RESEARCH ARTICLE

A probation of eco-friendly production by eco-output elasticity of energy consumption

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Abstract
Energy is one of the critical factors for economic growth, and carbon emissions are by-products of energy use that degrade environmental quality. This research thus establishes an index of eco-output elasticity of energy consumption to find an eco-friendly production stage in which not only output increases, but also energy consumption degrades. Our observation subject is China, which employs its own energy intensity index to monitor the nexus of economy, energy, and environment. While its energy intensity index is unable to point out the eco-friendly production stage, the index of eco-output elasticity of energy consumption herein does. This paper offers three main empirical findings on China: (i) it presents an eco-friendly production stage from 2012 to 2013; (ii) it has better improvement on energy savings than CO_2 reduction; and (iii) in general, its status quo is still high energy consumption, but this phenomenon is improving.

Introduction

The proper coordination between the economy and the environment has become an issue critically studied over the last couple of decades. One desirable outcome is that eco-friendly production creates a double dividend on the economy and the environment in which gross domestic product (GDP) increases and energy consumption and carbon dioxide (CO_2) emissions decrease. Daly (1991) argues the failure of environmental macroeconomics to spur humans' duty to bring the economy and environment into harmony. Up to today, the debate over the double dividend on economic growth and environmental protection is continuing (Yang et al. 2020; Degirmenci and Aydin 2021).

Environmental policy research involves a self-contained economic model in order to realize the targets of both the economy and environment via a market mechanism. China adopts energy intensity as an index to monitor its economy

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and environment development. In the latest Five-Year Plan, the country plans to continuously degrade energy intensity by 2025 in order to meet climate goals. However, energy intensity is defined as how much energy is used in one unit of output that directly connects to production and energy use, but it only indirectly touches upon the environmental issue. The environment Kuznets curve (EKC) is able to directly connect the issues of the economy and environment. Hence, for the nexus of economy, energy, and environment, this study shall simultaneously apply the index of energy intensity and EKC.

One available direction to take is to establish an index that targets the economy, energy, and environment, specifically on eco-friendly production whereby an increase in output decreases energy consumption. Indeed, energy consumption degradation causes carbon emissions to fall and the environment to improve. Figure 1 illustrates that the outcome from energy intensity index is unable to find an eco-friendly production stage. Though China's energy intensity is decreasing year by year as shown in Fig. 1, we cannot discriminate where eco-friendly production situation is. Lower energy intensity may be caused by both output and energy use simultaneously increasing, where the change in output amount is larger than that of energy use. However, the characteristic of eco-friendly production is that output increases and energy consumption decreases. Aside from the
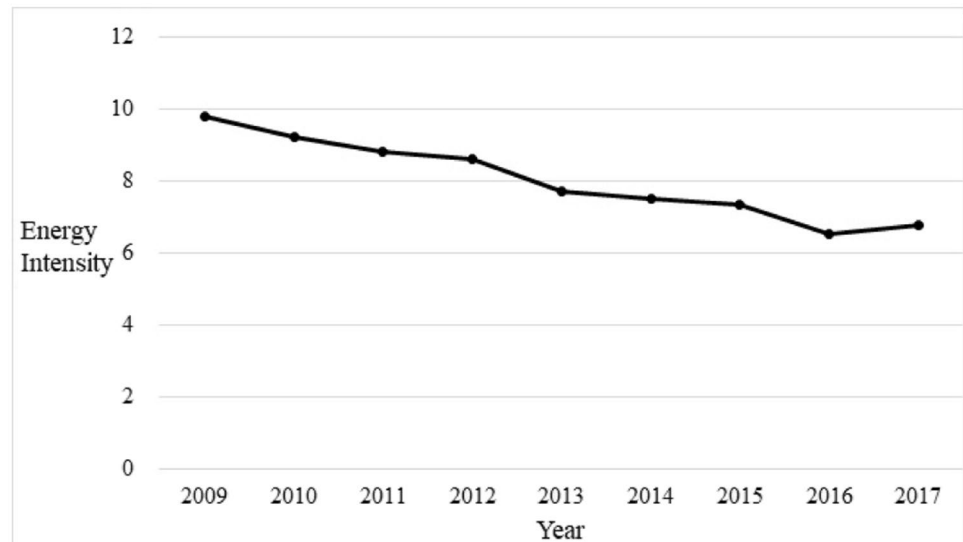
Fig. 1 The trend of energy intensity in China

energy intensity index and EKC, it is meaningful to explore an index that is able to confirm the eco-friendly production stage.

The EKC literature is helpful for investigating the nexus of the economy and environment, such as Nazir et al. (2018) and Usman et al. (2019) who focus on the shape of EKC. The EKC hypothesis states that economic growth harms the environment in the beginning, but then, the environment improves after a turning point in EKC when output continuously grows. Each country typically targets economic growth, but such growth and environmental protection are hard to focus on at the same time. One general case is that the cost of economic growth is environmental damage. Hanif (2017) indicates that carbon emissions negatively impact the environment and generate pollution. Based on the spirit of Sustainable Development Goals (SDGs) by the United Nations with goal numbers 8, 13, and 15 relating to the environment and clean energy, we aim to set up a framework in order to achieve a balance between economic growth and environment quality.

Environment quality correlates to carbon emissions, carbon emissions relate to energy consumption, energy consumption is relative to the production of goods and services, and production is connected to economic growth. The indicator of energy intensity is a critical medium for connecting energy consumption, economic growth, and environment protection, and so many studies have focused on the nexus of energy intensity, economic growth, and carbon dioxide emissions (Shahbaz et al. 2015; Wu et al. 2016; Emir and Bekun 2019). Based on Khan et al. (2018) and Hanif (2018), CO_2 emissions are viewed as a useful indicator to capture environmental quality. In order to achieve the target of environment quality improvement, one available way is to monitor energy consumption by some index such as energy

efficiency or energy intensity. Chang (2014) finds that energy efficiency or energy intensity has an inverse relationship in which higher energy efficiency or low energy intensity can control CO_2 emissions and improve environmental quality. Baloch et al. (2020) conduct research on energy efficiency, energy intensity, and environmental quality in which they provide an assessment of energy density and energy efficiency and create an indicator of environmental performance by using the approaches of data envelopment analysis and non-normative account aggregation.

