system is discussed.

After the evolution analysis of the actual system, further effects of carbon tax on energy intensity are discovered, and the statistical results which meet the real situation are obtained. The research results indicate that: The four-dimensional energy-saving and emission-reduction system with carbon tax constraints has better performances than the three-dimensional energy-saving and emission-reduction system in controlling carbon emissions and reducing energy intensity. By introducing carbon tax to the energy-saving and emission-reduction dynamic system timely and appropriately, carbon emissions could be easier controlled; hence energy intensity will decline.

Imposing carbon tax duties in developing countries such as China appropriately and timely, and setting up related policies and measures as soon as possible will facilitate the development of energy-saving and emission-reduction prodigiously.

5. Further perspectives

There might be some influence on the output parameters due to the lack of statistical data during the process of parameter identification. In addition, the carbon tax data of China is mainly based on assumption; therefore, more substitution data could be obtained by some more scientific computational methods. The statistical data of other similar countries could also be used. Although we analyzed the evolution behavior of energy-saving and emission-reduction, carbon emissions, economic growth and carbon tax, energy-saving and emission-reduction system contain lots more variables necessary to add and improve. This research is mainly focused on the impact on energy intensity. The impact on economic growth and other variables will be analyzed in the future.

Acknowledgements

The research is supported by the National Natural Science Foundation of China (Nos. 71073072, 51276081 and 71073071), Major Program of the National Social Science Foundation of China (No: 12&ZD062), Doctoral Fund of Ministry of Education of China (No. 20093227110012), Natural Science Foundation of Jiangsu (No. BK2010329), and Natural Science Foundation of the Jiangsu Higher Education Institutions (No. CXLX11_0589).

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