Does the rebound effect matter in energy import-dependent mega-cities? Evidence from Shanghai (China)

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ABSTRACT

The energy rebound effect is regarded as an obstacle of achieving the expected target of energy-saving policies, especially under a rapid urbanization background in developing counties, such as China. This has become a substantial drag of sustainable development in some cities. Shanghai is the economic center of China, and it is also a typical energy import-dependent mega-city. Investigating the evolution of Shanghai's energy-saving performance and the energy rebound effect is significant for the implementation of energy-saving policies in other similar cities of China and other developing countries. Using the state space model with time-varying parameters and based on the IPAT identity and the Solow residual approach, this paper is the first study to present a

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specific estimation on Shanghai's energy rebound effect caused by technological progress. The results show that, during the period of 1991-2016, the average energy rebound effect of overall economy and secondary industry in Shanghai was 93.96% and 73.10%, respectively, indicating a high partial rebound effect. Most of expected energy saving caused by improved energy efficiency is offset by extra energy consumption caused by technological progress. Regarding tertiary industry, the average rebound effect was 146.61%, indicating a backfire effect. However, the average energy rebound amount of tertiary industry is less than that of secondary industry. In particular, there is an increasingly negative impact of the rebound effect of tertiary industry on energy conservation in recent years, with the sector's rapid expansion and corresponding increase in energy demand. Furthermore, we estimate the carbon rebound amount (i.e., carbon emissions caused by the energy rebound effect) and find that, on average, the energy rebound effect caused 13.1% and 0.41% increases in carbon emissions in Shanghai and China, respectively. Therefore, mitigating the energy rebound effect can significantly reduce carbon emissions. Due to the substantial impact of the rebound effect, technological progress and energy efficiency improvement should not be the only way to achieve energy-saving target, especially in energy import-dependent mega-cities like Shanghai. Some supporting policies should be implemented to ensure that the expected outcome of energy-saving effort can be realized as far as possible.

Keywords: Energy efficiency; Rebound effect; Technological progress; Carbon emissions; Energy import-dependent mega-city; State space model

1. Introduction

As the world's second largest economy and the largest energy consumption country, China has huge energy demand and high energy-saving pressure, which impede the country's green and sustainable development. To resolve such a problem, various policies and measures focusing on improving energy efficiency have been taken in China. However, the energy rebound effect has become an obstacle of achieving the expected target of energy-saving policies, especially under a rapid urbanization background in China. In the process of rapid urbanization, a large amount of infrastructure, such as highway, road, and airport, needs to be constructed, inducing a great demand for steel, cement, and energy and not facilitating mitigating the energy rebound effect. A common phenomenon in such a process is that energy saving resulted from energy efficiency improvement is partly or even completely offset by added energy consumption from economic growth activated by urbanization, i.e., a substantial energy rebound effect [34,35]. Therefore, the energy rebound effect has become a drag of sustainable development in most cities in China.

As the economic center of China, as well as a typical energy import-dependent mega-city, Shanghai is confronted with such a problem. As energy is a strategic resource for economic development, its supply security has an important influence on economic sustainability and the improvement of people's living standards. At present, energy constraint has become a bottleneck for the social and economic sustainable development of Shanghai [10]. Moreover, economic growth caused by technological progress further accelerates energy consumption. This intensifies the conflict between energy supply and demand and restricts Shanghai's further economic growth. As Lin et al. [22] defined, the technological progress in this study can be regarded as all kinds of economic processes which can improve productivity, including the promotion and application of new technologies and the improvement of managing performance. Generally, technological progress can contribute to the promotion of energy efficiency and productivity.

At the same time, technological progress can lessen production costs, resulting in an increase in profits of enterprises and thus the activities of expanded reproduction, to induce more energy demand. The first explanation of such a phenomenon can be traced back to 1865 when Jevons [17] stated in his book "*The Coal Question*" that the improved energy efficiency would reduce energy costs, which in turn would stimulate more energy demand than ever. Simultaneously, an increase in energy efficiency is accompanied by technological progress, which motivates economic expansion and thus generates extra demand for energy. These two aspects together accelerate the growth of energy consumption. This inference is the well-known "Jevons' Paradox" [17]. After the 1980s, Jevons' Paradox" received much concern and scholarly discussion and led to some questions about the effectiveness of the government's energy policies. Therefore, technological progress can only partially solve the problem of energy use sustainability. Energy efficiency, economic expansion, and elasticities of substitution between energy and other production factors together affect energy consumption and should be considered comprehensively in the formulation and implementation of the government's energy policies.

Since 1992, Shanghai has achieved high-speed economic growth. Meanwhile, Shanghai's energy consumption has soared up. Total final energy consumption in Shanghai jumped from 3098.8 (10,000 tons of coal equivalent (tce)) in 1990 to 11861.7 (10,000 tce) in 2016, increasing by 282.8% (see Fig. 1). The final energy consumption of secondary and tertiary industries in Shanghai in 1990 accounted for 77.06% and 13.02% of total final energy consumption, respectively, while in 2016, their rates became 52.03% and 36.18%, respectively. The share of energy consumption of secondary industry in total energy consumption declined, while that of tertiary industry rose. At the same time, overall energy intensity in Shanghai dropped from 2.06 (100 tce/million yuan) in 1990 to 0.53 (100 tce/million yuan) in 2016, while the energy intensities of secondary and tertiary industries slumped from 3.27 (100 tce/million yuan) and 0.61 (100 tce/million yuan) to 0.73 (100 tce/million yuan) and 0.32 (100 tce/million yuan) in 2016, respectively (see Fig. 2). Energy intensity in Shanghai shows an obvious downward trend. In particular, the energy intensity of secondary and tertiary industries reduced by more than three quarters and nearly a half during the period of 1990-2016, respectively. This implies that Shanghai's secondary and tertiary industries became less energy intensive than ever. Moreover, the energy intensity of tertiary industry was less than half of that of secondary industry in 2016, indicating a more energy-saving characteristic. Obviously, the development of a service-based economy can lead to a greener industrial structure.

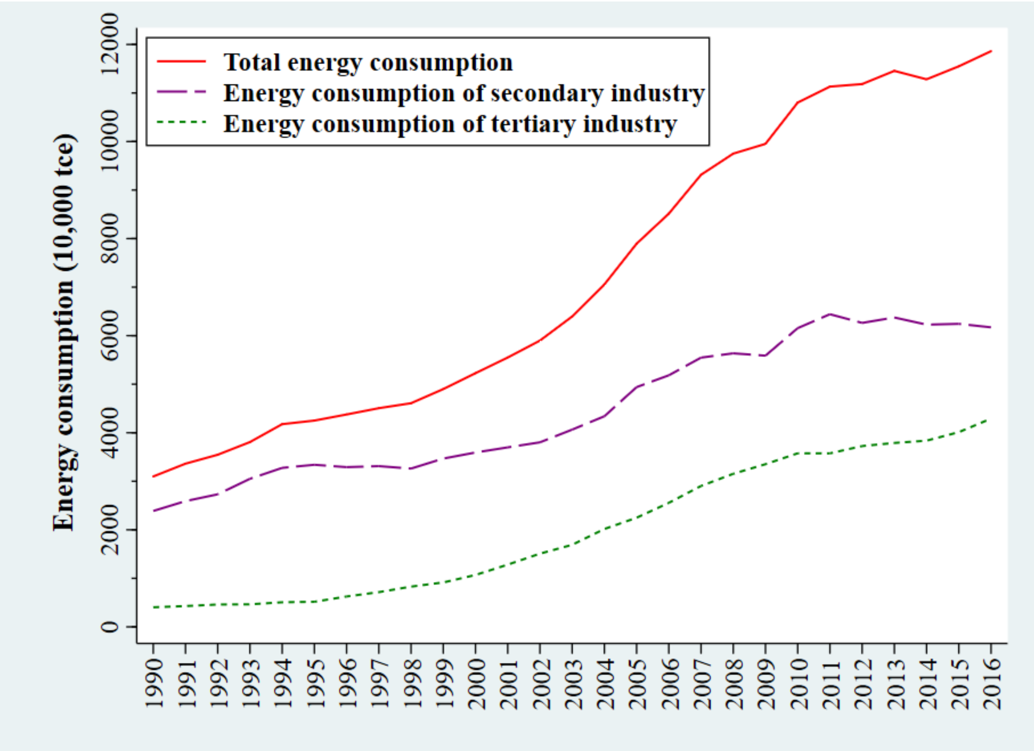

Fig. 1. Energy consumption of overall economy, secondary industry, and tertiary industry in Shanghai

Source: *Shanghai Statistical Yearbook*

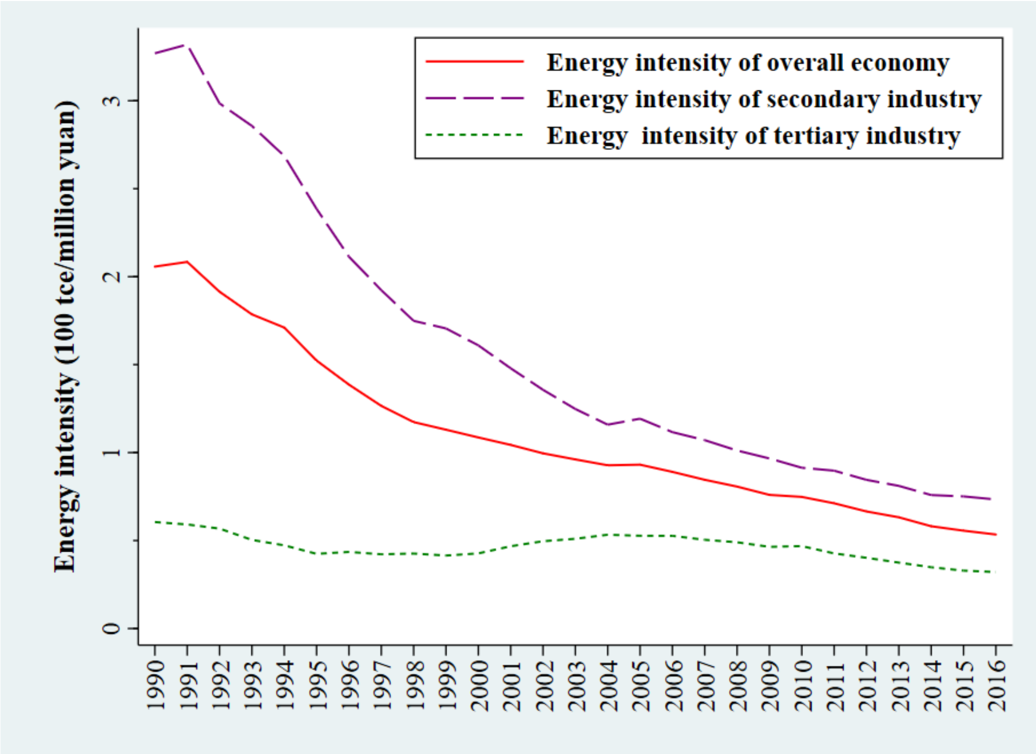

Fig. 2. Energy intensity of overall economy, secondary industry, and tertiary industry in Shanghai

Source: *Shanghai Statistical Yearbook* and *China Energy Statistical Yearbook*

In recent years, tertiary industry in Shanghai is in a leading position, while secondary industry has a smaller and smaller proportion in overall economy. However, Shanghai's overall energy efficiency is relatively low, and "carbon-rich" energy, including oil and coal, still accounts for a relatively high proportion in primary energy consumption [36]. Shanghai's economic growth still depends on the increase of factor inputs to some extent. However, given the rise of factor costs, especially environmental costs, the advantages of traditional manufacturing gradually weaken. Hence, it is an urgent task for Shanghai to improve the technological contents and added value of products through advanced technologies. Obviously, increasing investments in education and research and development (R&D) and improving the levels of human capital and technologies in production process are the keys to achieving sustainable economic development in Shanghai.

In addition, Shanghai is the most international city in China, known as a global city.