Economic growth momentum emphasizes being factor-driven in the past, but it is now innovation-driven. Innovation-driven refers to knowledge, technology, and other factors introduced in order to realize national sustainable development by improving use efficiency of traditional production factors such as energy. Technical innovation affects energy consumption, production, and CO_2 emissions. Hao et al. (2021) conduct energy research via technical innovation. Through energy technical advancement, less energy consumption is employed to produce more additional output. An energy intensity index can be used to monitor the effect of technical innovation on energy and production. Many recent studies in the literature have looked at the impact of energy technology innovation on output and energy consumption through EKC (Chien et al. 2021; Cheng and Yao 2021; Sun et al. 2021a, b). Our research involves the Cobb–Douglas production function, energy intensity index, and environmental Kuznets curve to observe the nexus of output, energy consumption, and environment quality in China.

Chen and Lei (2018) describe the nexus of economy, energy, and environment by energy being an essential input factor for economic growth. On the other hand, economic progress brings about environmental degradation due to

greenhouse gas (GHG) emissions caused by energy use. Among the six kinds of GHG, CO_2 has the most significant contribution to environmental pollution. According to an investigation in 16 European Union countries by Bekun et al. (2019), the concentration of energy-related CO_2 emissions in the environment has increased to 45%. The early literature independently focuses on examining energy and growth (Apergis and Payne 2011, 2012; Omri 2014), or growth and the environment (Heyes 2000; Lawn 2003; Al-Mulali et al. 2015), or the environment and energy (Dincer and Rosen 1999; Nakata 2004; Omer 2008), but our study connects together the fields of energy, growth, and environment such as Khan et al. (2020), Mohsin et al. (2021), and Sun et al. (2021a, b) who explore the nexus among energy, growth, and environment. While most studies employ statistic or econometric methods, the literature seldom starts from theoretical and empirical viewpoints. Our paper thus establishes the production function, EKC function, and CO_2 emission function to investigate the energy-economy-environment nexus.

The relationship between economic growth and environment quality can be better understood through a study of EKC. We expect to see a production situation after EKC's turning point, called the eco-friendly production stage, in which increased output brings about energy consumption degradation. Hence, this paper presents an index of eco-output elasticity of energy consumption to probe the eco-friendly production stage. Research on eco-output elasticity of energy consumption is necessary since the index of energy intensity is popularly applied by many countries such as China to monitor energy use, but this index is unable to find an eco-friendly production stage. Liddle et al. (2020) compute the values of GDP elasticity of energy demand on 26 middle-income countries. If a country has GDP elasticity of less than one, then it is on the right-hand side of an inverted U-shape energy intensity-GDP path, which suggests that energy intensity in this country will fall along with its economic growth.

Ivanovski et al. (2021) apply the output elasticity of non-renewable energy consumption to examine the time-varying impact of renewable and non-renewable energy consumption on economic growth. They find that the output elasticity of non-renewable energy consumption is not only positive but has also been increasing for countries in the Organization for Economic Cooperation and Development (OECD). This result implies that OECD countries rely on non-renewable energy to create economic growth. Lin and Raza (2021) take Pakistan's agriculture sector as an observation sample and find its output elasticity of energy is high, which implies that its agriculture is a high energy intensive sector. They suggest that its agriculture sector can improve capital and skilled labor to substitute for energy use. Naeem et al. (2021) collect data of Pakistan from 1985 to 2018 to compute its output elasticity for oil, natural gas, hydroelectricity, capital

per worker, and technology. Solarin et al. (2021) find that both hydropower and solar energy are substitutable for fossil fuels in Italy. They conclude that Italy has gradually moved to environmental friendly production through renewable energy use substituting for fossil fuel use.

A direct meaning of eco-friendly is not being harmful to the environment, and its indirect meaning is conserving resources like water and energy. Some studies are based on the viewpoint of "more renewable energy use and less fossil fuel use" when discussing the topic of being eco-friendly (Hosseinpour et al. 2020; Olabi et al. 2020; Song et al. 2020); other studies are based on the viewpoint of "a bit of fossil fuel use creates high economic growth." The latter usually monitor changes in energy intensity and/or energy efficiency in order to be eco-friendly (Chang 2014, 2015; Gao et al. 2021). The EKC hypothesis concludes that when economic growth surpasses a critical point, an eco-friendly production stage automatically starts in which economic growth naturally brings forth energy savings. Under the viewpoint of "a bit of fossil fuel use creates high economic growth," this study establishes an index of eco-output elasticity of energy consumption to find an eco-friendly production stage.

We next review and summarize the EKC studies on their mathematical framework, which help us understand the theoretical construction on probing eco-friendly production. The studies by Hasanov et al. (2021), Radmehr et al. (2021), Luo et al. (2021), and Ullah et al. (2022) have the common features of the application of the Cobb–Douglas production function and that CO_2 emissions are caused by a production outcome and energy consumption. In addition, another common feature is that they study the CO_2 source within an investigation of mixed factors, including GDP, energy consumption, emitting capital use, and foreign direction investment. Furthermore, Luo et al. (2021) and Ullah et al. (2022) investigate the EKC shape by the regression model in which the CO_2 emission function is a quadric form of GDP in the former paper and industrial growth in the latter study. Our paper focuses on the finding of the eco-friendly production stage in EKC by establishing an index of eco-output elasticity of energy consumption, which the literature seldom discusses.

We here provide the advantages of the index of eco-output elasticity of energy consumption established in this paper. Establishing an index of eco-output elasticity of energy consumption to find the eco-friendly production stage is different from using a regression model to find the EKC shape since the former emphasizes energy economics where "a bit of fossil fuel use creates high economic growth," and the latter focuses on environmental economics of negative externality caused by economic activity. Many studies apply a regression model to analyze the source of CO_2 emissions by using dependent variables such as GDP, FDI, emitting capital, and fossil fuel

energy consumption. However, our paper focuses and captures fossil fuel energy consumption as the source of CO_2 emissions to investigate the eco-friendly production stage in which an organization uses a bit of fossil fuel energy to create high economic growth and to emit a little CO_2. The energy intensity indicator is a popular estimator to monitor the relationship between energy consumption and economic output, but it cannot point out the eco-friendly production stage of "a bit of fossil fuel use creates high economic growth." The index of eco-output elasticity of energy consumption established in this paper involves the concept of energy intensity so that our index not only estimates energy use efficiency but also indicates the eco-friendly production stage.

