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Revealing the nexus among energy-economy system with Haken Model: Evidence from China's Beijing-Tianjin-Hebei Region

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Abstract

Economic growth (EG) and energy consumption (EC) are interacting, critical to regional sustainability. The evolution mechanism and the nexus between them in the development process of Jing-Jin-Ji Region, which is one of the most important agglomerations in China, remain unrevealed systematically. First, the trends in decoupling state between EG and EC during 2001-2016 are checked with the Impact-Gross domestic product-Technology (IGT) model. Then, EG and EC are defined as two sub-systems to form a whole system, with EG as the fast variable and EC as the slow one. The evolutional interactions among the two subsystems and the whole system are elaborated through the Haken model based on the synergetic theory. By identifying changes in the decoupling index (D_r) and the control variables (a, b, λ_1 and λ_2) simulated by the Haken model, it can be demonstrated that the development of Beijing reached a relatively good state, with synergetic coordination of EG and EC. The effect of EG on EC and EC on EG reversed in Tianjin (from positive to negative) and Hebei (from negative to positive), respectively. EC kept prompting EG in Tianjin and EG kept inhibiting EC in Hebei. Both regions have not achieved a complete synergy of EG and EC, calling for further ameliorations in economic development and energy consumption patterns in a transitional period. This study is a first attempt to apply Haken model in the field of energy and economy from the perspective of synergetics. The exploration of the evolutional nexus between EG and EC in the Jing-Jin-Ji Region is expected to provide important references for policy formulation both locally and for other regions.

Keywords

Economic growth; Energy consumption; Haken model; Synergetics; Evolutional nexus; Jing-Jin-Ji Region.

Variables and coefficients

I	environmental load, total energy consumption (TEC) in paper;
P	population;
A	per capita gross domestic product (GDP);
T	environmental load per unit GDP, energy intensity (EI) in paper;
G	GDP;
e	annual decrease rate of EI;
g	annual growth rate of GDP;
η	annual growth rate of TEC;
D_r	decoupling index;
e_k	the critical value of e;
q_1	state variable, TEC in paper;
q_2	state variable, GDP in paper;
λ_1	damping coefficient reflecting q_1's influence on the system;
λ_2	damping coefficient reflecting q_2's influence on the system;
a	control variable reflecting q_2's influence on q_1;
b	control variable reflecting q_1's influence on q_2.

1. Introduction

In the global context, with the growth of energy consumption accelerated by rapid economic development, the problem of energy supply and demand imbalance has become increasingly prominent (Yang et al., 2017; Tang et al., 2018). It prompts all countries to search for ways to achieve greater economic progress with less energy consumption. According to World Economic Situation and Prospects 2018 report from the UN, world energy consumption reached 123.5 billion tons (oil equivalent) in 2017 (UN, 2017), with China contributing to a third of global energy growth (NBS, 2018). As one of the three economic growth poles in China, the Beijing-Tianjin-Hebei (Jing-Jin-Ji) Region accounts for more than 10% of China's total energy consumption currently (Zhang et al., 2017). Although renewable energy utilization is being boosted vigorously, traditional fossil energy is dominating the energy structure currently, leading to tremendous emissions of greenhouse gases and air pollutants, which is aggravating climate change and the haze phenomenon. The effective and rational coordination of the relationship between regional economic growth and energy consumption is one of critical ways for both energy security and environmental quality regulations. In the above context, this research is motivated to analyze the evolutional nexus between economic growth and energy consumption for formulating more pertinent energy and economic policies.

Energy consumption is driven and affected by various factors, the identification of which is helpful to understand the mechanism of energy consumption. Thus a number of studies have been conducted to investigate the drivers of energy consumption. Some researchers used Logarithmic Mean Divisia Index (LMDI) method to study the factors that governed the changes in China's final energy consumption. The results show that the economic growth effect is found to be primarily responsible for driving final energy consumption. The investment effect and labor effect are also identified as critical affecting factors (Zhang and Song, 2015; Wang et al., 2014; Yu et al., 2017). In addition, some studies adopting hybrid energy input-output model found that energy input mix, industrial structure and technology improvements have great influences on energy demand (Lu, 2018; Chen and Chen, 2015; Igos et al., 2015). It could be found that most influential factors (such as investment, industrial structure, technology improvements) identified are either motivated or closely related to economic growth, which has been playing a key role in promoting the changes in energy consumption continuously. At the meanwhile, energy is also a necessity providing basis for economic activities (Chen, 2018; Narayan, 2016). The interaction between economic growth and energy consumption has major impacts on the robustness of regional development.

Decoupling analysis is recognized as an appropriate method to discuss whether an economy is gradually moving away from energy dependence (Song and Zhang, 2017; Chen et al., 2017). In recent years, many scholars attempted to study the relationship between economic growth and energy consumption or carbon emission with decoupling analysis. The Tapio model and IPAT (I, Impact; P, Population; A, Affluence; T, Technology) model are usually used to evaluate the decoupling state between variables. The former adopts the elastic analysis method to reflect the decoupling relationship between variables and is mainly applied in the researches of carbon emission. For example, Zhou (2017) used big data and Tapio expansion analysis model to analyze the decoupling relationship between regional carbon emissions and economic growth; Dong (2016) used Tapio model combined with the generalized LMDI to explore the decoupling reasons of energy consumption drivers. IPAT model has been repeatedly recognized as a way to explain the decoupling of environmental load and economic growth. The decoupling index is given, making it easier to judge the decoupling state (Wu, 2018; Marques et al., 2018). On the basis of IPAT model, IGT (I, Impact; G, gross domestic product (GDP); T, Technology) model proposed by Lu (2011), which is capable of analyzing the decoupling relationship between energy consumption and economic growth more directly, is an important reference for this paper.

Decoupling analysis of the interaction between economic growth and energy consumption provides superficial results without temporal evolutional details. The study of the nexus between economic growth and energy consumption, which is closely pertinent to energy and environmental policy formulation, remains to be scrutinized. According to many methods exploring the nexus between the two variables, it is a classical idea to start from the perspective of causality. Granger-causality is a widely used method for causality-checking (Ahmed and Azam, 2016; Lin and Moubarak, 2014). Ahmed et al. (2015) used the maximum entropy bootstrap approach to re-examine the nature of causal relationship between energy consumption and economic growth for Pakistan. Shahbaz et al. (2018) used the quantile-on-quantile approach to explore some nuanced features of the energy-growth nexus. However, causality analysis is limited to examining just the cause and effect between variables without the specific interactional mode to be discussed. In addition to causality analysis, in order to avoid the limitation and error of classical regression analysis, co-integration theory is often used in practical problems (Lin and Moubarak, 2014; Kyophilavong et al., 2015). For example, Lin (2014) employed Auto Regressive Distributed Lag (ARDL) approach and Johnson co-integration techniques to investigate the relationship between renewable energy consumption and economic growth. Kyophilavong (2015) applied Bayer and Hanck co-integration approach to test whether the long-run relationship exists between the variables among energy, economy and policy in Thailand. The above studies focused more on causality, leaving insufficiency in the revelation of process and mechanism of the mutual effects between economic growth and energy consumption during progressive temporal stages.

Beyond the above reviewed methods using statistical approaches, this paper attempts to find a new perspective, the synergistics, to explore the evolutional nexus between economic growth and energy consumption. Synergistics is a discipline that studies the mechanism of self-organizing structure of a system under certain conditions through the collaboration among subsystems.

Synergy means that two related individuals' changing processes promote each other and ultimately achieve overall optimization. Considering that energy and economy are two independent but interrelated systems, we draw lessons from Hermann Haken's synergistic theory and analyze the synergistic relationship between the two systems with Haken model (Haken, 1977). Previously, few researchers have ever discussed the energy and economic issues from a systematic perspective. Moreover, the research on the nexus between economic growth and energy consumption based on the synergistic theory is almost blank, although the theory has been practiced in some other fields. Guo (2005) and Zhao (2009) explored the synergies among various industries. Wu (2009) applied the theory of system evolution into the field of resources recycling and reuse. Haken model has also been taken advantage of on studying the evolution mechanism of carbon emission (Hu et al., 2015). Hu's study (2018) on the dominants in the evolution of urban energy metabolism in Beijing provides an important reference for the formulation of Haken model. This paper may potentially open up a new way for future research in the field of energy and economy.