Since China's reform and opening up, the Chinese government has placed its high hopes on Shanghai and has given a series of strong policy support for the city's development, such as the establishment of "Pudong New Area", "Four Centers" strategy (International Economic Center, International Financial Center, International Shipping Center, and International Trade Center), and the first domestic "Pilot Free Trade Zone" in Pudong New Area in 2013. Currently, Lujiazui is a window to display achievements in building "Socialism with Chinese Characteristics" and reform and opening up. Such measures and actions promote Shanghai to be a global mega-city with service-based economy majoring in finance, business, and trade as well as science and technology [7].

Meanwhile, as China's economic center and the core city of the "Yangtze River Delta Economic Zone", Shanghai's social and economic development level is at the forefront of China. Accordingly, the city has a huge energy demand. However, Shanghai is lack of natural resources, especially fossil energy. Its energy consumption largely depends on the import from other regions. Hence, the city is a typical energy import-dependent mega-city and has a great energy-saving pressure. As a result of the rebound effect, the rising technical level will not completely achieve expected energy saving. The magnitude of the rebound effect in such an energy import-dependent mega-city is particularly important for the city's sustainable development. In this case, it is extremely necessary and important to detailedly investigate the energy rebound effect in Shanghai, in order to provide some valuable reference for the formulation of energy policies in other similar cities in China and even the world.

Under such backgrounds, this is the first study to present a specific estimation on the energy rebound effect caused by technological progress in Shanghai. In particular, based on the IPAT identity and the Solow residual approach, we use the state space model with time-varying parameters to obtain more reasonable and accurate results, compared with most previous studies using fixed parameter methods. Moreover, our data set covers overall economy, secondary industry, and tertiary industry in Shanghai during the period of 1990-2016. This helps us grasp the general trends of the rebound effect in Shanghai at the economy-wide level. Furthermore, we estimate the carbon rebound amount (i.e., carbon emissions caused by the energy rebound effect) and provide an evidence of the argument that mitigating the energy rebound effect can significantly reduce carbon emissions. Through the detailed investigation of the rebound effect in Shanghai, we aim to enrich the application and empirical evidence of the rebound effect theory from the perspective of energy import-dependent cities in developing countries. In addition, this study can provide some important policy reference for other similar cities in China and even the world, to formulate and optimize their energy-saving policies.

The rest of this paper is arranged as follows. Section 2 reviews related studies. Section 3 introduces the estimation method of the energy rebound effect and the data used in this study. Section 4 presents and discusses related estimation results. Section 5 provides some concluding remarks.

2. Literature review

Previous studies have conducted a lot of exploration on the rebound effect. Overall, existing literature can be classified into three main aspects: the definition, theoretical explanation, and empirical evidence of the rebound effect.

2.1. Definition of the rebound effect

Generally, the energy rebound effect reflects a paradox phenomenon of the reduction in expected energy savings resulted from improved energy efficiency. However, different studies have different definitions of the rebound effect from various perspective. For example, Schipper and Grubb [33] argued that a weak rebound refers to a phenomenon that improved energy efficiency in fact fails to reduce the demand for energy use nearly as much as the expected savings, while a strong rebound is that energy efficiency improvement causes impacts that offset most of the expected or even leads to more energy use than before such an improvement occurred (known as a backfire effect). At the macroeconomic level, Shao et al. [34,35] claimed that the rebound effect refers to an additional increase in economy-wide energy consumption due to productivity growth induced by improved energy efficiency. That is to say, energy efficiency improvement can propel technological progress and economic growth to cause a rebound effect through a series of socioeconomic re-adjustments in products' prices and output, consumer behaviors, and technological innovation. At the microeconomic level, the rebound effect is quantitatively defined by some scholars as the elasticity of energy consumption to energy price [37,41].

In contrast, existing studies have reached an agreement on the typology of the rebound effect. Moreover, the rebound effect can be classified into three types: direct rebound, indirect rebound, and economy-wide rebound [14,34]. The direct rebound effect refers to an extra increase in energy consumption caused by energy efficiency improvement and the corresponding lower cost of an energy service to reduce expected energy savings. Subsequently, the indirect rebound effect refers to an extra increase in energy consumption from an increase in the demand for other goods and services that need energy to be produced. Finally, the economy-wide rebound effect, including the direct rebound effect and the indirect rebound effect, refers to an overall increase in energy consumption in whole economic system due to improved energy efficiency and productivity [14,34]. The direct rebound only exists at the micro-economic level, while the indirect rebound and economy-wide rebound occur at the medium- and macroeconomic levels, respectively [34].

2.2. Theoretical explanation on the rebound effect

Jevons [17] conducted the earliest study on the relationship between energy efficiency and energy consumption. He argued that energy efficiency had not reduced energy consumption and that energy efficiency and energy consumption were in a reverse state, known as Jevons' Paradox. His theory focuses on energy efficiency improvement from technological progress, which is often accompanied by advancement in social productivity, rapid growth of social economy, and continuous rise in social consumption level. Such changes can cause more energy demand. Also, the increased energy efficiency contributes to a decline in the prices of energy use and services, both of which lead to the growth of energy consumption.

Related debate on the existence of the rebound effect emerged in the 1980s. As one of the representative researchers, Brookes put forward three questions about the relationships among energy efficiency, energy consumption, productivity improvement, and macroeconomic growth [4,5,6]. In detail, first, high quality and efficient energy use promotes technological progress and then stimulates social economy into a faster growth period with an increase in energy consumption. Second, energy efficiency increases accompanied by price changes. Then, the original balance of the supply and demand of energy is broken and a new and higher-level balance will appear. Third, when estimating energy savings caused by the improvement in energy efficiency, a widely-used basic assumption that energy intensity is fixed at a certain historical level is irrational because there is an endogenous relationship between economic growth and energy efficiency improvement.

Most studies explain the rebound effect based on the neoclassical economic theory. Saunders [29] used the neoclassical economic growth theory and constructed a neoclassical production function to prove the existence of the backfire effect from energy efficiency improvement. Furthermore, Saunders [30,31] distinguished energy and energy service and adopted the mathematical simulation method to expound the existence of the economy-wide rebound. In particular, Saunders [32] compared eight types of production/cost functions when exploring how energy efficiency improvement affect energy consumption, and found that the estimates of the rebound are very sensitive to the forms of production/cost functions and that the Fourier cost function is able to describe various possible situations of the rebound effect and is sufficiently "rebound flexible". Moreover, the Translog cost function and a particular form of the constant elasticity of substitution (CES) production function may be suitable given certain conditions. Although a series of the theoretical analyses of Saunders are based on the relatively strict assumptions of the neoclassical theory, these studies provide a reasonable framework for the proof and explanation of the rebound effect. Wei [40] used a general form of the production function to conduct a more general discussion for the occurrence conditions of different types of the rebound effects.

However, all studies mentioned above have not relaxed the neoclassical assumption of exogenous energy efficiency and cost-free technological progress. It is noteworthy that, in reality, energy efficiency improvement is usually endogenous [6] and few studies concern this problem, which can lead to biased results. Based on the new growth theory of the "learning-by-doing" effect, Shao et al. [35] constructed a novel theoretical model of the economy-wide rebound effect with the consideration of an endogenous energy efficiency for the first time, followed by some studies (e.g., [20]), to carry out more accurate estimation of the rebound effect.

2.3. Empirical evidence on the rebound effect

The empirical studies on the rebound effect are abundant, and the methods used are various. Some literatures focus on the economy-wide or industrial-level rebound effects [15,16,21,23,24,36]. Due to data availability, existing studies on China's rebound effect mainly pay attention to the rebound effect at economy-wide and industrial levels. For example, Zhou and Lin [42] asserted that because China's energy prices depend on non-market economic factors, to a high degree, and the data of energy prices are difficult to be obtained in China. An alternative method should be used to estimate the energy rebound effect based on technological progress. Zhou and Lin's [42] results show that the energy rebound effect fluctuates between 30% and 80% at China's macro-economic level. Using a computable general equilibrium (CGE) model, Liu et al. [26] decomposed the rebound effect into production rebound and final demand parts and designed two simulation rebound scenarios. They concluded that improving the energy efficiency in production sectors would promote final energy use and that improving the efficiency of secondary energy use was more effective than improving primary energy use in terms of both economic impacts and the energy rebound effect.

Previous studies on some specific industries provide some relevant policy recommendations for decision-makers. For instance, Lin et al. [22] used the Logarithmic mean Divisia index (LMDI) method and a total factor productivity model to estimate the energy rebound effect of China's nonferrous metal industry. They pointed out that the rebound effect was closely related with economic growth and productivity. Hence, besides energy-saving policies, the government should implement other supporting measures, such as pricing mechanism reform, resource tax, and carbon tax, to realize energy saving and carbon emission reduction targets.

As mentioned above, Shao et al. [35] developed a novel theoretical model of the energy rebound effect based on the endogenous growth theory, they further estimated China's economy-wide rebound effect by using a time-varying parameter space state model for the first time. Following Shao et al. [35], Li and Lin [20] decomposed the rebound effect as substitution and output components, and found that heavy industry and light industry had the different magnitudes of the rebound effect, indicating that the government should combine energy subsides and technological progress to relieve excessive growth in energy demand. Based on the IPAT identity and the state space model, Shao et al. [34] estimated the economy-wide rebound effect in China, and found that the rebound effect showed a downward trend after China's reform and opening-up.

Although the economy-wide rebound effect can be estimated based on the technological progress, to some extent, the improvement degrees of energy efficiency from technology upgrade and adoption vary with economic development, technological level, industrial structure, and consumption behavior in different countries [11]. This leads to the corresponding difference in the rebound effect [13]. Li et al. [19] argued that, since the mechanisms for estimating the rebound effect were differentiated in different studies, the calculation results of the rebound effect based on different strategies were incomparable. Hence, some literatures focus on the rebound effect of a specific industry or an economic sector [1,20,22].

Regarding the direct rebound effect, home heating [2], household appliances (e.g., washing machines, refrigerators, and air-conditioners) [25,39], and automobiles [12] are mainly investigated by existing studies at family- or enterprise-level. In existing studies on road transportation, the changes in gasoline prices and the promotion of new energy vehicles were identified to estimate the rebound effect [12,38].

In addition, some scholars explore the impact of personal consumption psychology and consumption behavior on energy demand [8]. Santarius and Soland [28] argued that the falling energy service prices resulted from energy efficiency improvement could mentally affect consumer behavior and lead to more product demand than before. There are also other factors which may affect resident's energy consumption behavior, such as income, consumption habits, climate conditions, which can result in the different degrees of the rebound effect. Similarly, at the country- or regional levels, different factors, such as gross domestic product (GDP), energy intensity, and R&D, have different effects on the rebound effect. Lin and Tan [24] estimated energy-saving potential in China's energy intensive industries, and found that GDP and the scale of industries had a promotion effect on energy consumption, while R&D intensity had a negative effect on energy consumption.

Meanwhile, some scholars concentrate on the rebound effect in one or several specific industries. For example, using the dynamic ordinary least squares and seemingly unrelated regression methods, Ouyang et al. [27] investigated the rebound effect of industrial sectors in the Yangtze River Delta urban agglomeration, and found that financial development and structural reform in the supply side were beneficial to energy conservation and pollution alleviation. Furthermore, they pointed out that financial development was very important for the shift from energy-intensive industry to service and technology-intensive industry. Some studies also compare different countries' rebound effects and their time trends. For instance, Brockway et al. [3] estimated the rebound effects of China, US, and UK, and found that China had a higher rebound effect, while UK and US presented partial rebound effects. They attributed such a gap to China's "producer-sided economy" status.

Although related studies are rich in empirical estimation, measurement methods, and numerical simulation for the direct, the indirect, and the economy-wide rebound effects, the specific investigation on the rebound effect of an energy import-dependent mega-city is rare. Based on the IPAT identity and the Solow residual approach and using the state space model with time-varying parameters, this paper is the first study to estimate and compare the energy rebound effects of Shanghai's overall economy, secondary industry, and tertiary industry and the carbon emissions caused by the energy rebound effect. This study is expected to provide the empirical evidence and mitigation policy reference of the rebound effect from the perspective of energy import-dependent cities.