The rest of this study runs as follows. The "Model set-up" section is the model set-up. The "Theoretical analysis" section is the theoretical analysis. The "Empirical result" section is the empirical result. The "Conclusion" section is the conclusion.

Model set-up

Since the production function can describe the contribution of production factors, it has often been used to evaluate the problem of economic growth (Harhoff 1998). The model settings by Ouyang and Lin (2015), Yu (2021) and Wannakrairoj and Velu (2021) add energy input into a production function so as to fit a modern production style. Wang et al. (2021) employ the Cobb–Douglas production function to focus on investigating the nexus of energy, economy, and innovation. The production function in this study is $Y = f(K, L, E) = AK^a L^b E^c$, which can be linearized into a natural log form as

$$Ec : lnY = lnA + alnK + blnL + clnE, \quad (1)$$

where Y represents output, A represents a technical factor, L represents the labor number of employees, and K represents the amount of capital. Since Eq. (1) captures the relationship between economy activity and various input factors, it is a function for economic activity (Ec).

Kaya (1989) decomposes CO_2 emissions by Kaya identity in order to understand several affecting variables on CO_2 emissions. It is certain that energy consumption is a critical factor that causes CO_2 emissions, and the link between energy consumption and CO_2 emissions is the coefficient of CO_2 emissions (Ouyang and Lin 2015). The relationship between energy consumption and CO_2 emissions is

$$Em : CO_2 = e^*E, \quad (2)$$

where e is the coefficient of carbon emissions per unit energy consumption. Equation (2) is a function of CO_2 emissions (Em).

Yeh and Liao (2017) develop the model of "stochastic impact of regression on population, affluence, and technology (STIRPAT)" to explain human activity's impact on the environment. Khan et al. (2020) then include the idea of the environmental Kuznets curve into the STIRPAT model. Based on the STIRPAT model and its extension form, we present the relationship between environment and economy as $CO_2 = (-fY^2 + gY)$. Since the relationship between CO_2 emissions and energy consumption appears in Eq. (2), we have $e^*E = (-fY^2 + gY)$. In order to describe the relationship between energy consumption and output, we state the energy function as

$$En : E = (-fY^2 + gY)/e, \quad (3)$$

where $f > 0$ and $g > 0$. Here, they present an inverse U-shape correlation in which energy consumption initially increases

Fig. 2 The scenario of high energy intensity
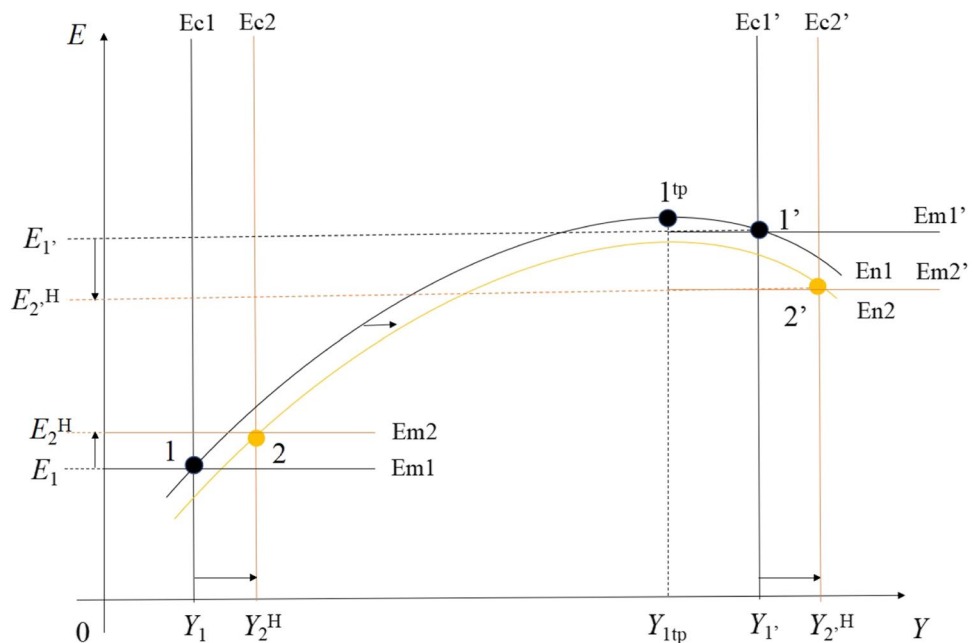
by a rise in output and then decreases after a turning point. Equation (3) is a function of energy consumption (*En*).

Theoretical analysis

In the $\{Y, E\}$ space, the slope of the *Ec* curve in Eq. (1) is positive and can be presented as

$$dE/dY|_{Ec} = (1/c)^*(E/Y) \geq 0, \tag{4}$$

where (E/Y) is energy intensity. Increases (decreases) in A (technical factor), L (labor number of employees), and K (amount of capital) generate rightward (leftward) shifts in the *Ec* curve of Eq. (1). If energy intensity is large (small), then the slope of the *Ec* curve is steep (flat), which means that the output change is smaller (larger) than the change in energy consumption. In other words, a flat *Ec* curve is an effective production mode to the environment under which an increase in the size of output is larger than that of energy consumption. Equation (4) can be rewritten into the formula of output elasticity of energy consumption (E_e^y) as

$$\begin{aligned} E_e^y &= |(dE/E)/(dY/Y)| = |(dE/dY)^*(Y/E)| \\ &= |(dE/dY)^*(1/(E/Y))| = \left|(1/MP_e)^*AP_e\right| = (1/c) \end{aligned} \tag{5}$$