With population growth and urbanization, there will be more agglomerations like the Jing-Jin-Ji Region in the future, where economic growth will continue with intensive energy consumption. It is of significance to manifest whether the mutual effects between economic growth and energy consumption keeps contradicted intractably or tends to be relieved progressively. For the purpose of solving the problem, this study takes the Jing-Jin-Ji Region as a typical study area and focuses on unrevealing the nexus between economic growth and energy consumption, so as to find out the evolutionary mechanism of them. From the perspective of synergetics, this study first delves the decoupling state between economic growth and energy consumption during 2001-2016 with the IGT decoupling model intuitively, and then explores the interactions between economic growth and energy consumption in detail by using Haken model. Finally, with the help of the evolution equations of Haken model, future development of economic growth and energy consumption of the Jing-Jin-Ji Region are extrapolated up to 2030.

The rest of this paper is organized as follows. **Section 2** introduces the methodology of IGT decoupling model and Haken model and presents data sources. **Section 3** shows the results of the IGT decoupling model and Haken model. **Section 4** provides some discussion according to the results and proposes some policy implications. **Section 5** draws conclusions for this research.

2. Method and data

2.1 Decoupling analysis

(1) Decoupling theory

At the end of the 20th century, the Organization for Economic Cooperation and Development (OECD) introduced the concept of decoupling into the field of environment. In some reports of OECD, there are two widely accepted understandings of decoupling between economic growth and energy consumption (OECD, 2002). (a) In a period of time, if the change rate of an environmental indicator, such as resource consumption or pollutant emission, is lower than the economic growth rate, it could be considered that relatively decoupling or weak decoupling occurred within this period. (b) If the total resource consumption is decreasing or the environmental quality is improving along with economic growth, absolute decoupling or strong decoupling is considered to take place during the time. In order to explain the decoupling degree between economic growth and energy consumption with simple indicators, the IGT model and decoupling index are introduced in this study (Lu et al., 2011).

(2) IGT model

In this paper, IGT model derived from the IPAT equation is used to explore the decoupling relationship between the total energy consumption (TEC) and GDP. The follows is a deduction to explain the principle of the IGT model.

$$I = P \times A \times T = G \times T \quad (1)$$

where *I* is environmental load, *P* is population, *A* is per capita GDP and *T* is environmental load per unit GDP. Environmental load may refer to the consumption of various resources or the production of wastes. In addition, *G* is used to replace *P*×*A*, which is GDP. So we have the IGT equation.

In this study, the environmental load is denoted by TEC, and the environmental load per unit GDP is denoted by the energy consumption per unit GDP. The relationship between them can be expressed as follows:

$$I_0 = G_0 \times T_0 \quad (2)$$

$$I_n = G_n \times T_n \quad (3)$$

$$G_n = G_0 \times \left(1+g\right)^n \quad (4)$$

$$T_n = T_0 \times \left(1-e\right)^n \quad (5)$$

where 0 and *n* denote the base year and year *n*, *g* is the annual growth rate of GDP from the base year to year *n*, *e* is annual decrease rate of energy consumption per unit GDP. When GDP grows, *g* is positive; when TEC decreases, *e* is positive.

Substitute Eqs. (5) and (6) for G_n and T_n of Eq. (4), then we have the following Eq. (7).

$$I_n = G_0 \times T_0 \times \left[\left(1+g\right) \times \left(1-e\right)\right]^n \quad (6)$$

If *n*=1, the calculation formula of TEC in the first year will be as:

$$I_1 = G_0 \times T_0 \times \left(1+g\right) \times \left(1-e\right) \quad (7)$$

Eq. (8) represents the annual growth rate of environmental load.

$$\eta = \frac{I_1 - I_0}{I_0} = \frac{I_1}{I_0} - 1 \quad (8)$$

$$\eta = \frac{G_0 \times T_0 \times \left(1+g\right) \times \left(1-e\right)}{G_0 \times T_0} - 1 = \left(1+g\right) \times \left(1-e\right) - 1 \quad (9)$$

As can be seen from the formulas above, TEC of year *n* is equal to that of the base year when $\left(1+g\right) \times \left(1-e\right) = 1$. Now we get the critical value e_k of *e*:

$$e_k = \frac{g}{1+g} \quad (10)$$

The decoupling index D_r is defined as:

$$D_r = \frac{e}{e_k} = \frac{e}{g} \times \left(1+g\right) \quad (11)$$

The following three scenarios are discussed respectively. (a) If $D_r \geq 1$, when $D_r=1$, $e=e_k$, indicating that TEC remains unchanged and is equal to that of the base year. At this time TEC starts to decouple from GDP. When $D_r>1$, $e>e_k$, indicating that TEC decreases year by year while GDP still keeps growing up. At this time, TEC is absolutely decoupled from GDP. (b) If $0<D_r<1$, $0<e<e_k<g$, indicating that TEC increases year by year, but its growth rate is lower than GDP's. At this time, TEC is relatively decoupled from GDP. (c) If $D_r \leq 0$, when $D_r=0$, $e=0$, indicating that TEC increases in step with GDP. When $D_r<0$, $e<0$, indicating that TEC increases year by year and its growth rate is higher than GDP's. And now, TEC is still coupled with GDP.

2.2 Haken model

(1) Synergetics and self-organization theory

Synergetics was founded in the early 1970s by Hermann Haken, a theoretical physicist from the federal republic of Germany. Synergy is the most basic concept in synergetics. A system is composed of many subsystems. If the subsystems cooperate with each other to produce synergistic effect, or cooperative effect, the system is in the state of self-organization.

The research object of the self-organization theory is the formation and development mechanism of a complex self-organized system, that is, how the system moves from disorder to order and from low order to high order spontaneously. The evolution from disorder to order must meet several basic conditions. (a) A self-organized system must be an open system. Only through the exchange of material, energy and information with the outside can the system maintain a stable and orderly structure; (b) when a system progresses from disorder to order, it must be in a state far from thermal equilibrium. Non-equilibrium is the source of order, and an open system must be in a state of non-equilibrium; (c) there are non-linear interactions among the subsystems within the system, which enable synergy among subsystems and make the system orderly from disordered.

(2) Haken model

The main content of synergetics is to use evolution equation to study the dynamic interactions between subsystems. According to the slaving principle, when it comes to the critical point of the process of system evolution, fast variable has disappeared or changed before exerting influence on the system for changing too rapidly, while the slow one changes slowly and becomes the order parameter dominating system evolution (Haken, 1977). Haken model describes the evolution process of the system under the interaction of two variables, in which the slow variable dominates system evolution and has an influence on the fast one. Without considering the random fluctuation terms, the model formulation is shown in Eq. (12) and Eq. (13).

$$\dot{q}_1 = -\lambda_1 q_1 - a q_1 q_2 \quad (12)$$

$$\dot{q}_2 = -\lambda_2 q_2 + b q_1^{\ 2} \quad (13)$$

where q_1 and q_2 are state variables, a, b, λ_1 and λ_2 are control variables.

In practice, q_1 and q_2 denote the quantitative indexes of subsystems; λ_1 and λ_2 are damping coefficients; a and b represent interactions between q_1 and q_2. By analyzing the values of a, b, λ_1 and λ_2, the relationship among q_1, q_2 and the system can be explained.

(a) a reflects the synergistic effect of q_2 on q_1. If a is negative, q_2 promotes q_1; if a is positive, q_2 restrains q_1.

(b) b reflects the synergistic effect of q_1 on q_2. If b is positive, q_1 promotes q_2; if b is negative, q_1 restrains q_2.

(c) λ_1 reflects the influence of q_1 on the whole system. When λ_1 is negative, q_1 has a positive effect on the system; when λ_1 is positive, q_1 has a negative impact on the system.

(d) λ_2 reflects the influence of q_2 on the whole system. When λ_2 is negative, q_2 has a positive effect on the system; when λ_2 is positive, q_2 has a negative impact on the system.

Based on Hermann Haken's theory about synergetics and self-organization, the order parameter, which dominates the process of system evolution, should be identified first when studying the synergy in a system. It is undoubted that energy consumption as a driver for economic growth plays a leading role in the energy-economy system, thus is determined as the order parameter in this study. Hence in this study, TEC is defined as q_1 and GDP is defined as q_2.