3. Methodology and data

3.1. Model specification

3.1.1. Decomposition of energy consumption

Referring to Shao et al. [34], this paper uses the following IPAT identity to decompose the total energy consumption:

$$I = P \times A \times T \qquad (1)$$

where I denotes the environmental load, P denotes population, A is per capita affluence degree reflected by GDP, and T is the environmental load per unit of GDP. Regarding energy consumption as the environmental load, we have the following equation: energy consumption = the size of population × (GDP/population) × (energy consumption/GDP), that can be rewritten as:

$$I = G \times T \qquad (2)$$

where I denotes energy consumption, G denotes GDP, and T is energy consumption per unit of GDP.

We can decompose Eq. (2) as follows:

$$\Delta I = I_t - I_0 = G_t T_t - G_0 T_0 = G_t (T_t - T_0) + T_0 (G_t - G_0) = G_t \Delta T_t + T_0 \Delta G_t \quad (3)$$

where ΔI is the change in energy consumption; I_t and I_0 are energy consumption in the report period and the base period, respectively; T_t and T_0 are energy consumption per unit of GDP in the report period and the base period, respectively; G_t and G_0 are GDP in the report period and the base period, respectively; $-G_t \Delta T_t$ means potential energy saving caused by improved energy efficiency from technological progress; $T_0 \Delta G_t$ denotes extra energy consumption caused by economic development.

3.1.2. **Measurement of the contribution rate of technological progress**

We let parameter ρ_t represent the contribution rate of technological progress to economic growth, which can be calculated by the Solow residual approach. According to the Cobb-Douglas production function, output can be expressed as:

$$G = AL^{\alpha} K^{\beta} E^{\gamma} \quad (4)$$

where G denotes gross output; A denotes technical level; L denotes labor input; K denotes capital input; E denotes energy consumption; α is output elasticity of labor; β represents output elasticity of capital; γ is output elasticity of energy consumption.

Taking logarithm on both sides of Eq. (4), Eq. (4) can be rewritten as follows:

$$\ln G = \ln A + \alpha \ln L + \beta \ln K + \gamma \ln E + u \quad (5)$$

Deriving with both sides of the above formula and replacing the differential with the difference, Eq. (5) can be converted as follows:

$$\Delta A / A = \Delta G / G - \alpha \Delta L / L - \beta \Delta K / K - \gamma \Delta E / E \tag{6}$$

We set *SA* as technological progress rate, and thus we can get:

$$SA = g - \alpha l - \beta k - \gamma i \tag{7}$$

where technological progress rate is $SA = \Delta A / A$; output growth rate is $g = \Delta G / G$; labor growth rate is $l = \Delta L / L$; capital growth rate is $k = \Delta K / K$; energy consumption growth rate is $i = \Delta E / E$. Therefore, the share of economic growth caused by technological progress (ρ) can be expressed as follows:

$$\rho_t = SA / g = (g - \alpha l - \beta k - \gamma i) / g \tag{8}$$

3.1.3. Estimation approach

The widely-used regression models have fixed coefficients, that is to say, their estimated parameters are constant in the sample period. However, in China, due to economic reform, various external shocks, and policy adjustment, economic structure is gradually changing, but fixed coefficient models cannot show such changes. The state space model with estimated time-varying parameters can reflect these changes [34]. According to Eq. (5), the state space model can be written as follows:

The signal equation is as follows:

$$\ln G_t = SV_1 \ln L_t + SV_2 \ln K_t + SV_3 \ln E_t + SV_4 + u_t \tag{9}$$

The state equation is as follows:

$$SV_1 = \lambda_1 SV_1(-1) + \varepsilon_{1t} \tag{10}$$

$$SV_2 = \lambda_2 SV_2(-1) + \varepsilon_{2t} \tag{11}$$

$$SV_3 = \lambda_3 SV_3(-1) + \varepsilon_{3t} \tag{12}$$

$$SV_4 = \lambda_4 SV_4(-1) + \varepsilon_{4t} \tag{13}$$

$$SV_1 = \alpha_t,\ SV_2 = \beta_t,\ SV_3 = \gamma_t \tag{14}$$

where the subscript *t* represents the time in years; $\ln G$, $\ln A$, $\ln L$, $\ln K$, and $\ln E$, represent the natural logarithms of GDP, technical level, labor input, capital input, and energy consumption, respectively; SV_1, SV_2, SV_3, and SV_4 denote output elasticities of labor, capital, and energy consumption, and the intercept term, respectively; $SV_1(-1)$, $SV_2(-1)$, $SV_3(-1)$, and $SV_4(-1)$ represent output elasticities of labor, capital, and energy consumption, and the intercept term in year *t*-1, respectively; $\ln Y_t$, $\ln K_t$, $\ln L_t$, and $\ln E_t$ are called the observable vectors, and the state equation is assumed to satisfy the AR(1) process; SV_1, SV_2, SV_3, and SV_4 are called the state vectors, which are unobservable variables and need to be estimated through the Kalman filter approach; u_t, ε_{1t}, ε_{2t}, ε_{3t}, and ε_{4t} are random disturbance terms, and they are assumed to be independent and identically distributed and follow normal distribution.

3.1.4. **Definition of the energy rebound effect**

Following Shao et al. [34], the energy rebound effect is quantitatively defined as the share of extra energy consumption from technological progress in theoretically expected energy saving ($-G_t \Delta T_t$). As mentioned above, we set ρ as the contribution rate of technological progress to economic growth, and thus we get:

$$T_0 \Delta G_t = \rho_t T_0 \Delta G_t + (1-\rho_t) T_0 \Delta G_t \tag{15}$$

where $\rho_t T_0 \Delta G_t$ stands for the extra energy consumption from technological progress (i.e., energy rebound amount), which is the outcome of economic expansion induced by technological progress. Thus, the rebound effect RE can be estimated as follows:

$$RE_t = \rho_t T_0 \Delta G_t / -G_t \Delta T_t = \rho_t T_0 (G_t - G_0) / G_t (T_0 - T_t) \tag{16}$$

Furthermore, the energy rebound amount can be calculated as follows:

$$\text{Energy rebound amount} = -RE_t G_t \Delta T_t \quad (17)$$

3.2. Data description

Considering that the added value and energy consumption of primary industry are much smaller than those of secondary and tertiary industries and that the technological progress of primary industry is relatively slow, primary industry contributes little to the GDP and technological progress of overall economy in Shanghai. Hence, we take Shanghai's overall economy, secondary industry, and tertiary industry as research samples. The input variables include capital stock (*K*), labor input (*L*), and energy consumption (*E*), and the output variable is GDP (*G*). The data of these input and output variables are derived from *Shanghai Statistical Yearbook*, *China Energy Statistical Yearbook*, and *CEInet Industry Database*. Based on the availability of data, our research samples cover the period of 1990-2016.

Following Fan et al. [9], we choose the number of employees to measure labor input. Energy consumption is measured by final energy consumption, with the unit of ten thousand tce. Capital stock is estimated by the perpetual inventory method as the following formula: $K_t = (1-\delta_t)K_{t-1} + I_t$, where K_t and K_{t-1} are capital stock in years t and $t-1$, respectively; δ_t represents the capital depreciation rate of 10.96%; and I_t is annual capital investment proxied by total investment in fixed assets at the 2000 constant price. The summary statistics of these input and output variables of Shanghai's overall economy, secondary industry, and tertiary industry are shown in Table 1.

Table 2 shows GDP, energy consumption, and energy intensity of overall economy, secondary industry, and tertiary industry in Shanghai. It can be seen that rapid economic growth promoted substantially energy consumption, whose annual average growth rate reached 5.3% for overall economy. Meanwhile, due to the continuous decline in the energy intensity of both secondary industry and tertiary industry, overall energy intensity in Shanghai continues to decrease, making Shanghai to be a cleaner city. The means of the energy intensity of overall economy, secondary industry, and tertiary industry are 1.10, 1.59, and 0.46 (100 tce/million yuan), respectively. This indicates that tertiary industry has an obvious energy-saving characteristic. Hence, the development of tertiary industry can play an important role in decreasing the energy intensity of overall economy. Based on the data listed in Table 4, we can get that the share of secondary industry in GDP in Shanghai dropped from 48.5% in 1990 to 37.9% in 2016, while that of tertiary industry increased from 44.3% in 1990 to 60.2% in 2016.

Table 1
Summary statistics of input and output variables.

Variable	Definition	Unit	Obs.	Mean	Std. Dev.	Min	Max
Overall economy							
G	GDP in Shanghai	100 million yuan	27	8859.63	6558.83	1506.3	22193.78
K	Total capital stock in Shanghai	100 million yuan	27	14018.25	9776.41	1538.3	31533.94
L	Number of employees in Shanghai	10,000 persons	27	951.28	209.8	752.26	1368.91
E	Total final energy consumption in Shanghai	10,000 tce	27	7238.9	3106.52	3098.82	11861.72
Secondary industry							
G	GDP of Shanghai's secondary industry	100 million yuan	27	3972.66	2689.32	730.32	8413.63
K	Capital stock of Shanghai's secondary industry	100 million yuan	27	4147.8	2765.14	239.44	7884.76
L	Number of employees of Shanghai's secondary industry	10,000 persons	27	409.78	56.37	309.91	479.22
E	Total final energy consumption of Shanghai's secondary industry	10,000 tce	27	4480.62	1386.65	2387.88	6442.28
Tertiary industry							
G	GDP of Shanghai's tertiary industry	100 million yuan	27	4760.86	3863.97	666.67	13360.24
K	Capital stock of Shanghai's tertiary industry	100 million yuan	27	9177.9	7464.16	130.48	23587.68
L	Number of employees of Shanghai's tertiary industry	10,000 persons	27	472.99	205.63	218.13	871.29
E	Total final energy consumption of Shanghai's tertiary industry	10,000 tce	27	2016.75	1388.59	403.47	4291.17

Table 2

GDP, energy consumption, and energy intensity of overall economy, secondary industry, and tertiary industry in Shanghai.

Year	Final energy consumption of overall economy (10,000 tce)	Final energy consumption of secondary industry (10,000 tce)	Final energy consumption of tertiary industry (10,000 tce)	GDP of overall economy (100 million yuan)	GDP of secondary industry (100 million yuan)	GDP of tertiary industry (100 million yuan)	Energy intensity of overall economy (100 tce/million yuan)	Energy intensity of secondary industry (100 tce/million yuan)	Energy intensity of tertiary industry (100 tce/million yuan)
1990	3098.82	2387.88	403.47	1506.30	730.32	666.67	2.06	3.27	0.61
1991	3362.87	2591.11	428.25	1613.80	780.63	723.94	2.08	3.32	0.59
1992	3546.35	2731.13	460.69	1852.34	914.89	810.77	1.91	2.99	0.57
1993	3807.56	3050.85	464.45	2132.23	1067.82	921.88	1.79	2.86	0.50
1994	4176.63	3275.86	506.68	2441.38	1219.42	1071.24	1.71	2.69	0.47
1995	4250.45	3339.73	517.05	2790.60	1400.00	1217.97	1.52	2.39	0.42
1996	4376.37	3291.05	626.39	3156.36	1556.92	1438.37	1.39	2.11	0.44
1997	4505.70	3312.18	715.31	3560.29	1721.84	1694.39	1.27	1.92	0.42
1998	4608.13	3261.21	828.84	3926.69	1864.77	1945.15	1.17	1.75	0.43
1999	4899.60	3467.49	915.48	4335.07	2032.69	2205.83	1.13	1.71	0.42
2000	5226.79	3592.86	1069.32	4812.15	2231.93	2503.54	1.09	1.61	0.43
2001	5549.69	3698.28	1282.08	5317.22	2499.80	2741.35	1.04	1.48	0.47
2002	5898.56	3802.12	1508.46	5923.43	2802.32	3040.07	1.00	1.36	0.50
2003	6394.49	4063.76	1690.50	6651.77	3256.44	3313.70	0.96	1.25	0.51
2004	7055.08	4339.27	2016.48	7602.75	3744.87	3781.01	0.93	1.16	0.53
2005	7895.17	4940.24	2249.12	8476.76	4141.68	4264.92	0.93	1.19	0.53
2006	8514.40	5183.29	2555.08	9561.96	4642.77	4849.22	0.89	1.12	0.53
2007	9314.77	5547.36	2902.64	11015.47	5181.18	5756.12	0.85	1.07	0.50
2008	9750.47	5636.03	3153.79	12084.13	5569.66	6429.67	0.81	1.01	0.49
2009	9951.81	5587.85	3351.64	13099.35	5781.23	7220.60	0.76	0.97	0.46
2010	10802.03	6154.82	3576.70	14435.18	6735.10	7632.26	0.75	0.91	0.47
2011	11131.41	6442.28	3575.33	15633.60	7179.56	8372.59	0.71	0.90	0.43
2012	11183.99	6262.81	3725.52	16805.95	7409.45	9268.36	0.67	0.85	0.40
2013	11456.08	6374.75	3789.85	18116.97	7861.56	10111.71	0.63	0.81	0.37
2014	11281.72	6227.77	3835.88	19403.17	8207.40	11011.73	0.58	0.76	0.35
2015	11549.55	6243.33	4012.19	20761.26	8314.01	12190.03	0.56	0.75	0.33
2016	11861.72	6171.32	4291.17	22193.78	8413.63	13360.24	0.53	0.73	0.32
Mean	7238.90	4480.62	2016.75	8859.63	3972.66	4760.86	1.10	1.59	0.46