We usually take an absolute value on elasticity measurement. According to Eq. (1), a large coefficient of energy consumption (c) causes large output, which indicates small output elasticity of energy consumption based on Eq. (5). In addition, the output elasticity of energy consumption is also relative to the slope of the production function (dE/dY) and energy intensity (E/Y), and ($1/(dE/dY)$) and (E/Y) also mean marginal productivity of energy (MP_e) and average productivity of energy (AP_e), respectively. In order to apply Eq. (5) on a probation of the eco-friendly production stage, this research establishes an index of eco-output elasticity of energy consumption as follows:

$$\begin{aligned} E_e^y\big|_{eco} &= (dE/E)/(|dY|/Y) = (dE/|dY|)^*(Y/E) \\ &= (dE/|dY|)^*(1/(E/Y)) = \left(1/MP_e\right)^*AP_e \end{aligned} \tag{6}$$

If $E_e^y|_{eco} < 0$, then it is an eco-friendly production process, which means that a country exhibits economic growth and its energy consumption is decreasing. The symbol $|dY|$ in Eq. (6) can avoid an error probation in the case when the country is in an economic depression, and the economic depression brings forth an inefficient increase of energy consumption; i.e., energy use increases during an economic depression. The index of eco-output elasticity of energy consumption established by this paper involves the index of energy intensity. If low energy intensity caused by energy consumption reduction brings positive economic growth, then it exhibits an eco-friendly

production stage. Based on our index, low energy intensity is only a candidate of the eco-friendly production stage. The necessary conditions of this are energy consumption reduction and positive economic growth. This finding justifies the advantage of our index and distinct from the index of energy intensity.

The slope of the *En* curve in Eq. (3) is presented as

$$\begin{aligned} dE/dY|_{En} &= (-2fY + g)/e > 0 \; if \; Y < g/2f, \\ &= (-2fY + g)/e < 0 \; if \; Y > g/2f \end{aligned} \tag{7}$$

The term ($g/2f$) indicates a turning point on the *En* curve, which means that if the output is before (after) ($g/2f$), then the slope of the *En* curve is positive (negative). A positive (negative) slope on the *En* curve means that an increase in output causes energy consumption to increase (decrease). A high (low) coefficient of carbon emissions (e) flattens (steepens) the slope of the *En* curve. When an increase (decrease) in the *Ec* curve arises due to a change in A, L, or K, the *En* curve in Eq. (7) shifts downward (upward).

Comparative static analysis

A crossing point on the curves of *Ec*, *Em*, and *En* presents an equilibrium in economic activity, CO_2 emissions, and energy consumption, and the equilibrium point decides the levels of output, CO_2 emissions, and energy consumption. Because of a fixed ratio between CO_2 emissions and energy consumption, this study only pays attention to the relationship between output and energy consumption. If we consider a technical innovation effect in economic bodies with different energy intensities, then there are three scenarios as follows.

Scenario 1: High energy intensity causes dE/dY|_Ec → ∞

This scenario is described by Fig. 2 in which the *x*-axis means output and the *y*-axis means energy consumption. The turning point 1^{tp} in Fig. 2 means the directional changes on output and energy consumption. Before (after) the turning point, a positive (negative) slope of the *En* curve indicates that increased output increases (decreases) energy consumption. Technical innovation generates a rightward shift in the *Ec* curve and a downward shift in the *En* curve. Based on the result in Fig. 2, technical innovation makes the outputs increase from Y_1 to Y_2^H and from $Y_{1'}$ to $Y_{2'}^H$, but is uncertain on energy consumption. Before (after) the turning point, energy consumption increases from E_1 to E_2^H (decreases from $E_{1'}$ to $E_{2'}^H$) from an increase in output. This result implies that if technical innovation appears in an economic body with high energy intensity and its output is over the turning point, then this economic body can realize

an eco-friendly production environment in which output increases and energy consumption decreases.

Scenario 2: Low energy intensity causes $dE/dY|_{Ec} \rightarrow 0$

In this scenario, we take the case of energy intensity being zero in which the slope of the *Ec* curve is horizontal, implying that the *En* curve shift does not change the amount of energy consumption. The description is like that of Fig. 3, whereby technical innovation increases output, but the amount of energy consumption does not change; i.e., $E_1 = E_2$, where the production stage is before the turning point 1^{tp}. Because energy intensity is zero, it is not necessary to form an inverse U-shape EKC, and the *En* curve does not also present a stage with a downward slope such as the marked gray part in Fig. 3. Hence, an economic body with energy intensity being zero is at eco-friendly production under which technical innovation only brings higher output without increasing energy consumption. This finding indicates that the creation of low energy intensity is comparable to achieving a turning point on the *En* curve; i.e., output increases and energy consumption decreases. This is more important when an economic body plans to realize eco-friendly production.

Scenario 3: Average energy intensity causes $dE/dY|_{Ec} > 0$

This is a more general scenario for many economic bodies in which their energy intensities are between positive infinity and zero. In this scenario, technical innovation increases output and energy consumption before the turning point stage. However, the production stage after the turning point decreases energy consumption, but the output also probably decreases.

Figure 4 shows that the output scale is positive (from Y_1 to $Y_2{}^A$) and energy consumption is also positive (from E_1 to $E_2{}^A$) before turning point 1^{tp}. After turning point 1^{tp}, energy consumption decreases (from $E_{1'}$ to $E_{2'}{}^A$), but output increases (from $Y_{1'}$ to $Y_2{}^A$) given the downward size of the *En* curve being small (from *En*1 to *En*2). On the other hand, given the downward size of the *En* curve being large (from *En*1 to *En*2′), energy consumption decreases (from $E_{1'}$ to $E_{2'}{}^A$), but output also decreases (from $Y_{1'}$ to $Y_{2''}{}^A$). For an economic body with average energy intensity, an eco-friendly production stage is when energy consumption decreases, and the production effect is stronger than the energy saving effect. On the contrary, if the production effect is weaker than the energy saving effect, then energy savings also increase output. To avoid the effect that energy savings cause output to decrease, the production effect being stronger than the energy saving effect can bring forth an eco-friendly production outcome; i.e., a win–win situation of increasing output and energy savings.

Equilibrium path analysis

Technology innovation generates output change and energy consumption change, and the change in size depends on an economic body's energy intensity score. By equilibrium path analysis, this study looks to find the scenario of eco-friendly production.