Eqs. (12) and (13) can be further discretized and improved as the follows:

$$q_1\left(t+1\right) = (1-\lambda_1)q_1(t) - aq_1(t)q_2(t) \quad (14)$$

$$q_2\left(t+1\right) = (1-\lambda_2)q_2(t) + bq_1(t)^2 \quad (15)$$

(3) Extrapolation equations

Based on the adiabatic elimination method, we can simplify the Haken equation (Haken, 1977). Let the rate of change of the fast variable be 0, that is, let the value of Eq. (13) be 0:

$$-\lambda_2 q_2 + bq_1{}^2 = 0 \quad (16)$$

$$q_2 = \frac{b}{\lambda_2} q_1{}^2 \quad (17)$$

Eq. (17) indicates that q_1 dominates q_2 and the latter varies with the former. Substitute Eq. (17) for q_2 of Eq. (12), then we have the following Eq. (18):

$$\dot{q}_1 = -\lambda_1 q_1 - \frac{ab}{\lambda_2} q_1{}^3 \quad (18)$$

$$\frac{\mathrm{d}q_1}{\mathrm{d}t} = -\lambda_1 q_1 - \frac{ab}{\lambda_2} q_1{}^3 \quad (19)$$

Solve the differential equation Eq. (19) and make α replace λ_1, β replace a, γ replace λ_2 and ρ replace b for subsequent expressions. Eqs. (20) and (21) are the extrapolation equations for the evolution trends of q_1 and q_2.

$$q_1 = \sqrt{\frac{\alpha}{\exp(c-2\alpha t) - \dfrac{\beta\rho}{\gamma}}} \quad (20)$$

$$q_2 = \frac{\alpha\rho}{\lambda \exp(c-2\alpha t) - \beta\rho} \quad (21)$$

where c is a constant term. Since q_2 is dominated by q_1, the extrapolation result of q_2 can also be expressed as Eq. (22).

$$q_2 = \frac{\rho}{\gamma} q_1{}^2 \quad (22)$$

Since TEC has been identified as the slow variable, the extrapolation equations in this study are as follows:

$$TEC = \sqrt{\frac{\alpha}{\exp(c-2\alpha t) - \dfrac{\beta\rho}{\gamma}}} \quad (23)$$

$$GDP = \frac{\rho}{\gamma} TEC^2 \quad (24)$$

2.3 Data sources

The data on TEC and GDP of Beijing, Tianjin and Hebei from 2001 to 2016 can be obtained from the statistical yearbooks of Beijing, Tianjin and Hebei. All economic variables of each year are adjusted to price level in the base year 2001 to make them comparable. The components of TEC, coal, oil, natural gas, heat and electricity are unified as tons of standard coal equivalent (tce). The statistical data of TEC and GDP in the Jing-Jin-Ji Region from 2001 to 2016 are shown in **Table 1**.

Table 1. GDP and TEC in the Jing-Jin-Ji Region from 2001 to 2016.

Year	Beijing	Tianjin	Hebei

	GDP (10^6 yuan)	TEC (10^6tce)	GDP (10^6 yuan)	TEC (10^6tce)	GDP (10^6 yuan)	TEC (10^6tce)
2001	3769.90	42.29	1919.09	29.18	5516.76	121.44
2002	4214.75	44.36	2162.81	30.22	6046.37	134.05
2003	4682.59	46.48	2482.91	32.15	6747.75	152.98
2004	5352.19	51.40	2875.21	36.97	7618.21	173.48
2005	6010.51	55.22	3309.37	41.15	8639.05	198.33
2006	6779.86	59.04	3799.15	45.25	9796.68	217.94
2007	7756.16	62.85	4391.82	49.44	11050.65	235.85
2008	8454.22	63.27	5125.26	53.64	12166.77	243.22
2009	9299.64	65.70	5976.05	58.74	13395.61	254.19
2010	10266.80	69.54	7027.83	68.18	15029.88	262.01
2011	11098.41	69.95	8194.45	75.98	16728.26	280.75
2012	11986.28	71.78	9341.68	82.08	18350.90	287.62
2013	12909.23	67.24	10509.39	78.82	19855.67	296.64
2014	13864.51	68.31	11570.84	81.45	21146.29	293.20
2015	14821.16	68.53	12658.49	82.60	22584.24	293.95
2016	15829.00	69.62	13810.42	82.45	24119.96	297.94

3. Results

3.1 Economic growth and energy consumption

GDP and TEC of three regions are compared respectively, and the corresponding annual change rates are calculated. According to the results, both economic growth and energy consumption are steady but at a lowering speed. As presented in **Fig. 1**, in the past 16 years, economic development in the Jing-Jin-Ji Region underwent continuous growth with an increase rate between 6.5% and 12%. However, the growth rate showed a gradually declining trend. Stepping into the 21st century, China experienced rapid economic development, however increasingly serious environmental problems, including the staggering air pollution in the north China, especially the Jing-Jin-Ji Region. The air pollutants were primarily caused by exceeding fossil energy consumption. To cope with the air environmental problems, a series of measures have been adopted locally, including the policy of energy conservation and emission reduction, which explains why the growth rate of TEC presents a fluctuated downward trend in the past decade, as depicted in **Fig. 2**. The bottom of the energy consumption growth rate in all three regions might be related to the stringent control of environmental quality after 2008 Beijing Olympic Games.

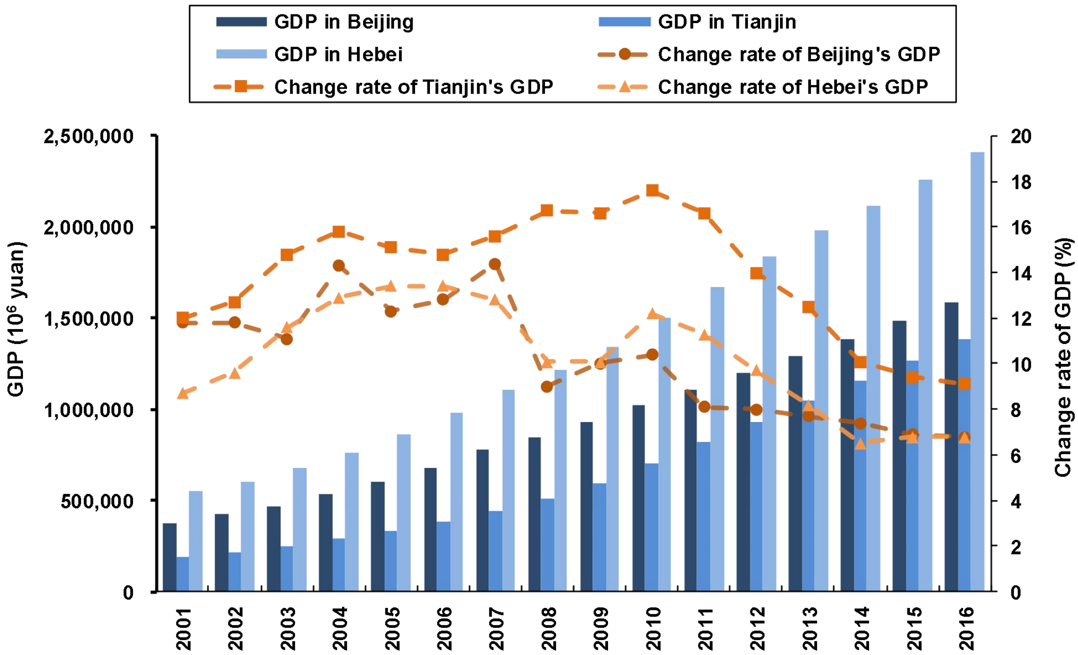

Fig. 1. GDP and its change rate in the Jing-Jin-Ji Region (2001-2016)