4. Results and discussion

4.1. Unit root and co-integration tests

The unit root test is used to determine whether a set of time series data is stationary, and the ADF (Augmented Dickey-Fuller) test is a widely-used method. The results of the ADF test based on Shanghai's overall economy data are shown in Table 3 and Fig. 3. We find that $\ln G$, $\ln L$, $\ln K$, and $\ln E$ are non-stationary, while their second-order differences, i.e., $\Delta 2 \ln G$, $\Delta 2 \ln \mathrm{L}$, $\Delta 2 \ln K$, and $\Delta 2 \ln E$ are all stationary. Therefore, $\ln G$, $\ln L$, $\ln K$, and $\ln E$ are all second-order stationary sequences.

The co-integration test is used to distinguish a spurious regression caused by a non-stationary sequence. We use the Engle-Granger's two-step approach to conduct the co-integration test. The test results are shown in Table 4. We find that the residual sequences reject the null hypothesis at the significance level of 5%. Thus, there are positive co-integration relationships among $\ln G$, $\ln L$, $\ln K$, and $\ln E$, indicating that a long-term equilibrium relationship exists among these four variables.

Table 3
Results of the ADF test based on Shanghai's overall economy data.

	ln*G*	ln*L*	ln*K*	ln*E*	Δ2ln*G*	Δ2ln*L*	Δ2ln*K*	Δ2ln*E*
ADF value	0.02	-1.31	-2.48	-1.94	-3.63	-3.64	-3.63	-2.38
1% critical value	-4.38	-4.38	-4.38	-4.38	-2.55	-2.55	-2.55	-2.55
5% critical value	-3.60	-3.60	-3.60	-3.60	-1.73	-1.73	-1.73	-1.73
10% critical value	-3.24	-3.24	-3.24	-3.24	-1.33	-1.33	-1.33	-1.33
Stationarity	No	No	No	No	Yes	Yes	Yes	Yes

Notes: $\ln G$, $\ln L$, $\ln K$, and $\ln E$ represent the natural logarithms of G, L, K, and E, respectively; $\Delta 2 \ln G$, $\Delta 2 \ln L$, $\Delta 2 \ln K$, and $\Delta 2 \ln E$ are their corresponding second-order differences.

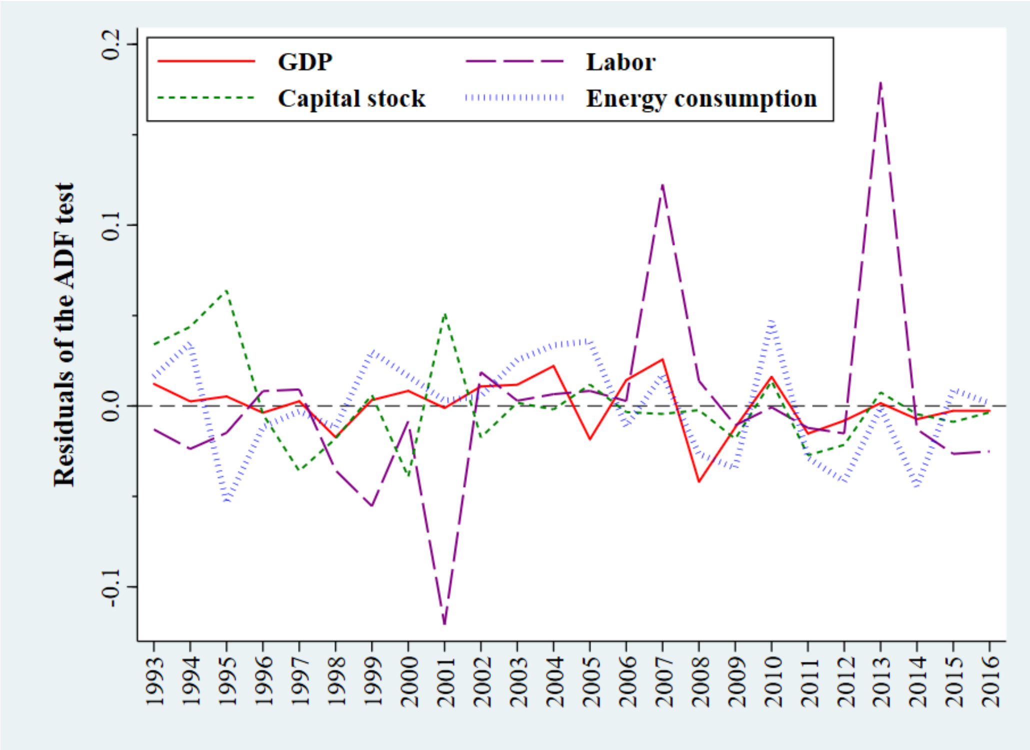

Fig. 3. Residuals of the ADF test of GDP ($\ln G$), labor input ($\ln L$), capital stock ($\ln K$), and energy consumption ($\ln E$)

Table 4
Results of the co-integration test based on Shanghai's overall economy data.

Maximum rank	Trace statistics	5% critical value	Null hypothesis
0	156.63	47.21	Reject
1	79.59	29.68	Reject
2	30.06	15.41	Reject
3	2.14*	3.76	Accept

4.2. Technological progress rate

As shown in Table 5 and Fig. 4, the average technological progress rate of overall economy between 1991 and 2016 in Shanghai was 4.81%, with a peak of 10.84% in 1995. Although Shanghai's overall economy was shocked by the "2008 International Financial Crisis", due to the lag effect of macroeconomic factors, the technological progress rate of overall economy in Shanghai remained a high level in 2008 and 2009 and then declined to 1.12% in 2010. After then, the technological progress rate returned a normal level of 4.5%-6.5% until 2014 (see Fig. 4), when the rate reached a peak of

8.26% in nearly a decade. This indicates Shanghai's macroeconomy has a strong ability of withstanding external risks.

Table 5
Technological progress rates of overall economy, secondary industry, and tertiary industry in Shanghai during the period of 1991-2016 (Unit: %).

Year	Overall economy	Secondary industry	Tertiary industry
1991	-0.73	-7.25	-1.80
1992	7.95	6.44	1.73
1993	6.58	3.27	-0.11
1994	4.13	-3.58	-2.46
1995	10.84	3.36	-2.84
1996	8.84	4.18	0.20
1997	8.57	2.98	2.78
1998	7.08	3.37	1.64
1999	3.40	-0.14	9.97
2000	3.66	4.64	1.49
2001	3.45	3.75	11.41
2002	4.32	6.70	-0.59
2003	3.11	6.50	-2.32
2004	3.01	5.78	3.19
2005	-0.48	-2.39	3.42
2006	3.95	4.92	4.91
2007	4.52	4.89	4.64
2008	4.26	3.33	2.49
2009	5.66	2.59	6.68
2010	1.12	5.52	0.29
2011	4.59	1.38	5.18
2012	6.48	4.84	7.23
2013	4.75	4.45	-19.18
2014	8.26	5.83	6.35
2015	4.09	0.84	6.83
2016	3.66	2.39	5.23
Mean	4.81	3.02	2.17