Combining the changes of output and energy consumption in Fig. 5, the gray area means eco-friendly production

Fig. 3 The scenario of energy intensity being zero
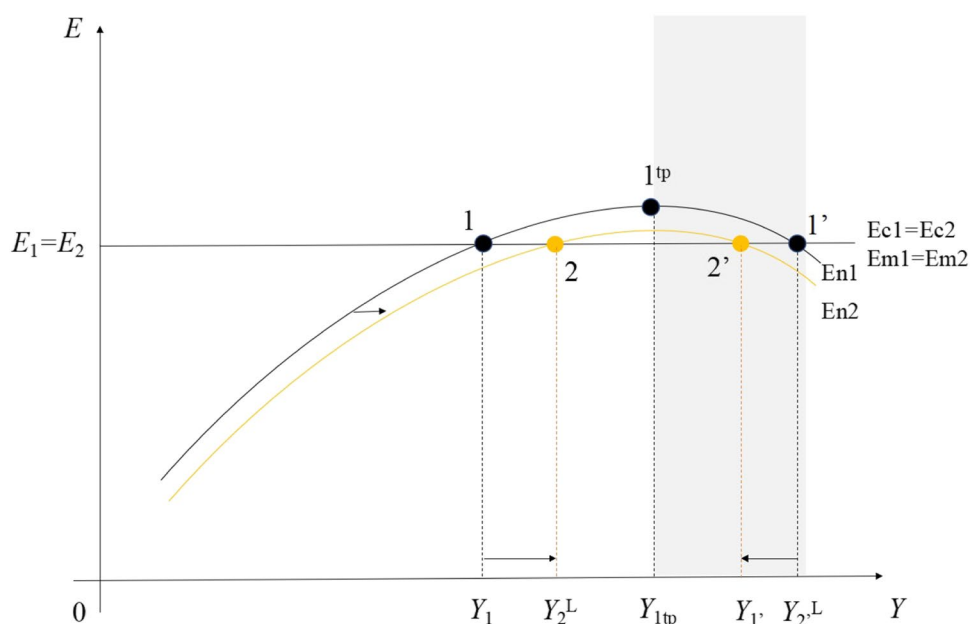
**Fig. 4** The scenario of average energy intensity
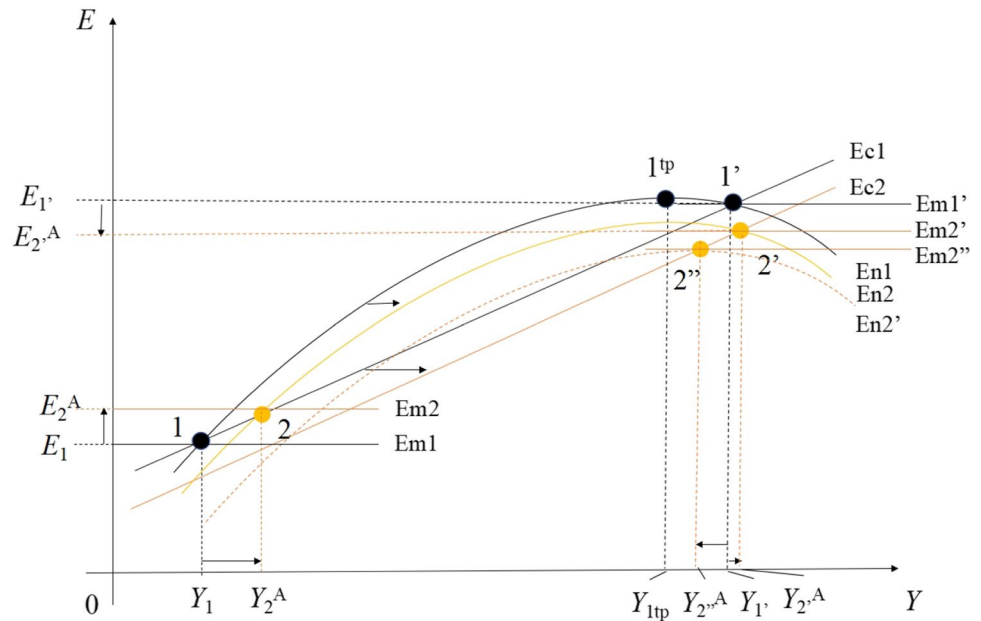
whereby output increases and energy consumption decreases. For an economic body with high energy intensity, technical innovation increases output and decreases energy consumption when its output level is over the turning point. An economic body with zero energy intensity does not care about the turning point in which output increases and energy consumption decreases, because its energy consumption does not change by an increase in output. Before the turning point, technical innovation only brings about higher output, but energy consumption does not change. For an economic body with an average energy intensity, technical innovation still brings eco-friendly production as long as the production effect is stronger than the energy saving effect. If the energy saving effect dominates the production effect, then technical innovation makes both output and energy consumption decrease.

A turning point is the benefit of a high energy intensive country increasing its output and decreasing energy consumption. A turning point also benefits a low energy intensive country, but is conditional on the fact that the production effect is stronger than the energy saving effect. For an economic body with high energy intensity or low energy intensity, eco-friendly production always occurs in output over the turning point, which satisfies the viewpoint of the EKC hypothesis that economic growth naturally brings forth energy savings.