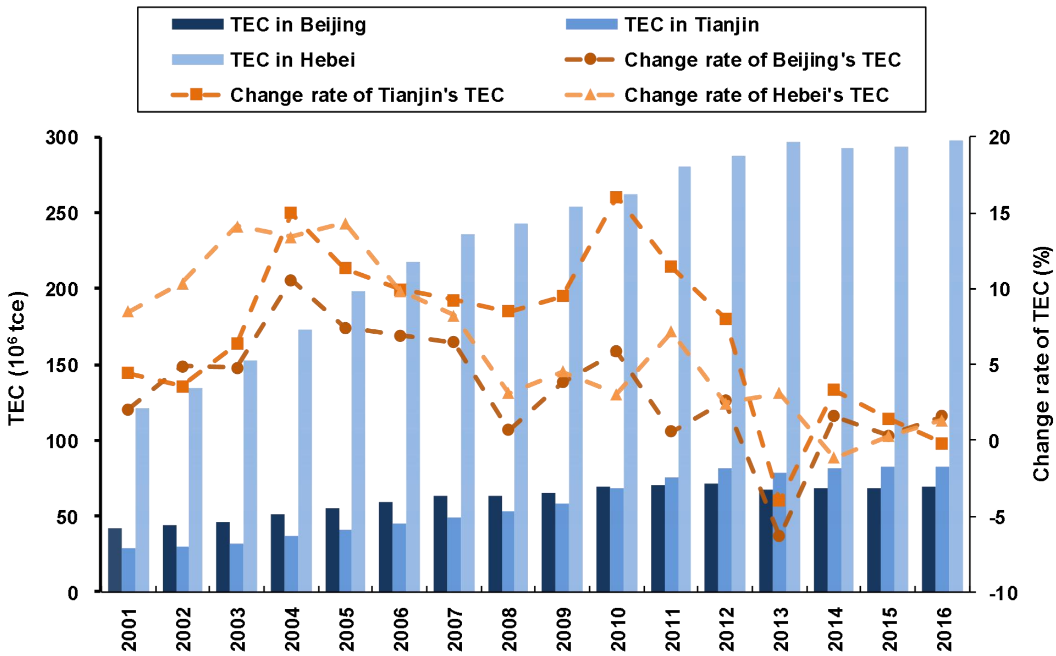

Fig. 2. TEC and its change rate in the Jing-Jin-Ji Region (2001-2016)

3.2 Decoupling analysis

Through the observation of the changes in GDP and TEC in the Jing-Jin-Ji Region from 2001 to

2016, it could be found that there exists a gap between the change rate of GDP and TEC. As delineated in **Table 2**, a decoupling analysis is carried out to verify whether there is a possibility of decoupling between GDP and TEC. **Fig. 3** shows the changes in the decoupling coefficient D_r in three regions within the study period. The values of D_r of Beijing and Tianjin are between 0 and 1, indicating that TEC in Beijing and Tianjin kept relatively decoupled from GDP within 2001-2016. D_r goes through a process of decreasing then increasing. GDP and TEC in Beijing and Tianjin had a strong correlation around 2003, after which the correlation gradually weakened. TEC in Hebei changed from coupled with to relatively decoupled from GDP after 2005. It is obviously that the values of D_r of three regions will remain stable between 0 and 1 in the future with an increasing trend, implying that GDP and TEC will be relatively decoupled in the future for a period of time, and the decoupling degree will be enhanced to a certain extent.

Table 2. Results of decoupling state between GDP and TEC in the Jing-Jin-Ji Region (2001-2016).

Region	Year	TEC (10^6 tce)	GDP (10^6 yuan)	EI	g	e	e_k	D_r	Decoupling State
Beijing	2001	42.29	376990.00	1.122	-	-	-	-	-
	2002	44.36	421474.82	1.053	11.800	6.179	0.106	0.585	Relatively decoupled
	2003	46.48	468258.53	0.993	11.449	5.933	0.103	0.578	Relatively decoupled
	2004	51.40	535219.49	0.960	12.392	5.051	0.110	0.458	Relatively decoupled
	2005	55.22	601051.49	0.919	12.369	4.871	0.110	0.443	Relatively decoupled
	2006	59.04	677986.08	0.871	12.455	4.939	0.111	0.446	Relatively decoupled
	2007	62.85	775616.08	0.810	12.777	5.277	0.113	0.466	Relatively decoupled
	2008	63.27	845421.53	0.748	12.229	5.619	0.109	0.516	Relatively decoupled
	2009	65.70	929963.68	0.707	11.948	5.616	0.107	0.526	Relatively decoupled
	2010	69.54	1026679.90	0.677	11.775	5.452	0.105	0.518	Relatively decoupled
	2011	69.95	1109840.97	0.630	11.402	5.602	0.102	0.547	Relatively decoupled
	2012	71.78	1198628.25	0.599	11.088	5.547	0.100	0.556	Relatively decoupled
	2013	67.24	1290922.63	0.521	10.802	6.194	0.097	0.635	Relatively decoupled
	2014	68.31	1386450.90	0.493	10.537	6.133	0.095	0.643	Relatively decoupled
	2015	68.53	1482116.01	0.462	10.273	6.135	0.093	0.659	Relatively decoupled
	2016	69.62	1582899.90	0.440	10.038	6.052	0.091	0.663	Relatively decoupled
Tianjin	2001	29.18	191909.00	1.521	-	-	-	-	-
	2002	30.22	216281.44	1.397	12.700	8.103	0.113	0.719	Relatively decoupled
	2003	32.15	248291.10	1.295	13.745	7.719	0.121	0.639	Relatively decoupled
	2004	36.97	287521.09	1.286	14.426	5.438	0.126	0.431	Relatively decoupled
	2005	41.15	330936.77	1.243	14.594	4.904	0.127	0.385	Relatively decoupled
	2006	45.25	379915.42	1.191	14.635	4.766	0.128	0.373	Relatively decoupled
	2007	49.44	439182.22	1.126	14.796	4.885	0.129	0.379	Relatively decoupled

	2008	53.64	512525.65	1.047	15.066	5.197	0.131	0.397	Relatively decoupled
	2009	58.74	597604.91	0.983	15.256	5.307	0.132	0.401	Relatively decoupled
	2010	68.18	702783.38	0.970	15.514	4.870	0.134	0.363	Relatively decoupled
	2011	75.98	819445.42	0.927	15.623	4.825	0.135	0.357	Relatively decoupled
	2012	82.08	934167.77	0.879	15.474	4.864	0.134	0.363	Relatively decoupled
	2013	78.82	1050938.75	0.750	15.223	5.720	0.132	0.433	Relatively decoupled
	2014	81.45	1157083.56	0.704	14.821	5.752	0.129	0.446	Relatively decoupled
	2015	82.60	1265849.41	0.653	14.425	5.864	0.126	0.465	Relatively decoupled
	2016	82.45	1381041.71	0.597	14.062	6.043	0.123	0.490	Relatively decoupled
Hebei	2001	121.44	551676.00	2.201	-	-	-	-	-
	2002	134.05	604636.90	2.217	9.600	-0.709	0.088	-0.081	Coupled
	2003	152.98	674774.78	2.267	10.595	-1.483	0.096	-0.155	Coupled
	2004	173.48	761820.72	2.277	11.358	-1.135	0.102	-0.111	Coupled
	2005	198.33	863904.70	2.296	11.865	-1.055	0.106	-0.099	Coupled
	2006	217.94	979667.93	2.225	12.171	-0.211	0.109	-0.019	Coupled
	2007	235.85	1105065.42	2.134	12.275	0.514	0.109	0.047	Relatively decoupled
	2008	243.22	1216677.03	1.999	11.962	1.368	0.107	0.128	Relatively decoupled
	2009	254.19	1339561.41	1.898	11.727	1.839	0.105	0.175	Relatively decoupled
	2010	262.01	1502987.90	1.743	11.780	2.559	0.105	0.243	Relatively decoupled
	2011	280.75	1672825.54	1.678	11.732	2.676	0.105	0.255	Relatively decoupled
	2012	287.62	1835089.61	1.567	11.546	3.041	0.104	0.294	Relatively decoupled
	2013	296.64	1985566.96	1.494	11.263	3.178	0.101	0.314	Relatively decoupled
	2014	293.20	2114628.81	1.387	10.889	3.493	0.098	0.356	Relatively decoupled
	2015	293.95	2258423.57	1.302	10.592	3.684	0.096	0.385	Relatively decoupled
	2016	297.94	2411996.38	1.235	10.335	3.779	0.094	0.403	Relatively decoupled