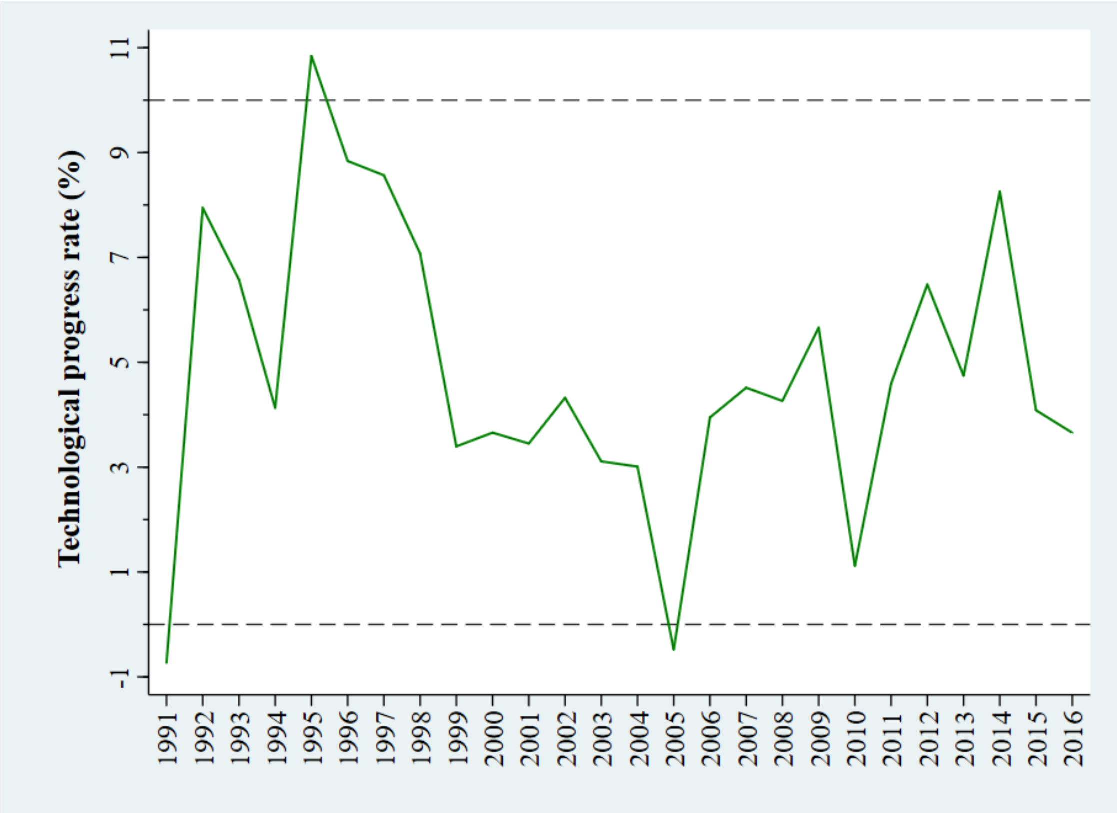

Fig. 4. Technological progress rate of overall economy in Shanghai

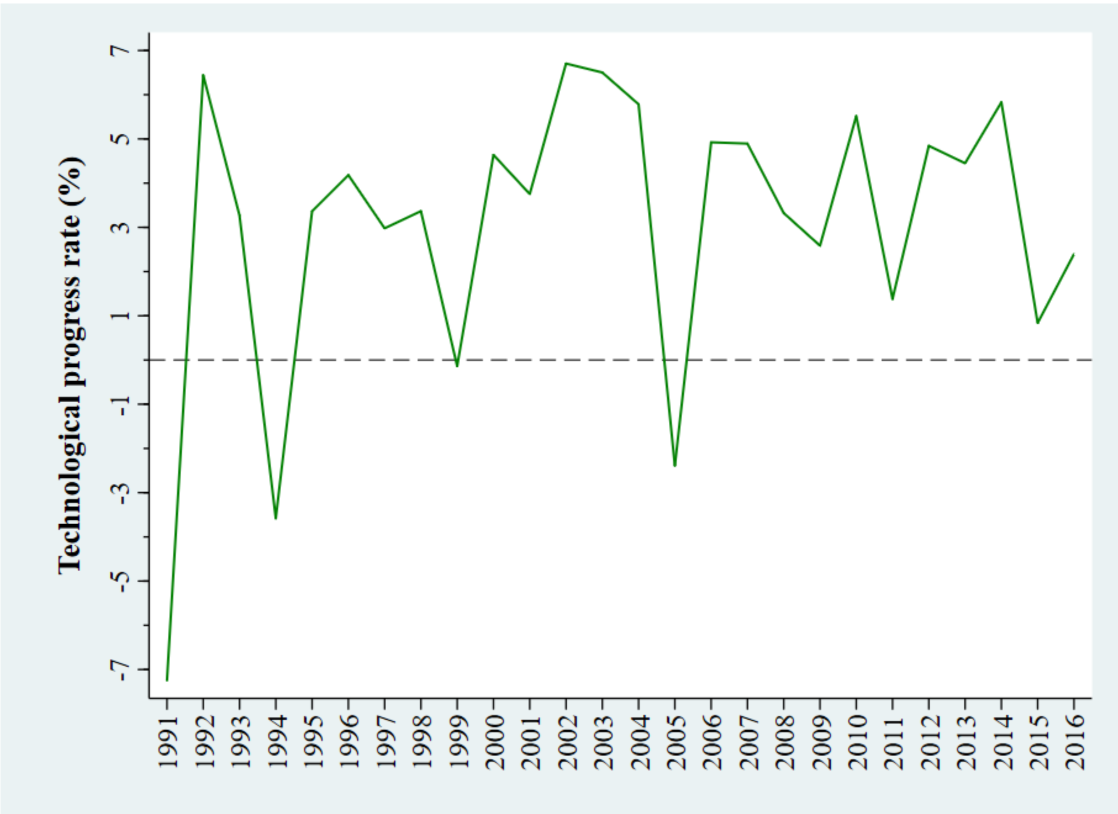

Fig. 5. Technological progress rate of secondary industry in Shanghai

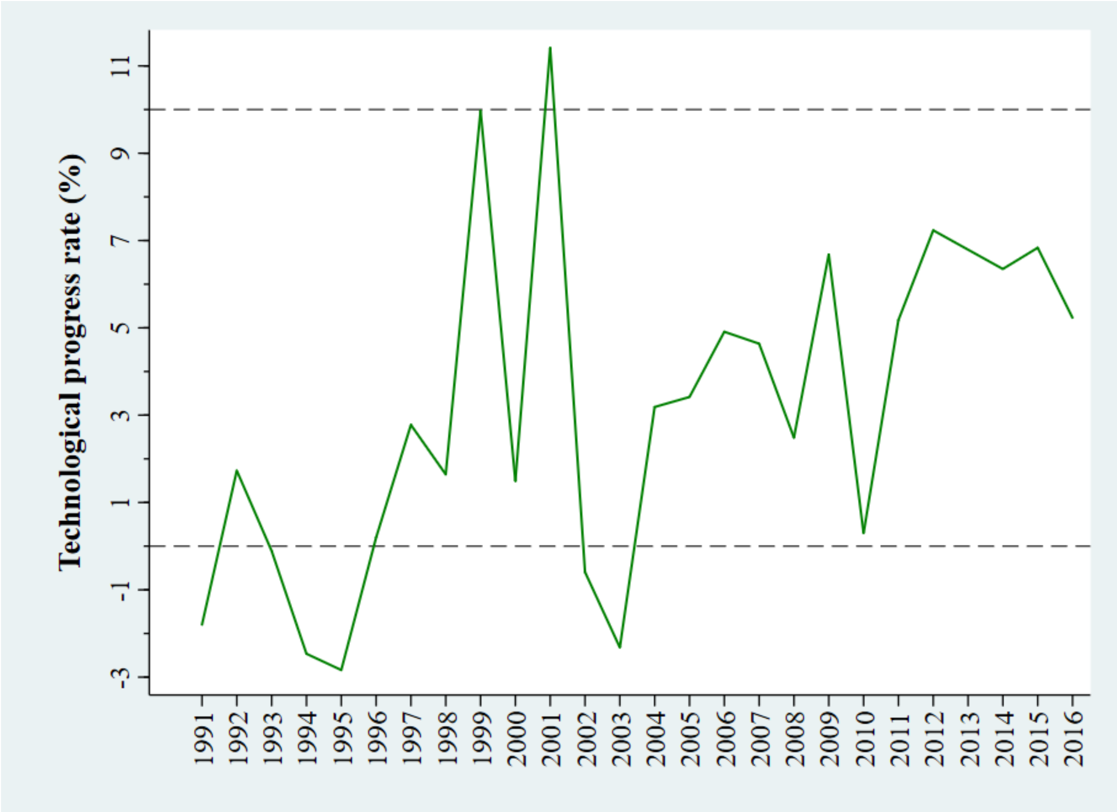

Fig. 6. Technological progress rate of tertiary industry in Shanghai

Regarding secondary industry, the technological progress rate presented an obvious fluctuation trend, with a peak of 6.70% in 2002. The average technological progress rate of this sector was 3.02% during the period of 1991-2016. During the period of 1994-1999, the technological progress rate remained at a relatively low level, with the average of 1.7%. In 1992, 2002, and 2003, the technological progress rates were more than 6%, while the rates were between 2% and 5% in most years (see Table 5 and Fig. 5). In particular, during the period of 2002-2004, the technological progress rate of secondary industry maintained a high level of more than 5% (see Fig. 5). This can be attributed to the rapid development of China's economy and China's accession to the World Trade Organization (WTO) in 2001. Accession to the WTO allows China to further participate in the global market and thus improves the country's international trade conditions. As the economic and trade center of China, Shanghai continues to deepen marketization reform and to enhance opening-up degree. The advanced management concepts and technologies of foreign companies facilitate upgrading industrial technological level in Shanghai.

It is noteworthy that a small number of negative technological progress rates appeared in some years. This can be attributed to industrial restructure and adjustment caused by some policy implementation or external impacts, such as the development and opening of the Pudong New Area of Shanghai, the tax system reform, and the Asian financial crisis. After 2006, the technological progress rate presented a drastically fluctuating trend. This may be due to Shanghai's attempting to change economic development mode in recent years. Due to environmental constraints and increasing environmental costs, the industries with high pollution, high energy consumption, and high emissions are moving to other regions, leading to a small number of enterprises in these industries. Since secondary industry has economies of scale, such a reduction in production scale causes a lower technological progress rate in the short run, though it is expected to be benefit to the improvement of energy efficiency.

In fact, Shanghai has carried out some industrial structure adjustment. For example, the *13th Plan of Transformation and Upgrade of Shanghai's Manufacturing Industry* suggests developing some major industries, including a new generation of information technology, bio-pharmaceutical and high-end medical equipment, and intelligent manufacturing equipment. The plan proposes that, by 2020, the added value of strategic emerging industries will account for 20% of Shanghai's GDP. Because these industries all have lower energy consumption and higher added value than traditional industries, it is expected that the further industrial structure adjustment in Shanghai can play an important role in reducing energy intensity in the future.

The average technological progress rate of tertiary industry is smaller than that of secondary industry (see Table 5 and Fig. 6). Shanghai has some particular backgrounds in the development of tertiary industry. In 2006, the State Council of China put forward the plan for Shanghai to construct four centers, i.e., international financial center, international economic center, international trade center, and international shipping center. The realization of these goals relies on the development of financial industry, wholesale and retail industry, transportation, warehousing and postal services, and shipping industry. Overall, the development of these industries facilitates saving energy and thus reducing the energy import-dependent degree in Shanghai. The share of tertiary industry in GDP in Shanghai increased to more than 50% in 1999 for the first time. By 2016, tertiary industry has contributed to 60.2% of GDP in Shanghai. It's obvious that tertiary industry has possessed a dominant position in Shanghai's economy, facilitating energy efficiency improvement in Shanghai.

4.3. Energy rebound effect

Generally, the energy rebound effect can be divided into five categories [35] as follows: (1) $RE<0$ means a super-conservation case, i.e., actual energy saving is more than theoretical (expected) energy saving; (2) $RE=0$ means a zero rebound case, i.e., theoretical (expected) energy saving is completely achieved; (3) $0<RE<1$ means a partial rebound case, i.e., actual energy saving is less than theoretical (expected) energy saving; (4) $RE=1$ means a full rebound case, i.e., actual energy saving is equal to theoretical (expected) energy saving; (5) $RE>1$ means a backfire effect case, i.e., energy rebound amount is more than theoretical (expected) energy saving. The estimated rebound effect, expected energy saving and energy rebound amount are shown in Table 6.

Table 6

Estimation results of the rebound effect, expected energy saving, and energy rebound amount in Shanghai.

Year	Overall economy			Secondary industry			Tertiary industry		
	Rebound effect (%)	Expected energy saving (10,000 tce)	Energy rebound amount (10,000 tce)	Rebound effect (%)	Expected energy saving (10,000 tce)	Energy rebound amount (10,000 tce)	Rebound effect (%)	Expected energy saving (10,000 tce)	Energy rebound amount (10,000 tce)
1991	56.59 [a]	-42.89	-24.27	477.53 [a]	-38.74	-184.98	-79.75 [b]	9.88	-7.88
1992	97.80	313.59	306.69	64.01	305.66	195.64	43.86	18.92	8.30
1993	97.75	274.64	268.47	76.16	136.79	104.19	-0.97 [b]	59.38	-0.58
1994	98.46	182.98	180.16	-59.92 [b]	208.11	-124.69	-40.28 [b]	33.02	-13.30
1995	98.86	523.62	517.64	30.04	421.24	126.54	-27.69 [b]	59.03	-16.35
1996	98.55	431.18	424.94	36.72	423.03	155.33	-7.58 [a]	-15.78	1.20
1997	98.19	430.73	422.92	33.10	327.48	108.41	90.82	22.57	20.50
1998	97.33	361.26	351.61	37.05	325.92	120.76	-176.06 [a]	-7.67	13.50
1999	92.00	187.78	172.76	-5.63 [b]	87.39	-4.92	383.56	24.44	93.72
2000	93.84	212.01	198.96	82.33	214.50	176.60	-51.22 [a]	-30.28	15.51
2001	88.29	225.69	199.27	46.37	325.79	151.07	-120.17 [a]	-111.19	133.62
2002	94.17	283.84	267.30	80.87	343.72	277.97	9.75 [a]	-86.67	-8.45
2003	89.83	229.36	206.03	81.05	354.50	287.31	82.48 [a]	-46.27	-38.16
2004	86.75	253.60	220.00	80.93	334.01	270.30	-70.19 [a]	-87.58	61.47
2005	130.03 [a]	-29.04	-37.76	81.14 [a]	-141.18	-114.55	305.52	25.44	77.72
2006	89.78	391.51	351.52	76.87	354.66	272.64	5789.62 [c]	2.17	125.59
2007	89.67	493.90	442.90	119.46	237.02	283.14	107.95	130.29	140.65
2008	93.08	467.97	435.59	60.59	327.27	198.30	91.07	88.50	80.60
2009	96.84	617.83	598.33	57.68	262.27	151.27	124.50	190.11	236.68
2010	74.39	164.63	122.46	101.19	355.00	359.23	-30.68 [a]	-33.98	10.43
2011	94.70	567.42	537.33	76.35	118.70	90.62	58.31	348.31	203.11
2012	99.21	782.15	775.96	83.49	385.75	322.08	123.23	232.33	286.31
2013	95.30	600.36	572.13	109.43	270.21	295.69	-283.81 [b]	274.66	-779.54
2014	102.59	987.68	1013.27	90.77	427.41	387.97	89.95	291.30	262.01
2015	94.50	521.81	493.14	80.83	65.34	52.81	123.95	234.15	290.23
2016	93.12	484.74	451.37	102.98	146.82	151.20	216.62	106.18	230.00
Mean	93.96	381.48	397.11	73.10	253.03	206.32	146.61	66.59	160.82

Note: The following three types of anomalous values are excluded when calculating the means of the energy rebound effect and the energy rebound amount.