Fig. 5 Equilibrium paths for different energy intensities
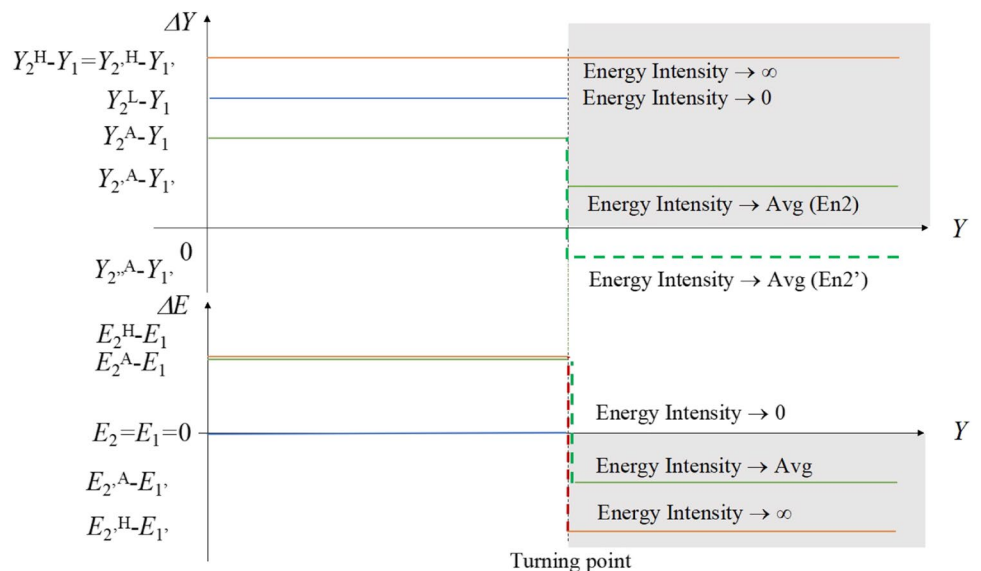
Empirical result

This study takes China as the research observation. The data sources are *China Statistical Yearbook* and *China Statistical Yearbook on Environment*. The data period is from 2009 to 2017.

Descriptive statistics

Table 1 presents the descriptive statistics of all variables. An economic body employs capital (K), labor (L), and energy (E) to create gross domestic product (GDP) (Y) and generates an undesirable output, carbon dioxide (CO_2) emissions. Here, E/Y, CO_2/Y, and e computed by row data are defined as energy intensity, carbon intensity, and the coefficient of carbon emissions per unit energy consumption. After observing the row data, the quantities of input and output present a positive trend, which implies that China employs more input factors to create more GDP during the data period. Energy intensity and carbon intensity in China are decreasing year by year, and the coefficient of carbon emissions per unit energy consumption maintains a stable situation.

We next care about the coefficient of variation (CV) for all variables. In all input factors, labor employees have the smallest CV, meaning that the labor market in China has strong rigidity. The capital market owns the largest CV, which implies prosperous development in the capital market. The CV of energy consumption ranks in the middle of the three input factors, denoting that China has good energy consumption management in economic development. In two output factors, the CV of GDP is larger than that of CO_2 emissions, which means that China controls CO_2 emissions very well and obtains good performance in economic growth during its economic development. Comparing the performances between energy consumption and CO_2 emissions, we find the management of energy consumption is better than that for CO_2 emissions since the CV of energy intensity is larger than that of carbon intensity, which means that energy intensity shows greater improvement than carbon intensity. It is reasonable that the coefficient of carbon emissions per unit of energy consumption is stable, because of a stable chemical reaction between energy consumption and CO_2 emissions after using energy.

We conclude with the following findings of descriptive statistics: (i) China is moving toward eco-friendly production and (ii) China exhibits better improvement in energy savings than in CO_2 reduction.

Data analysis

We separate the data into two parts with the first part from 2009 to 2013 and the second part from 2014 to 2017. Here, Ec and En are estimated production function and estimated energy function from 2009 to 2013, and Ec' and En' are estimated production function and estimated energy function from 2014 to 2017, respectively.

Comparing Ec and Ec' in Fig. 6, the slope of Ec' is flatter than that of Ec, which means energy intensity in China presents improvement from 2014 to 2017. In addition, Ec' is downward from Ec, which means there is technical innovation in China from 2014 to 2017. Both En and En' present the relationship that the more energy consumption there is, the greater is the output, but technical innovation also causes En' to be downward from En. There are turning points in En and En'. The data of output and energy consumption in 2013 are over the turning point of En, and the data of 2016 and 2017 are over the turning point of En'. In addition, the

Table 1 Data description

Year	Y	K	L	E	CO_2	E/Y	CO_2/Y	e
2009	36486.233	21844.080	762932.500	357238.000	82,769.000	9.791	2.268	0.232
2010	42261.037	26225.929	775756.500	389511.000	91360.000	9.217	2.162	0.235
2011	47843.099	28045.988	790235.200	422305.000	102755.000	8.827	2.148	0.243
2012	51555.386	32939.337	799423.300	443217.000	105646.000	8.597	2.049	0.238
2013	55279.403	38372.031	811797.800	427490.000	112505.000	7.733	2.035	0.263
2014	58463.728	43172.964	826953.000	439945.000	118729.000	7.525	2.031	0.270
2015	60888.139	50574.795	830105.300	447317.000	116030.000	7.347	1.906	0.259
2016	69957.823	52441.122	834421.300	455766.840	113039.700	6.515	1.616	0.248
2017	68860.446	51618.516	832400.200	466547.000	115533.200	6.775	1.678	0.248
Average	54621.699	38359.418	807113.900	427704.093	106485.211	8.036	1.988	0.248
Std.	11343.685	11737.791	26477.686	34505.116	12287.840	1.126	0.219	0.013
CV	0.208	0.306	0.033	0.081	0.115	0.140	0.110	0.053

Y real GDP (RMB billion), *K* real capital (RMB billion), *L* labor (1,000 people), *E* energy consumption (10,000 tce), *CO₂* CO_2 emissions (100 kg), *E/Y* energy intensity, *CO₂/Y* emission intensity, *e* coefficient of carbon emissions

data of energy consumption and output in 2013 and 2016 are individually under *En* and *En'*, which implies that China may have achieved eco-friendly production in 2013 and 2016.

We next compare the data for 2016 and 2017 and find that energy consumption is more, but the output level is less in 2017. Based on the data from 2014 to 2017, China presents technical innovation, which exhibits a trend in which output increases and energy consumption decreases. In other words, China will enter an eco-friendly production stage in the future.