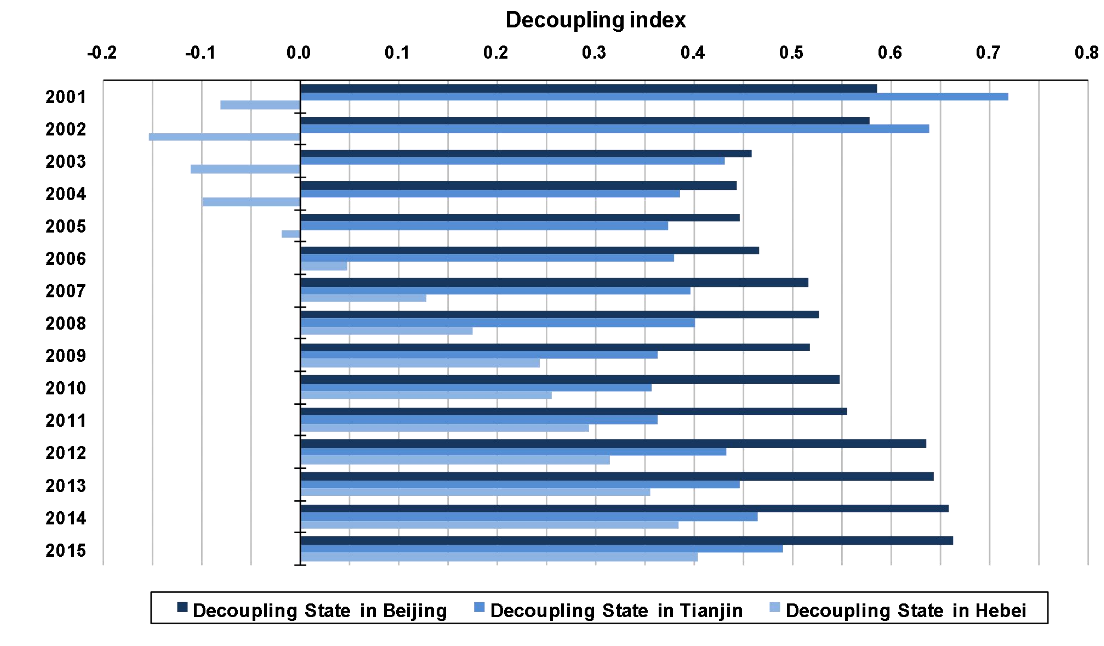

Fig. 3. Decoupling state of GDP and TEC in the Jing-Jin-Ji Region (2001-2016)

3.3 Results of the Haken model

TEC in the Jing-Jin-Ji Region was coupled with or relatively decoupled from GDP within 2001-2016, which indicates that TEC's evolution during this period still had an impact on GDP's. Therefore, economic growth and energy consumption are taken as a holistic system to analyze the nexus between the economic subsystem and energy subsystem.

Experience has verified that energy consumption plays a leading role in the energy-economy system (As economic growth definitely depends on energy consumption, while energy consumption is induced by multiple factors among which economic growth is one.), thus is determined as the order parameter. The values of GDP and TEC of three regions from 2001 to 2016 are put into Eqs. (15) and (16) for fitting using Eviews. Considering several critical events occurred (such as the establishment of Ministry of Environmental Protection in 2008, the 2008 Beijing Olympic Games and so on) with significant impacts on the evolution of the energy-economy system, the whole study period is separated into two periods: 2001-2008 and 2009-2016. **Table 3** shows the model fitting results of Beijing, Tianjin and Hebei, respectively. As appeared in **Fig. 4**, **Fig. 5**, and **Fig. 6**, the values of the coefficients *a* and *b* reflect the interactions between the evolution of GDP and TEC and the values of the coefficients λ_1 and λ_2 reflect the effect of the evolution of GDP and TEC on that of the energy-economy system.

Table 3. Fitting results of the Haken model.

Region	Stage	Model results	Comment
Beijing	2001-2008	$e(t+1) = \underset{(-2.67)}{1.131}e(t) - \underset{(1.57)}{1.276\times10^{-5}}e(t)g(t)$	Model is effective
		$g(t+1) = \underset{(-0.83)}{1.204}g(t) - \underset{(-0.34)}{1.682\times10^{-5}}e(t)e(t)$	
	2009-2016	$e(t+1) = \underset{(-0.69)}{1.069}e(t) - \underset{(0.62)}{5.116\times10^{-6}}e(t)g(t)$	Model is effective
		$g(t+1) = \underset{(-1.55)}{1.027}g(t) + \underset{(2.84)}{1.275\times10^{-5}}e(t)e(t)$	
Tianjin	2001-2008	$e(t+1) = \underset{(-1.72)}{1.086}e(t) + \underset{(-0.15)}{2.200\times10^{-6}}e(t)g(t)$	Model is effective
		$g(t+1) = \underset{(-2.64)}{1.095}g(t) + \underset{(1.69)}{1.192\times10^{-5}}e(t)e(t)$	

	2009-2016	$e(t+1)=\underset{(-2.92)}{1.244}e(t)-\underset{(2.51)}{2.105\times10^{-5}}e(t)g(t)$ $g(t+1)=\underset{(0.43)}{0.961}g(t)+\underset{(1.72)}{2.499\times10^{-5}}e(t)e(t)$	Model is effective
Hebei	2001-2008	$e(t+1)=\underset{(-6.25)}{1.263}e(t)-\underset{(4.15)}{1.956\times10^{-5}}e(t)g(t)$ $g(t+1)=\underset{(-3.39)}{1.124}g(t)-\underset{(-0.11)}{9.107\times10^{-8}}e(t)e(t)$	Model is effective
	2009-2016	$e(t+1)=\underset{(-2.41)}{1.120}e(t)-\underset{(2.01)}{5.354\times10^{-6}}e(t)g(t)$ $g(t+1)=\underset{(1.34)}{0.001}g(t)+\underset{(2.45)}{4.168\times10^{-6}}e(t)e(t)$	Model is effective

As depicted by **Fig. 1** and **Fig. 2**, seen overall, GDP's evolution presented as keeping increasing continuously, with fluctuantly accelerating growth rate in the first period and with slowly decelerating growth rate in the second period. TEC's evolution presented as keeping increasing in the first period and tending to be stable in the second period, with fluctuantly decelerating growth rate. The details of the nexus between two variables for each region are stated as follows.

(A) Beijing.

(a) From 2001 to 2008, $a=1.276E\text{-}05>0$, $b=-1.682E\text{-}05<0$, $\lambda_1=-0.131<0$, $\lambda_2=-0.204<0$.

$a>0$ and $b<0$ indicate that the evolution of GDP and TEC had negative impacts on each other. $\lambda_1<0$ and $\lambda_2<0$ indicate that the evolution of GDP and TEC both had positive effects on that of the energy-economy system.

(b) From 2009 to 2016, $a=5.116E\text{-}06>0$, $b=1.275E\text{-}05>0$, $\lambda_1=-0.069<0$, $\lambda_2=-0.027<0$.

$a>0$ and $b>0$ indicate that GDP's evolution had negative impacts on TEC's, while TEC's evolution had positive impacts on GDP's. $\lambda_1<0$ and $\lambda_2<0$ indicate that the evolution of GDP and TEC both had positive feedbacks on that of the energy-economy system.

GDP's evolution had negative effect on TEC's during both periods. It indicates that economic growth of Beijing had an inhibitory effect on energy consumption growth to some extent. During the second period, the inhibitory effect was enhanced, suggesting the transition to better economic development patterns. In the early 21st century, Beijing's policy of promoting the development of service industries and restraining that of the energy-intensive industries accelerated the improvement of overall energy efficiency. The effect of TEC's evolution on GDP's changed from negative to positive. Such a transition signifies better energy consumption patterns of Beijing during the second period that contributed to synergistic effect on economic growth. As innovations and upgrading of technologies, lower energy turned to be capable of producing more economic benefits, at the meanwhile resulting in less environmental impacts.

In both periods, the evolution of GDP and TEC had positive feedbacks on the energy-economy system. It indicates that the development of Beijing's energy and economy conforms to the objective law, and the system is in good condition.