[a] The year when energy intensity increased.

[b] The year when energy intensity decreased with the negative contribution of technological progress to GDP growth.

[C] The year when energy intensity was almost unchanged.

During the period of 1991-2016, the average rebound effect of overall in Shanghai was 93.96%, indicating a high partial rebound effect. The corresponding energy rebound amount was 397.11 (10,000 tce). This indicates that 93.96% and 3971.1 thousand tce of expected energy saving caused by improved energy efficiency is offset by extra energy consumption caused by technological progress. In other words, only 6.04% of expected energy saving in Shanghai is achieved. As shown in Fig. 7, the rebound effect of overall economy was between 0 and 100% except two anomalous values and the value in 2014, when a "backfire" effect appeared. In most years, the rebound effect was between 85% and 100%. This indicates that economic growth caused by technological progress leads to an increase in energy consumption to largely offset the expected energy saving, and thus that the effort in energy saving in Shanghai is low effective.

During the period of 1991-2016, the average rebound effect of Shanghai's secondary industry was 73.10% after anomalous values were excluded. The corresponding average energy rebound amount was 206.32 (10,000 tce). This means that only 26.90% of expected energy saving in Shanghai's secondary industry is achieved. As shown in Fig. 8, a backfire effect appeared in 2007, 2010, 2013, and 2016 when the rebound effect was more than 100%. Overall, the rebound effect of Shanghai's secondary industry presents a circuitously upward trend.

Regarding tertiary industry, the average rebound effect during the period of 1991-2016 was 146.61% after anomalous values were excluded. The corresponding average energy rebound amount was 160.82 (10,000 tce), less than that of secondary industry. As shown in Fig. 9, the rebound effects in 1999, 2005, 2007, 2009, 2012, 2015, and 2016 were more than 100%, indicating a backfire effect in those years. Compared with secondary industry, the rebound effect of tertiary industry shows an obvious volatility.

These findings indicate that, as mentioned above, although tertiary industry has an energy-saving characteristic, the sector's energy demand is more sensitive to improved energy efficiency and technological progress. However, because of less energy consumption, tertiary industry has smaller energy rebound amount than secondary industry. Therefore, once the rebound effect of tertiary industry can be effectively mitigated, more expected energy saving in Shanghai will be achieved.

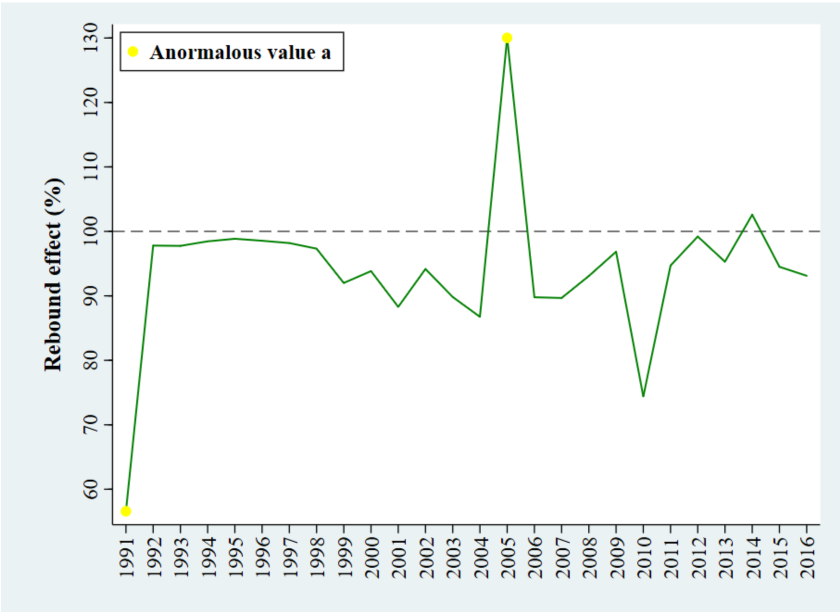

Fig. 7. Rebound effect of overall economy in Shanghai

Note: Legend "anomalous value a" refers to the first (a) type of anomalous values in Table 6.

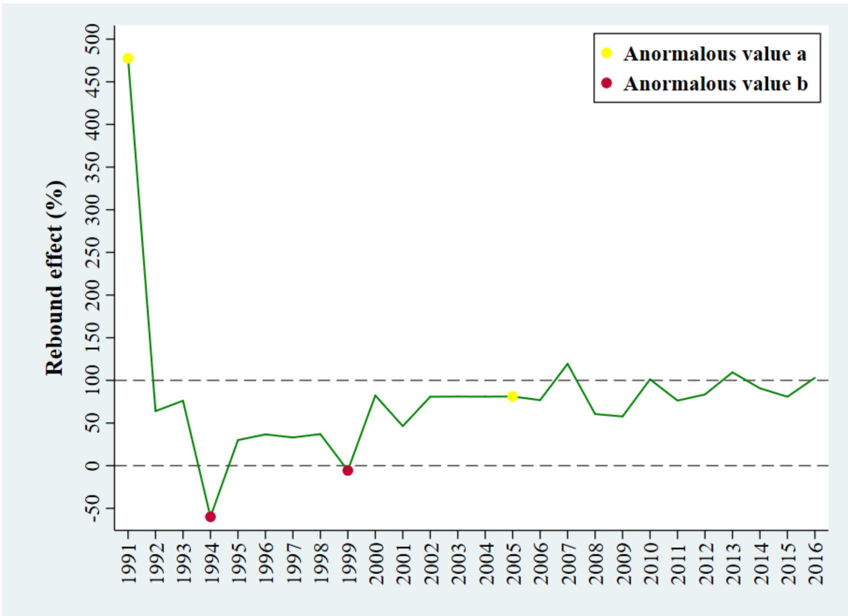

Fig. 8. Rebound effect of secondary industry in Shanghai

Note: Legend "anomalous value a" and "anomalous value b" refer to the first (a) and the second (b) types of anomalous values in Table 6, respectively.

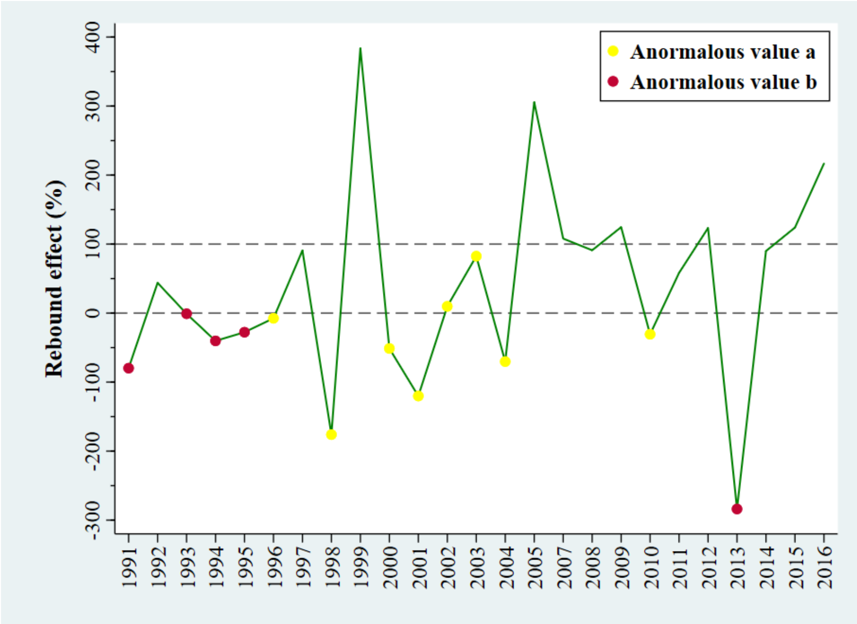

Fig. 9. Rebound effect of tertiary industry in Shanghai

Notes: Legend "anomalous value a" and "anomalous value b" refer to the first (a) and the second (b) types of anomalous values in Table 6, respectively; for the convenience of observation, we exclude the anomalous value in 2006.

It is noteworthy that there are some anomalous values (especially some negative values) of the rebound effect in Table 6 and Figs. 7, 8 and 9. Generally, there are two types of abnormal values of the rebound effect due to the following two reasons [34]: (i) an increase in energy intensity and (ii) a decrease in energy intensity with a negative contribution of technological progress to output growth. The first case means that energy efficiency decreases and thus the requirement of the existence of the rebound effect is absent. Therefore, in Case (i), the rebound effect is false and the value of the rebound effect has no real economic meaning. The second case indicates that the improved energy efficiency fails to cause the technological progress and corresponding economic growth, as well as added energy consumption. Hence, in Case (ii), the "rebound effect" is neither the direct outcome of the improved energy efficiency nor super-conservation.

In addition, a particular case appeared in tertiary industry in 2006, when energy intensity had an infinitesimal decrease compared with that in 2005. That is to say, energy intensity in 2006 was almost unchanged compared with that in 2005, leading to a minimal value of expected energy saving and an extreme value of the rebound effect. Obviously, in this case, energy efficiency is not improved substantially, and thus the requirement of the existence of the rebound effect is inadequate. Hence, we also can consider that the value of the rebound effect in this case is no substantial economic meaning. Thus, since these three cases do not satisfy the prerequisite of the estimation model in this study, the corresponding estimation results have no substantial meaning. All the negative values of the rebound effect in Table 6 and Figs. 7, 8 and 9 belong to Case (i) or Case (ii), rather than super-conservation. In particular, tertiary industry has much more anomalous values than secondary industry, indicating that the energy demand and energy efficiency of tertiary industry are more volatile and more sensitive to external environment.

As shown in Fig. 10, the energy rebound amount of overall economy in 2014 was the largest in the sample period. Moreover, the energy rebound amount of secondary industry is larger than that of tertiary industry in most years, indicating that improving the energy efficiency of tertiary industry has a more evident effect in reducing energy consumption. However, in recent years, this situation is gradually reversed. The energy rebound amount of tertiary industry exceeded that of secondary industry in 2009, 2011, 2015, and 2016. This indicates an increasingly negative impact of the rebound effect of tertiary industry on Shanghai's energy saving in recent years, due to the rapid development of tertiary industry and a corresponding increase in energy demand. Hence, both secondary industry and tertiary industry should be the main objects of mitigating the rebound effect.

Although Shanghai is better off compared with other cities in China, the city still does not thoroughly get rid of factor-driven growth mode, and thus the city's economic growth quality needs to be improved. This study uses the Slow residual approach to estimate Shanghai's technological progress rate. The generalized technological progress rate measured by the Slow residual term is regarded as the crucial promotion factor of economic growth except production factor inputs. Thus, in this study, the contribution of pure technological progress to economic growth may be overestimated, resulting in a higher rebound effect value than its actual value. However, this study can at least provide an upper bound of the rebound effect. Even considering the existence of such overestimation, a partial rebound effect still exists in most years, indicating that technological progress still has an energy saving effect, to some extent. Hence, technological progress is a key way to improve energy efficiency and conserve energy. In addition, the feasible direction of the government's endeavor for energy saving should lie in mitigating the potential rebound effect as far as possible.