The status quo of output and energy consumption is shown in Fig. 7 in which the axis of ΔE presents an average level of CO_2 emissions, and the axis of ΔY presents an average level of output. The axes of ΔE and ΔY separate the plane into four parts in which $\Delta E > 0$ and $\Delta Y > 0$, $\Delta E < 0$ and $\Delta Y > 0$, $\Delta E < 0$ and $\Delta Y < 0$, and $\Delta E > 0$ and $\Delta Y < 0$ are individually defined as quadrants I, II, III, and IV. Quadrant IV is an eco-friendly production area where the output is over an average level, but energy consumption is under an average level; quadrant II is an eco-unfriendly production area where the output is under an average level, but energy consumption is over an average level; and quadrant I (III) is a general production area where more (less) energy consumption generates more (less) output.

According to the scatter chart of data from 2009 to 2017, there is a trend whereby output and energy consumption exhibit a positive relationship. A positive relationship is obvious from 2009 to 2012, and there is an inverse U-shape curve from 2013 to 2017. Based on the slope of the dataset,

the output elasticity of energy consumption from 2013 to 2017 is smaller than that from 2009 to 2012, which implies that not only does China use less energy to create more output but also that its energy intensity is falling. The status quo of production in China is that high output is created by high energy consumption, but this phenomenon is improving. The year 2012 in quadrant II exhibits the most obvious eco-unfriendly production, and the year 2013 in quadrant IV is closest to an area of eco-friendly production. The outcome of 2017 compared to that of 2016 does not present a good phenomenon since output decreases and energy consumption increases in 2017.

An investigation into eco-output elasticity of energy consumption in Table 2 can probe into the eco-friendly production stage. The result shows that China appears to be in an eco-friendly production stage from 2012 to 2013 in which its output increases and energy use decreases. The smallest (largest) eco-output elasticity of energy consumption in Table 2 is 0.143 (1.450) for 2015–2016 (2016–2017), which implies that China in 2015–2016 (2016–2017) has the smallest (largest) percentage change of energy consumption compared to the percentage change of output. Based on Eq. (6), the eco-output elasticity of energy consumption can be decomposed into the elements of dE/dY, E/Y, MP_e, and AP_e, where dE/dY, E/Y, MP_e, and AP_e are the slope of the *En* curve, energy intensity, marginal productivity of energy, and average productivity of energy, respectively. The inverse of the slope of the *En* curve is marginal energy productivity, and the inverse of energy intensity is average energy
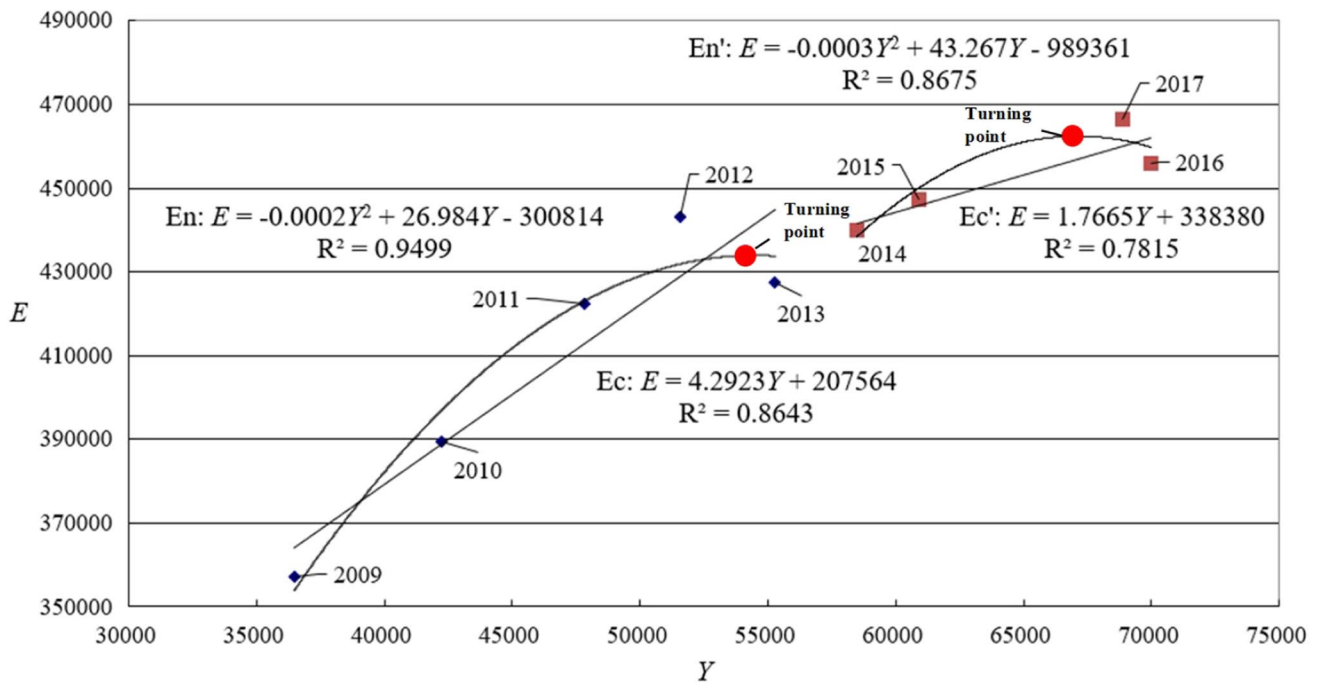