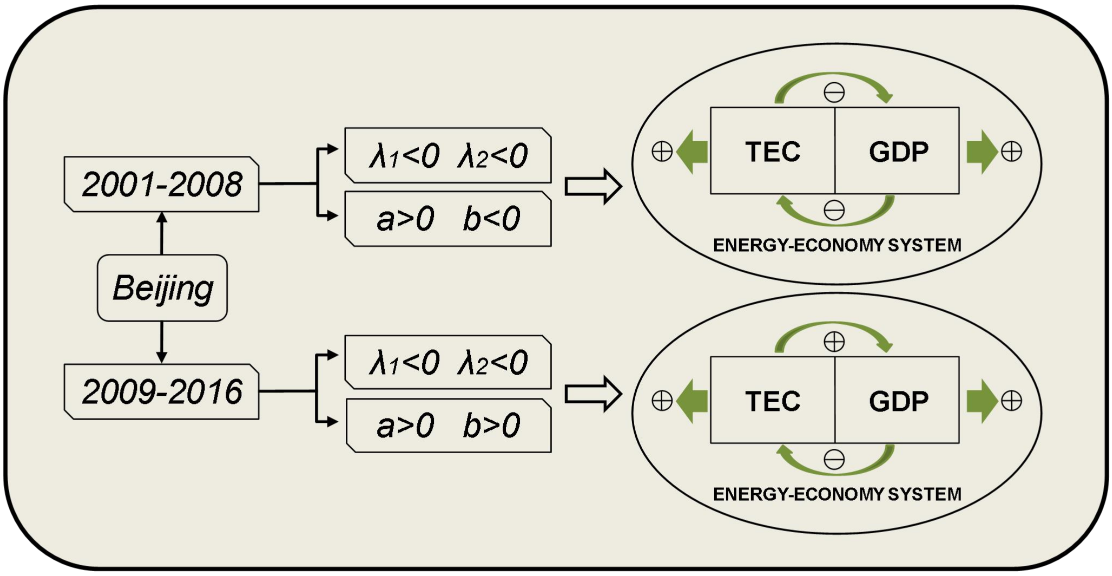

Fig. 4. The interaction between GDP's and TEC's evolution and the effects on the energy-economy system in **Beijing**.

(B) Tianjin.

(a) From 2001 to 2008, a=-2.200E-06< 0, b=1.192E-05>0, $\lambda_1=-0.086<0$, $\lambda_2=-0.095<0$.

a<0 and *b*>0 indicate that the evolution of GDP and TEC had positive impacts on each other. λ_1<0 and λ_2<0 indicate that the evolution of GDP and TEC both had positive feedbacks on that of the energy-economy system.

(b) From 2009 to 2016, a=2.105E-05>0, b=2.499E-05>0, $\lambda_1=-0.244<0$, $\lambda_2=0.039>0$.

a>0 and *b*>0 indicate that GDP's evolution had negative impacts on TEC's, while TEC's evolution had positive impacts on GDP's. λ_1<0 and λ_2>0 indicate TEC's evolution had positive feedbacks on that of the energy-economy system, while GDP's evolution had the opposite.

In the first period economic growth accelerated energy consumption growth in Tianjin, while in the second period the effect reversed to be inhibitory. The previous economic development patterns focused on GDP growth excessively, which aggravated energy consumption. As the local government attached more importance to environment protection, the economic development strategies were adjusted with a transition to ensuring steady economic growth (which is termed as economic development with high quality currently) while reducing energy consumption as much as possible. TEC's evolution had an increasingly enhanced positive effect on GDP's, spanning two periods. It proves the continuous amelioration of the energy consumption patterns reflected as the increase the energy efficiency and decrease in energy intensity.

TEC's evolution had positive effects on the energy-economy system in both periods, while GDP's presented negative impacts in the second period. This implies that although the level of energy consumption is within a reasonable range, economic growth and energy consumption have not come to a holistic synergy. The policies to facilitate to better economic development patterns (e.g. further optimization of industrial structure) are still in need in Tianjin.

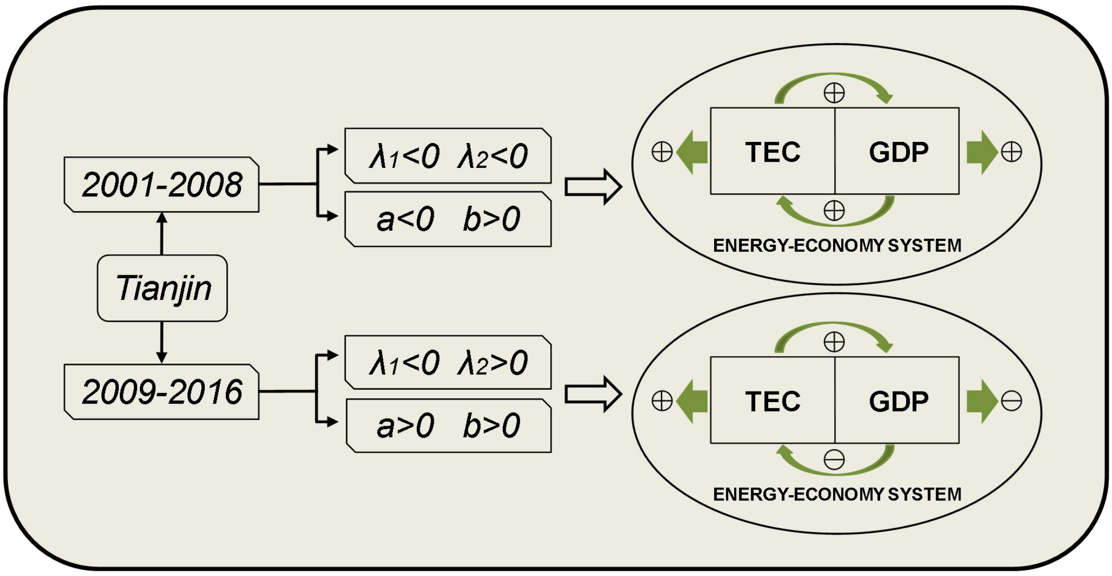

Fig. 5. The interaction between GDP's and TEC's evolution and the effects on the energy-economy system in **Tianjin**.

(C) Hebei

(a) From 2001 to 2008, a=1.956E-05>0, b=-9.107E-08<0, λ_1=-0.263<0, λ_2=-0.124<0.

a>0 and *b*<0 indicate that the evolution of GDP and TEC had negative impacts on each other. λ_1<0 and λ_2<0 indicate that the evolution of GDP and TEC both had positive effect on that of the energy-economy system.

(b) From 2009 to 2016, a=5.354E-06>0, b=4.168E-05>0, λ_1*=-0.120<0,* λ_2*=0.099>0.*

a>0 and *b*>0 indicate that GDP's evolution had negative impacts on TEC's, while TEC's evolution had positive impacts on GDP's. λ_1<0 and λ_2>0 indicate TEC's evolution had positive feedbacks on that of the energy-economy system, while GDP's evolution had the opposite.

The evolutional trends in both periods in Hebei are similar to those in Beijing, as reflected by **Fig. 1** and **Fig. 2**. In both periods, economic growth in Hebei had an inhibitory effect on energy consumption and the inhibitory effect increased during the second period. This proves a healthier trend in economic development patterns. The relatively balanced industrial layouts keep energy consumption in Hebei at appropriate levels so that economic growth and energy efficiency can be guaranteed simultaneously. The effect of TEC's evolution on GDP's changed from negative to positive between two periods, reflecting the outcomes of the reform in energy consumption patterns in Hebei.

The positive feedback of TEC's evolution on the energy-economy system lasted across two periods, while that of GDP's transferred from positive to negative. The adjustment of the industrial structure and the cutting-overcapacity policy may have made an impact on the synergy of Hebei's energy and economy. This could be hopefully regarded as a transitional period.