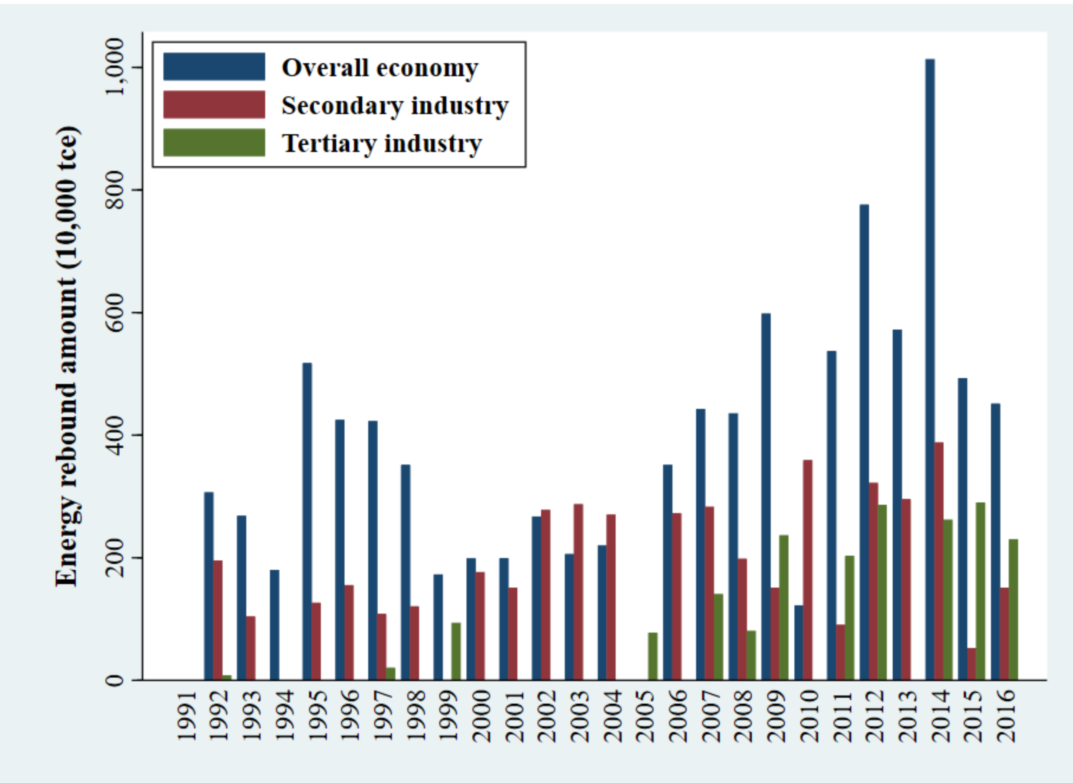

Fig. 10. Energy rebound amount of overall economy, secondary industry, and tertiary industry in Shanghai

Notes: All the sample values of energy rebound amount corresponding to the anomalous values of the rebound effect in Table 6 are excluded.

4.4. Carbon emissions caused by the energy rebound effect

Due to increasing energy consumption caused by the energy rebound effect, carbon emissions and atmospheric pollutant emissions increase. Obviously, this is detrimental to achieving carbon emission peak target committed by the Chinese government. In terms of this, we further estimate the carbon rebound amount (i.e., carbon emissions caused by the energy rebound effect), to grasp the effect of the rebound effect on carbon emissions in Shanghai. Specifically, we estimate increased carbon emissions by multiplying the energy rebound amount by weighted carbon emission coefficient. We set the annual shares of the consumption of 17 fossil fuels (raw coal, cleaned coal, briquettes, other washed coal, coke, coke oven gas, other gases, crude oil, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas, refinery gas, natural gas, other petroleum products, and other coking products) in the total energy consumption in Shanghai as their weights. Thus, the weighted carbon emission coefficient can be regarded as the weighted mean of the carbon emission coefficients of 17 fossil fuels in Shanghai. Energy consumption data are from Shanghai's energy balance sheet in *China Energy Statistics Yearbook*, and the carbon emission coefficients of various fossil fuels are from Fan et al. [9] and IPCC (Intergovernmental Panel on Climate Change). Because energy balance sheet before 1995 is incomplete, we estimate the carbon emissions caused by the energy rebound effect during the period of 1995-2016.

As shown in Table 7 and Fig. 11, during the period of 1995-2016, the mean of carbon emissions caused by the energy rebound effect of overall economy in Shanghai was 13231.9 thousand tons. Overall, the carbon rebound amount of overall economy experienced a first descending and then ascending trend, with a peak of 31489 thousand tons in 2014 and a valley of 3830 thousand tons in 2010. The mean of the carbon rebound amount of secondary industry in Shanghai was 6918 thousand tons. With a peak of 12416.5 thousand tons in 2014, the trend of the carbon rebound amount of secondary industry is close to that of overall economy in most years, indicating that secondary industry (especially industrial sector) can play a crucial role in reducing the total carbon emissions of Shanghai [9,36]. After excluding the anomalous values, the mean of the carbon rebound amount of tertiary industry in Shanghai was 5311.1 thousand tons, less than that of secondary industry. Overall, the carbon rebound amount of tertiary industry experienced a circuitously upward trend, with a peak of 8813.2 thousand tons in 2015, when the sector's energy rebound amount also reached a peak. This indicates that, with the rapid expansion and corresponding increase in energy demand of Shanghai's tertiary industry, the sector is becoming a crucial sector in energy saving and carbon emission reduction.

To observe the influence degree of carbon rebound amount, we further calculate the proportions of carbon rebound amount in the total carbon emissions of Shanghai and China (see Table 8). Referring to Fan et al. [9], we estimate carbon emissions in Shanghai and China. As shown in Table 8 and Figs. 12 and 13, the proportion of carbon rebound amount of overall economy in the total carbon emissions of Shanghai and China all experienced a first descending and then ascending trend, and exceeded 15% in 1995, 1996, 1997, 1998, 2009, 2012 and 2014, with a peak of 27.55% in 1995. Although the proportion in the total carbon emissions of China is much less than that in the total carbon emissions of Shanghai, they have identical trends. On average, the carbon rebound amount of overall economy in Shanghai accounts for 13.1% and 0.41% of the total carbon emissions of Shanghai and China, respectively. This means that, on average, the energy rebound effect caused 13.1% and 0.41% increases in carbon emissions in Shanghai and China, respectively. In other words, if mitigating the energy rebound effect, carbon emissions in Shanghai and China will reduce on average by at most 13.1% and 0.41%, respectively.

Table 7
Carbon rebound amount of overall economy, secondary industry, and tertiary industry in Shanghai (Unit: 10,000 tons).

Year	Overall economy	Secondary industry	Tertiary industry
1995	1714.25	451.90	-49.65 [b]
1996	1407.25	554.74	3.63 [a]
1997	1394.32	372.28	62.54
1998	1159.84	407.10	41.10 [a]
1999	568.06	-16.59 [b]	285.16
2000	651.29	594.22	48.91 [a]
2001	623.42	477.34	403.78 [a]
2002	863.20	925.15	-25.70 [a]
2003	660.66	949.38	-116.16 [a]
2004	700.04	885.44	186.91 [a]
2005	-119.86 [a]	-374.47 [a]	236.97
2006	1110.35	885.61	382.19 [c]
2007	1388.22	909.06	427.34
2008	1363.25	635.53	245.15
2009	1871.88	486.45	719.90
2010	383.00	1155.92	31.78 [a]
2011	1679.06	291.92	618.41
2012	2411.18	1027.82	871.36
2013	1774.87	940.59	-2369.69 [b]
2014	3148.90	1241.65	796.32
2015	1524.41	167.47	881.32
2016	1389.62	476.37	697.78
Mean	1323.19	691.80	531.11

Note: The following three types of anomalous values are excluded when calculating the means.

[a] The year when energy intensity increased.

[b] The year when energy intensity decreased with the negative contribution of technological progress to GDP growth.

[C] The year when energy intensity was almost unchanged.

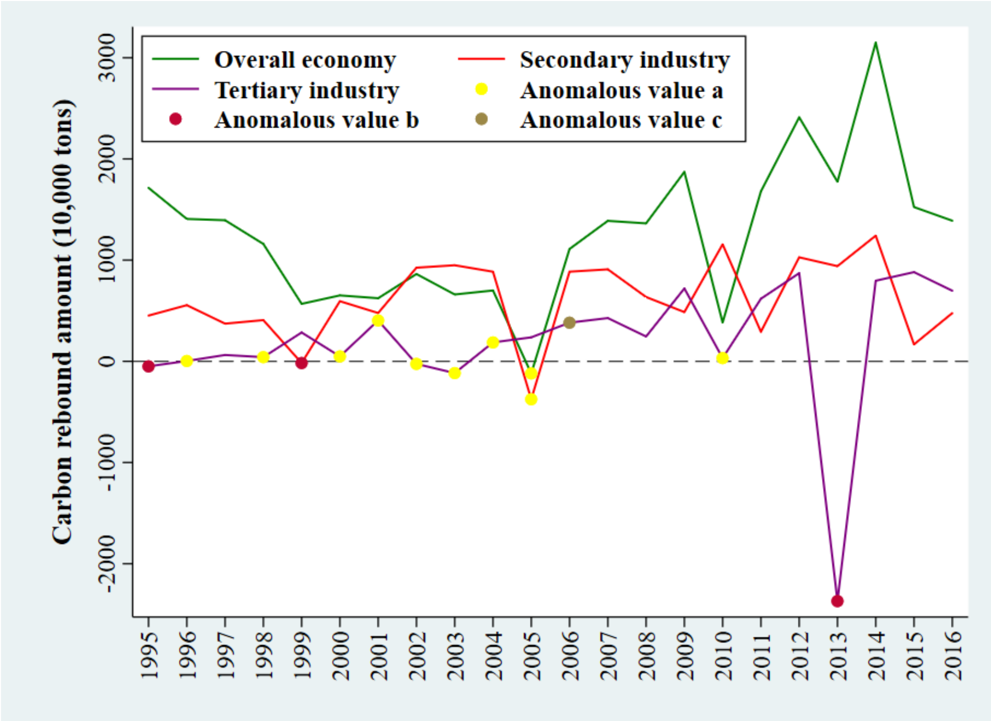

Fig. 11. Carbon rebound amount of overall economy, secondary industry, and tertiary industry in Shanghai

Notes: Legend "anomalous value a", "anomalous value b", and "anomalous value c" refer to the first (a), the second (b) and the third (c) types of anomalous values in Table 6, respectively.

Regarding secondary industry, on average, the carbon rebound amount accounts for 6.8% and 0.22% of the total carbon emissions of Shanghai and China, respectively. The proportions account for more than half of those of overall economy (13.1% and 0.41%). This can be attributed to a high energy intensity and a large carbon emission coefficient (a large high-carbon fuel consumption proportion) of secondary industry. Compared with secondary industry, tertiary industry has less proportions (4.45% and 0.12%) of carbon rebound amount in the total carbon emissions of both Shanghai and China, due to a low energy intensity and a large low-carbon fuel consumption proportion. However, the proportions of the carbon rebound amount of tertiary industry in the total carbon emissions of both Shanghai and China have an overall upward trend, with peaks of 7.19% and 0.18% in 2015 in Figs. 12 and 13, respectively. As mentioned above, this can be attributed to the rapid development and corresponding increases in energy consumption and carbon emissions of tertiary industry in Shanghai in recent years. Hence, both secondary industry and tertiary industry in Shanghai should be the main objects of energy saving and emission reduction.

In a word, these findings indicate that if we take additional measures to effectively relieve the rebound effect, carbon emissions will be significantly mitigated, being conducive to achieving China's and Shanghai's carbon emission reduction targets.

Table 8
Proportion of carbon rebound amount in total carbon emissions (Unit: %).