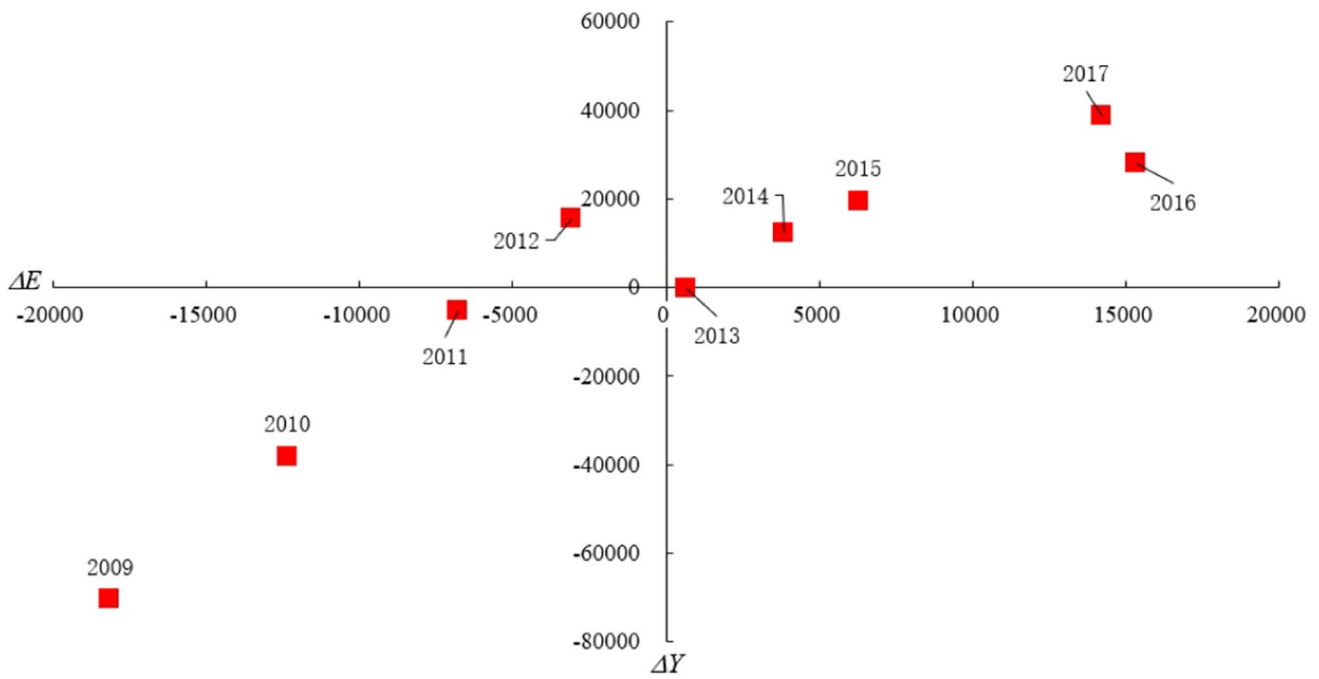**Fig. 6** The trend of output and energy consumption

Fig. 7 The status quo of output and energy consumption

productivity. Hence, we find that the smallest eco-output elasticity of energy consumption in 2015–2016 comes from the largest marginal productivity and average productivity on energy consumption. This result implies that MP_e, AP_e, and E/Y can be monitors on energy consumption, and $E_e^y|_{eco}$ can probe for an eco-friendly production stage.

Energy consumption in 2012–2013 shows that negative marginal productivity comes from lower energy consumption. Given a country has economic growth, it is a desirable case to have eco-friendly production. Tracking back to Fig. 7, we find that 2012–2013 is an eco-friendly production stage that locates after the EKC's turning point. China's energy intensity in Table 2 is downgrading year by year before 2016, but the index of energy intensity is unable to investigate an eco-friendly production stage. The result implies that it is beneficial to use the eco-output elasticity of energy

consumption for a probation of eco-friendly production in which there are energy savings in the output growth process.

Conclusion

Economy, energy, and environment have the same important position in current and future production activities. Thus, a definition of eco-friendly production to balance the three is necessary. The index of energy intensity is popularly used by many countries such China to monitor the economy and energy, but it lacks any monitoring of the environment. We thus employ the production function, emission function, and energy function to establish the index of eco-output elasticity of energy consumption for a balance among economy, energy, and environment. The established index in this paper also involves the idea of energy intensity to monitor economy and energy, and it also extends to an environmental monitor.

Past studies have pointed out two viewpoints on being eco-friendly: (i) more renewable energy use and less fossil fuel use and (ii) a bit of fossil fuel use creates high economic growth. The latter viewpoint is based on EKC's idea that when GDP per capita surpasses a critical level, energy consumption will decrease. Based on the latter viewpoint, we establish the index of eco-output elasticity of energy consumption and take China as an observation sample to find its eco-friendly production stage. This paper not only offers theoretical analysis but also includes empirical application.

Table 2 The eco-output elasticity of energy consumption

Year	$E_e^y|_{eco}$	$dE/|dY|$	E/Y	MP_e ($|dY|/dE$)	AP_e (Y/E)
2009–2010	0.606	5.589	9.217	0.179	0.108
2010–2011	0.666	5.875	8.827	0.170	0.113
2011–2012	0.655	5.633	8.597	0.178	0.116
2012–2013	-0.546	-4.223	7.733	-0.237	0.129
2013–2014	0.520	3.911	7.525	0.256	0.133
2014–2015	0.414	3.041	7.347	0.329	0.136
2015–2016	0.143	0.932	6.515	1.073	0.153
2016–2017	1.450	9.824	6.775	0.102	0.148

In theoretical analysis, we conclude the following: (i) a country with high energy intensity can realize eco-friendly production when its energy use continuously decreases and output continuously increases. This not only exhibits energy intensity degradation but also simultaneously goes into an eco-friendly production stage. Hence, energy intensity degradation caused by the output's increasing size being larger than energy use's increasing size does not exhibit eco-friendly production. (ii) A country with zero energy intensity means it does not use fossil fuel energy any more and is always in an eco-friendly production stage. Hence, the real meaning of eco-friendly production for energy intensity is decreasing energy use instead of increasing output. The eco-output elasticity of energy consumption established in this paper is a meaningful index to probe an eco-friendly production stage.

In empirical analysis we employ data from China spanning 2009 to 2017 and find the following: (i) China's production status quo most of the time is high output and high energy use. However, China was in an eco-friendly production stage from 2012 to 2013 in which its output increased, but energy use decreased. (ii) Compared to energy use and its by-product of CO_2 emissions, we find that China exhibits better improvement on energy savings than CO_2 reduction.

Some traditional indices such as marginal productivity, average productivity, and energy intensity only monitor energy consumption and the output situation, but ignore an environmental monitor. The index of eco-friendly elasticity of energy consumption proposed by our paper has the advantage of probing an eco-friendly production stage. We provide two directions to apply our index in future research. (i) Our index can be used on other big size economies like the European Union's 27 states in order to find each country's eco-friendly production stage. (ii) Our index can also coordinate with EKC research to confirm the eco-friendly production stage.

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Declarations

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