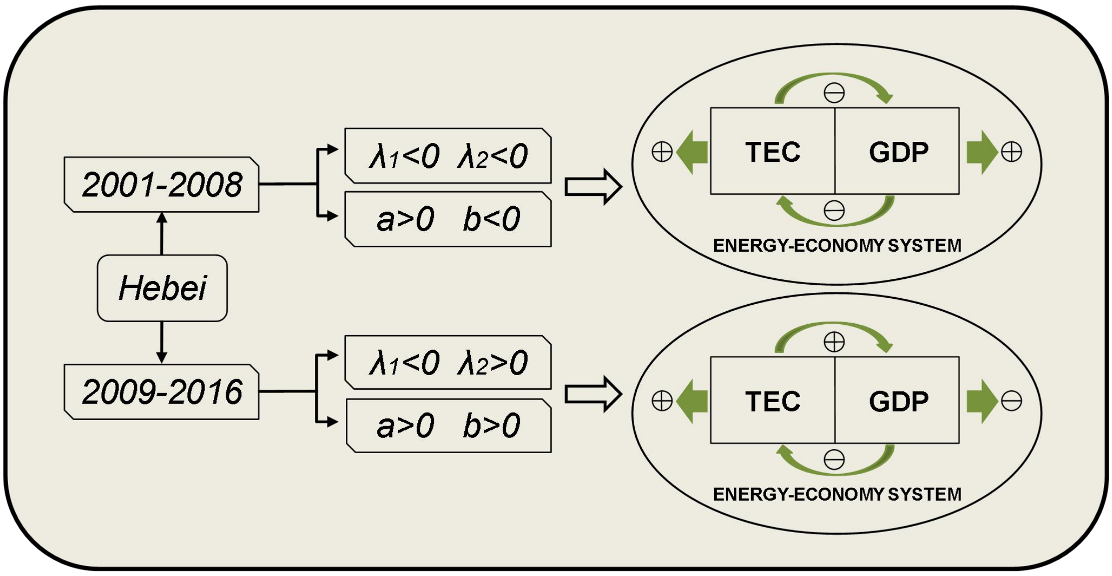

Fig. 6. The interaction between GDP's and TEC's evolution and the effects on the energy-economy system in **Hebei**.

3.4 Extrapolation of trends in economic growth and energy consumption

Based on the IGT decoupling model and Haken model, the relationship and interaction between economic growth and energy consumption in the Jing-Jin-Ji Region from 2001 to 2016 have been analyzed. The development trends in GDP and TEC in three regions are also noteworthy. Therefore, we use the extrapolation equations in Haken model to extrapolate the possible development trends of the two variables until 2030 based on the data of the past 16 years. The extrapolation equations of GDP and TEC for three regions and the parameters are provided in **Table 4**. **Fig. 7** illustrates the trends in GDP and TEC from 2001 to 2030. Meanwhile, the actual statistics of GDP and TEC from 2001 to 2016 are also presented for comparison.

It can be observed from **Fig. 7** that the evolution of GDP and TEC in Beijing and Hebei may enter a stable period with slow growth in the future that tends to be constant. A different trend may appear in Tianjin for GDP and TEC, where the emerging of the constant states for both variables tends to be prolonged. It could be asserted that the slowdown of economic growth is an inevitable trend, and energy consumption will enter a period of dynamic balance ultimately. Since the results of the extrapolation are disturbed by early data and the changes in two variables are heavily influenced by policy, the results may somewhat differ from actual trends. However, from the perspective of evolution, the possibility of achieving dynamic balance of both still exists.

Table 4. The values of control parameters of the extrapolation model.

Region	Extrapolation equation	*α*	*β*	*c*	*ρ/γ*
Beijing	$E=\sqrt{\frac{0.0783}{\exp(-0.8194-0.1566t)+0.0811}}$ $G=24.64E^2$	0.0783	-0.00329	-0.82	24.64
Tianjin	$E=\sqrt{\frac{0.0770}{\exp(-0.38714-0.154t)+0.0251}}$ $G=17.064E^2$	0.0770	-0.00147	-0.39	17.06

Hebei	$E=\sqrt{\dfrac{0.0732}{\exp(-3.5720-0.1464t)+3.9377\times10^{-3}}}$ $G=2.33E^2$	0.0732	-0.00169	-3.57	2.33

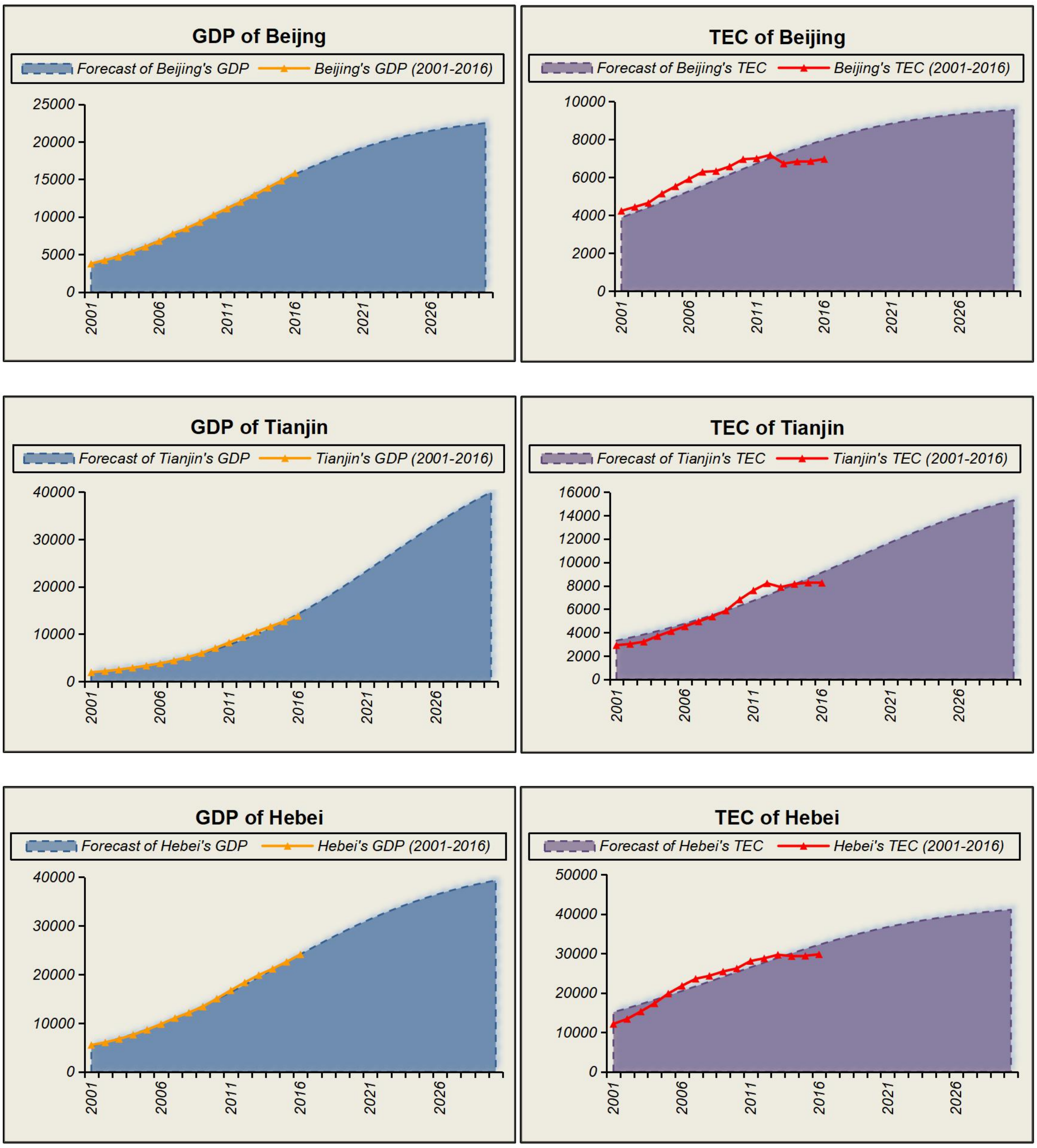

Fig. 7. Extrapolations of the trends in GDP and TEC in the Jing-Jin-Ji Region up to 2030

4. Discussion and policy implications

(1) Comparison of the Haken model with other methods

Granger causality, co-integration and other econometrical methods are widely used in the existing studies to manifest the long-term steady relationship between regional energy and economy within a certain stage. The results place emphasis on the effect of one of the variables on the other, without demonstrating respective effect on the entirety of the two variables. There is still blank in the dynamic analysis of the nexus between economic growth and energy consumption during evolutional processes. In order to reflect on the evolution of energy and economy from a new perspective, this study introduces the idea of system theory and synergetics. The advantage of the Haken model is that it can analyze the interaction between the subsystems that consists of the system and the influence of the subsystems on the system. Compared with other methods, Haken model can express the mode of action through coefficients (a, b, λ_1 and λ_2). This study is a new attempt to analyze the problem of energy and economy from the perspective of synergectics and self-organization. However, due to the lack of practical cases and the complexity of modeling theory, only a preliminary attempt at the provincial level was made, and the reliability of the model still needs more exploration to verify. In the future, scholars may consider continuing to carry out similar studies with the application of Haken model at the city-level or industry-level.