Year	Proportion of carbon rebound amount in total carbon emissions in Shanghai			Proportion of carbon rebound amount in total carbon emissions in in China		
	Overall economy	Secondary industry	Tertiary industry	Overall economy	Secondary industry	Tertiary industry
1995	27.55	7.26	-0.80 [b]	0.88	0.23	-0.03 [b]
1996	19.14	7.55	0.05 [a]	0.72	0.28	0.002 [a]
1997	19.77	5.28	0.89	0.71	0.19	0.03
1998	16.51	5.80	0.59 [a]	0.58	0.20	0.02 [a]
1999	6.85	-0.20 [b]	3.44	0.29	-0.01 [b]	0.15
2000	8.22	7.50	0.62 [a]	0.33	0.30	0.02 [a]
2001	7.62	5.83	4.93 [a]	0.31	0.24	0.20 [a]
2002	10.26	11.00	-0.31 [a]	0.40	0.43	-0.01 [a]
2003	7.62	10.95	-1.34 [a]	0.28	0.40	-0.05 [a]
2004	7.12	9.01	1.90 [a]	0.26	0.33	0.07 [a]
2005	-1.22 [a]	-3.82 [a]	2.42	-0.04 [a]	-0.11 [a]	0.07
2006	8.87	7.08	3.05 [c]	0.31	0.25	0.11 [c]
2007	10.23	6.70	3.15	0.35	0.23	0.11
2008	10.10	4.71	1.82	0.32	0.15	0.06
2009	15.73	4.09	6.05	0.41	0.11	0.16
2010	3.20	9.65	0.27 [a]	0.08	0.25	0.01 [a]
2011	13.22	2.30	4.87	0.33	0.06	0.12
2012	19.33	8.24	6.98	0.46	0.20	0.17
2013	14.58	7.73	-19.47 [b]	0.36	0.19	-0.48 [b]
2014	25.55	10.07	6.46	0.63	0.25	0.16
2015	12.43	1.37	7.19	0.31	0.03	0.18
2016	11.30	3.87	5.67	0.29	0.10	0.14
Mean	13.10	6.80	4.45	0.41	0.22	0.12

Notes: Carbon emissions in Shanghai and China are estimated by authors; the following three types of anomalous values are excluded when calculating the means.

[a] The year when energy intensity increased.

[b] The year when energy intensity decreased with the negative contribution of technological progress to GDP growth.

[C] The year when energy intensity was almost unchanged.

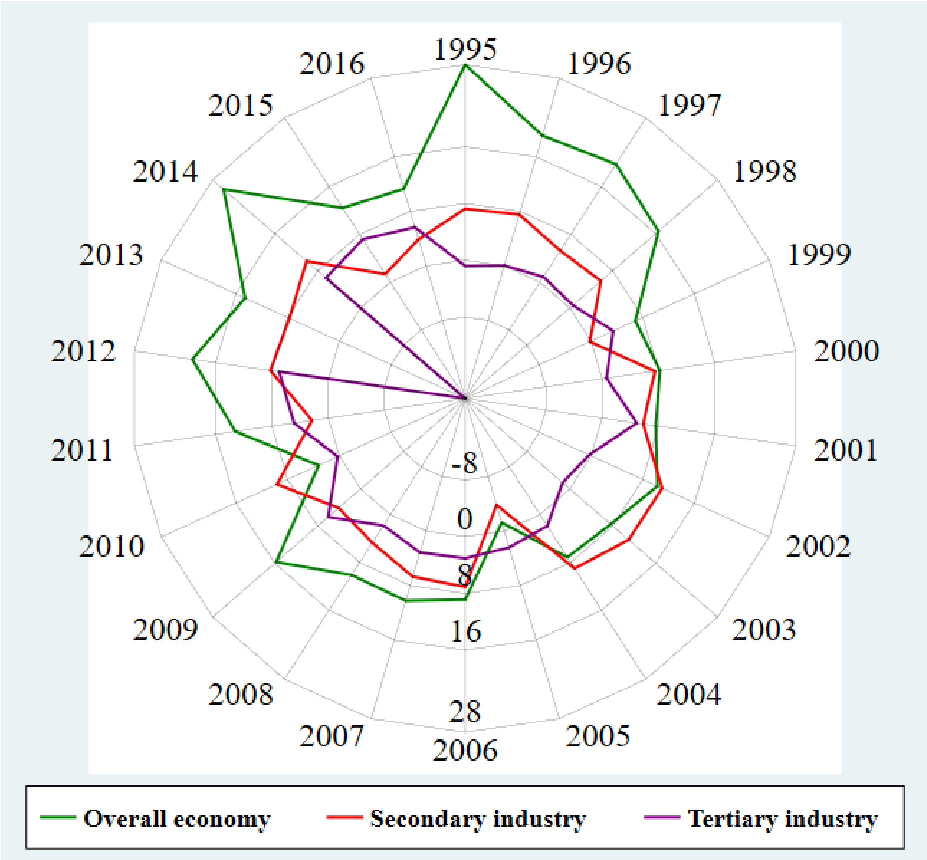

Fig. 12. Proportion of carbon rebound amount in total carbon emissions in Shanghai (Unit: %)

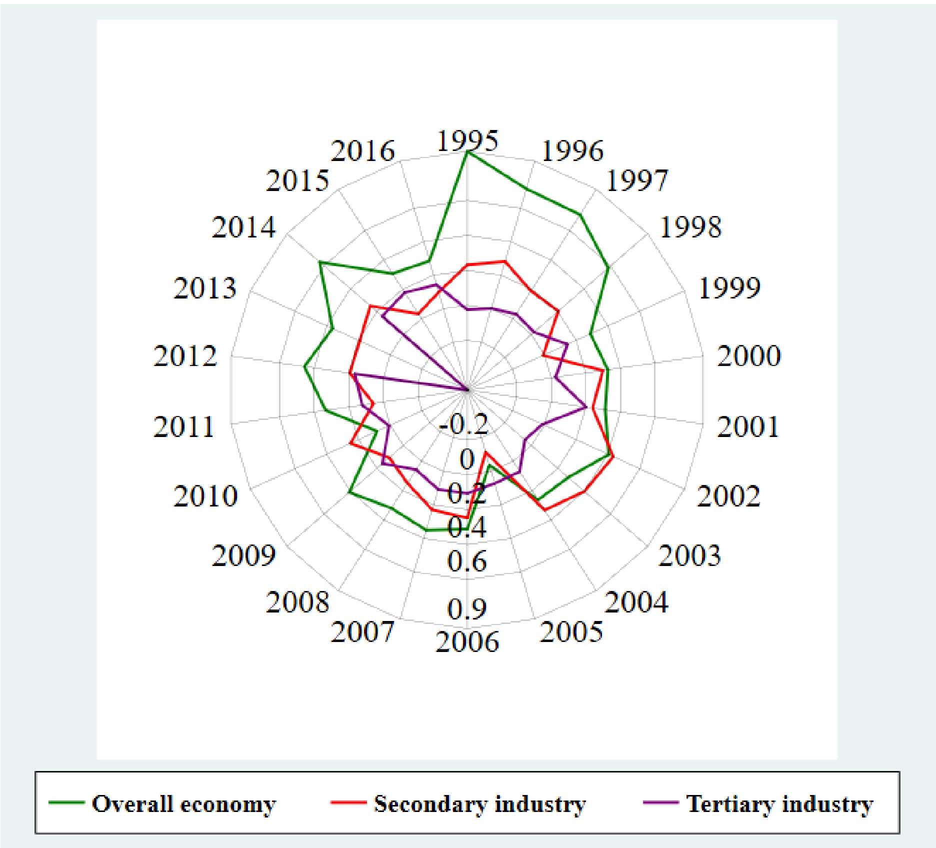

Fig. 13. Proportion of carbon rebound amount in total carbon emissions in China (Unit: %)

5. Concluding remarks

The energy rebound effect has become a substantial obstacle of achieving the expected target of energy-saving policies under the rapid urbanization background of China. As the economic center of China and a typical energy import-dependent mega-city, Shanghai's social and economic sustainable development is confronted with severe energy constraints. In this paper, based on the IPAT identity and the Solow residual approach, we use the state space model with time-varying parameters to estimate the energy rebound effect of overall economy, secondary industry, and tertiary industry in Shanghai caused by technological progress during the period of 1991-2016. Furthermore, we estimate the carbon rebound amount (i.e., carbon emissions caused by the energy rebound effect) based on the energy rebound amount and weighted carbon emission coefficient. The results show that, during the period of 1991-2016, the average energy rebound effect of overall economy in Shanghai was 93.96%, indicating a high partial rebound effect. In most years, the rebound effect of overall economy was between 85% and 100%. Hence, economic growth resulting from technological progress causes an increase in energy consumption to largely counteract expected energy saving from improved energy efficiency, and thus that the effort in energy conservation in Shanghai is low effective. The average rebound effect of Shanghai's secondary industry was 73.10%. That is to say, only 26.90% of expected energy saving from improved energy efficiency in Shanghai's secondary industry is achieved. Overall, the rebound effect of secondary industry has a circuitously upward trend. Even in some years, a backfire effect appears.

Regarding tertiary industry, the average rebound effect during the period of 1991-

2016 was 146.61% after excluding anomalous values, indicating a backfire effect. Compared with secondary industry, the rebound effect of tertiary industry shows an obvious volatility. However, due to less energy consumption, the average energy rebound amount of tertiary industry is less than that of secondary industry. Therefore, although tertiary industry has an energy-saving characteristic, the sector's energy demand is more sensitive to energy efficiency improvement and technological progress. In particular, the energy rebound amount of tertiary industry exceeded that of secondary industry in some recent years. This finding indicates an increasingly unfavorable impact of the rebound effect of tertiary industry on Shanghai's energy saving in recent years, with the rapid expansion and corresponding increase in energy demand of Shanghai's tertiary industry. Hence, both secondary industry and tertiary industry should be the main objects of mitigating the rebound effect, as well as energy saving and emission reduction. Overall, although technological progress can be a key way to improve energy efficiency and conserve energy, the potential rebound effect should be relieved as far as possible to improve the effectiveness of the endeavor for energy saving.

The estimated results of carbon rebound amount reinforce the significant impact of the energy rebound effect on achieving energy saving and emission reduction targets. On average, the energy rebound effect caused 13.1% and 0.41% increases in carbon emissions in Shanghai and China, respectively. Regarding secondary industry, the carbon rebound amount accounts for 6.8% and 0.22% of the total carbon emissions of Shanghai and China on average, respectively, more than half of those of overall economy. Compared with secondary industry, tertiary industry has less proportions (4.45% and 0.12%) of carbon rebound amount in the total carbon emissions of both Shanghai and China, because of a low energy intensity and a large low-carbon fuel consumption proportion. Therefore, mitigating the energy rebound effect can significantly abate carbon emissions.

In summary, due to the substantial impact of the rebound effect, improving technological progress and energy efficiency should not be the only way to achieve energy-saving target, especially in energy import-dependent mega-cities like Shanghai. Some supporting policies should be carried out to ensure that the expected outcome of energy-saving effort can be realized as far as possible.

First, because of objective existence of the energy rebound effect, only if policy makers should take into account the rebound effect when formulating related policies, energy saving and carbon emission reduction targets will be more effectively achieved. By doing this, the expected energy-saving outcome can be more precisely grasped, so that more rational decision is made. Specifically, as pointed out by a lot of researchers [18,34,35], some market-oriented policies and measures, such as energy-saving technology subsidies and carbon tax, can be implemented to mitigate the rebound effect and ensure energy-saving outcome.

Second, because the rebound effect exists widely in economic development process, with economic development and production scale expansion, energy demand and corresponding carbon emissions will continuously increase without the adjustment of energy consumption structure. The green and low-carbon of energy consumption structure can be expected to resolve the rebound effect problem in the long run, especially for secondary industry. In fact, the Chinese government and Shanghai municipal government recently have made some effort in energy structure adjustment by supporting the application of clean and renewable energy. Relevant measures should be persistently taken. Moreover, the development of new energy can drive investments in R&D and facilitate the development of related industries.

Third, the rise in energy price is regarded as an effective way to mitigate the rebound effect [35]. Therefore, some appropriate price policies need to be carried out to abate the increase in energy demand caused by improved energy efficiency and thus to minimize the rebound effect. Considering that China's low energy price policies counteract energy conservation effort and government's frequent intervention makes energy price far from real marketization [34], the Chinese government should take some measures, such as marketization reform of energy price and an environmental tax (a carbon tax), to reflect real energy costs and arouse producers' and consumers' energy-saving awareness and activities.

Last but not least, to achieve energy saving and emission reduction targets, the green and low-carbon transformation of industrial development mode is very necessary for both secondary industry and tertiary industry in energy import-dependent mega-cities like Shanghai. Secondary industry in Shanghai still has a relatively high proportion compared with other international mega-cities, such as New York, London, and Tokyo. With the implementation of more stringent environmental governance policies, traditional economic development mode at the expense of environmental pollution is no longer feasible in China. The development of high-end manufacturing and producer services is expected to facilitates improving energy efficiency and reducing total energy consumption in both Shanghai and China.

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