(2) Findings for Beijing, Tianjin and Hebei

Beijing is the important political, economic and cultural center of China. Over nearly the past two decades, economic growth curbed the surge in energy consumption, while energy consumption has gradually produced synergies with economic growth (a changes from 1.28×10^{-5} to 5.12×10^{-6} and b changes from -1.68×10^{-5} to 1.28×10^{-5}). Before 2008, Beijing witnessed continuous economic growth, along with high energy consumption level and low energy efficiency (1.00×10^{4} yuan/tce in average). The increasingly serious air pollution problem impelled the optimization of energy governance and intensification of adjustment of industrial and product structure. With the 2008 Beijing Olympics as an opportunity, energy consumption reduction got greater attention. Beijing has made remarkable achievements in structural adjustment, with the proportion of the tertiary industry rising steadily (80.2% in 2016) and energy efficiency continuously improved (from 1.48×10^{4} yuan/tce in 2010 to 2.03×10^{4} yuan/tce in 2016) since 2008. The existing tremendous momentum will continue to promote Beijing's energy and economic transformation and development.

Tianjin is one of the industrial and commercial hubs directly governed under the central government. Within the study period, energy consumption maintained positive to economic growth, and economic growth evolved from promoting to inhibiting energy consumption (a

changes from -2.20×10^{-6} to 2.11×10^{-5} and *b* changes from 1.19×10^{-5} to 2.50×10^{-5}). The heavy chemical industry and large power plants kept the growth rate of energy consumption in Tianjin at a high level until about 2010 (the growth rate was above 10%). In addition, developed trade activities in Binhai New District have driven the industrial transformation of the city. Since 2008, the proportion of the tertiary industry has been rising continuously (from 46.8% in 2008 to 56.4% in 2016), and the proportion of the secondary industry was finally surpassed in 2015. New industrial and energy structures bring both benefits and impacts on economic growth. The metabolism of urban pillar industries is a major test for Tianjin, through which the evolution of economic growth and energy consumption will enter a new normal in the future.

Hebei is a powerful industrial province and a heavy polluted area in China with iron-steel and petrochemical industries as major energy consumers. Within the study period, economic growth had a continuous inhibitory effect on energy consumption, while the effect of energy consumption on economic growth experienced a transition from inhibition to promotion (*a* changes from 1.96×10^{-5} to 5.35×10^{-6} and *b* changes from -9.11×10^{-8} to 4.17×10^{-5}). Before 2008, Hebei's economy developed rapidly inducing a large amount of energy consumption and air pollutant emissions. To get ready for the Beijing Olympics, Hebei curtailed energy consumption stringently, with the growth rate of energy consumption dropping rapidly (deceased to 3.12% in 2008). Optimization of the industrial structure, elimination of outdated production capacity and development of clean energy have been vigorously prompted since 2008. The proportion of the tertiary industry began to rise gradually (increased to 41.54% in 2016). Owing to huge size and rich industrial types, Hebei has enjoyed a relatively stable development for years (10.26% in average). However, the energy-intensive industries are bound to be gradually replaced in the future calling for more active industrial upgrading. Shijiazhuang, Tangshan, Qinhuangdao and other cities have gradually developed into agglomeration, which is linked with Beijing, Tianjin and the surrounding regions. With the help of diversified industrial development, possibilities for long-term synergy between energy and economy are promising in Hebei.

As one of the representatives of China's agglomerations, the Jing-Jin-Ji Region is experiencing transitions in an all-round way. As the results of the nexus between economic growth and energy consumption demonstrated ($a>0$, $b>0$ in all regions), the transitions are towards better synergetic effects on economy and energy mutually. Beijing has reached an overall good state, with synergetic effect of either economic growth or energy consumption on the energy-economy system (λ_1<0 and λ_2<0) prior to Tianjin and Hebei (λ_1<0 and λ_2>0).

(3) Implications behind the extrapolated future trends

After analyzing the historical nexus between economic growth and energy consumption in the Jing-Jin-Ji Region, the possible development trends in both are extrapolated based on historical data. It can be seen from the results that economic growth of the Jing-Jin-Ji Region will maintain optimistic with the help of increasingly powerful national strength and healthy development environment. A slowdown in GDP growth rate is inevitable as the competitive advantage of labor prices wanes and other emerging markets make an impact. According to the extrapolation, after 2020 the GDP growth rate will be lower than 3% in Beijing and Hebei, and it will decrease to about 4% in Tianjin. In fact, lower economic expectations are more conducive to motivating the transformation of the regional economy to a high-quality development mode. In terms of energy consumption, the statistical data in recent years are lower than the extrapolated results (the average predicted regional TEC growth rate in 2030 will be about 1%, which has been achieved around 2016 in practice), which is a good phenomenon. It benefits from the effective control of the government on energy consumption. However, it is worth noting that future management plans should be formulated more reasonably to avoid rushing into acute decrease in energy consumption and pollutant emissions, which may lead to depressing consequences.

5. Conclusion

Given the context of energy shortage and severe air pollution in China along with surging economic growth, it is of necessity to coordinate the relationship between economic growth and energy consumption effectively and reasonably. Explicit understanding of the interaction between the two variables is a premise for coordinating them. Decoupling analysis and synergetic theories are combined to analyze the nexus between the evolution of regional economic growth and energy consumption in this research. Taking the Jing-Jin-Ji Region as the study area, GDP and TEC from 2001 to 2016 are introduced into the IGT model, and the Haken model derived from the self-organization theory, to unravel the mutual effects of the evolution of energy and economy within two periods of 2001-2008 and 2009-2016.

Several findings can be revealed as follows:

(1) In the Jing-Jin-Ji Region, the decoupling level of GDP and TEC decreased in the years at the beginning of the 21th century, but kept wavelike increasing in the following years and finally reached a moderately decoupled state, with the average decoupling index ranging around 0.5.

(2) It can be seen from the decrease of *a* (from 1.28×10^{-5} to 5.12×10^{-6}) and the change of *b* (from -1.68×10^{-5} to 1.28×10^{-5}) that the overall development of Beijing is in a good condition. Along with economic growth, energy consumption continued to be restrained, and the evolution of economic growth and energy consumption gradually coordinated with each other. The energy-economy system is coming into a state of benign development.

(3) In Tianjin, the change of *a* (from -2.20×10^{-6} to 2.11×10^{-5}) and the increase of *b* (1.19×10^{-5} to 2.50×10^{-5}) show that the situation of rapid economic growth with high energy consumption has passed away. The effect of economic growth on energy consumption reversed from promotive to inhibitory. Energy consumption kept prompting economic growth. As a complete synergy of economy and energy has not formed, it still entails to facilitate to better economic development patterns.

(4) The decrease of *a* (from 1.96×10^{-5} to 5.35×10^{-6}) and the change of *b* (from -9.11×10^{-8} to 4.17×10^{-5}) indicate that the improved economic development patterns in Hebei maintained inhibitory effect on energy consumption. The adjustment in energy consumption patterns turned the negative effect to positive on economic growth. Though approaching to a synergistic state, the energy-economy system needs to experience a transitional period.

(5) The extrapolations of the development trends in GDP and TEC through Haken extrapolation equations based on the historical data indicate that the evolution of GDP and TEC in Beijing and Hebei may enter a stable period with slower growth rate in the future that tends to be constant. Such a process might be delayed for Tianjin.

Seen overall, Beijing is leading one step ahead (λ_1<0 and λ_2<0), providing examples and reference for Tianjin and Hebei. Significant efforts have been made in the Jing-Jin-Ji Region. It calls for the continuation and expansion of the implementation of current economic and energy policies to accomplish the complete synergy of economic growth and energy consumption. Beyond current studies on exploring the relationship between two variables, this research puts forward a new idea, a systematic and evolutionary way, to deal with the issues of energy and economy by using Haken model. This work is an attempt on the provincial level. In the future, it will be a good choice to apply the theories and methods of synergetics to more specific dimensions such as cities or industries, and practice further study about the synergetic effects of terminal subsystems.

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