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Dynamic Linkages Among Energy Consumption, Environment and Health Sustainability: Evidence from the Different Income Level Countries

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Abstract

Environment pollution was closely related to human health. The energy consumption is one of the important sources of environmental pollution in the development of economy. This paper used undesirable two-stage meta-frontier DDF (distance difference function) data envelopment analysis model to explore the impact of environment pollutants from energy consumption on the mortality of children and the aged, survival rate of 65 years old and health expenditure efficiency in 27 high income countries, 21 upper middle income countries, and 16 lower middle income countries from 2010 to 2014. High income countries had higher efficiency of energy and health than middle income countries in general. But whether in high income or middle income countries, the efficiency of non-renewable energy is higher than renewable energy. There was much room for both high income countries and middle income countries to improve renewable energy efficiency. Besides, middle income countries need to improve the efficiency of non-renewable energy and reduce pollutant emissions per unit of GDP. In terms of health efficiency, upper middle income countries performed worse than lower income countries. This phenomenon might indicate there was a U-shaped relationship between health efficiency and income level. Upper income countries should pay more attention to the environmental and health problems and cross the U-shaped turning point. The contribution of this article was to consider the heterogeneous performance of energy efficiency, environmental efficiency, and health efficiency under the influence of income level differences, and found that there might be a U-shaped relationship between health efficiency and income level.

Keywords

energy efficiency, health efficiency, high income countries, middle income countries, two-stage meta-frontier DDF data envelopment analysis model

What do we already know about this topic?

There was a relationship between energy consumption, environmental quality and health quality in a country, such as the input-output relationship. Countries with different regions and income levels might have different energy efficiency, environmental efficiency, and health efficiency.

How does your research contribute to the field?

This paper had 2 main contributions. First, this paper analyzed the input-output relationships and differences in energy consumption efficiency, environmental efficiency, and health efficiency in different countries at different income levels. The second contribution of this article was to divide income levels into 3 levels and found that there might be a U-shaped relationship between health efficiency and income level.

What are your research's implications toward theory, practice, or policy?

(1) Middle income countries should increase the efficiency of non-renewable energy use, increase supervision of environmental pollution problems, promote the progress of energy-saving and emission-reduction technologies, and reduce pollutant emissions per unit of GDP.
(2) High income countries should take advantage of economic development and technological bases to increase investment in research and development of renewable energy technologies and improve the efficiency of renewable energy. In addition, high income countries should take the initiative to help the surrounding middle income countries to improve efficiency, because efficiency may have spatial autocorrelation and there will be spillover effects.

(3) Middle income countries should increase their fiscal expenditures to meet the medical needs of residents, popularize medical common sense, strengthen the construction of basic medical systems, improve the health conditions of children and reduce mortality rate of children.
(4) Upper income countries should pay attention to the environmental and health problems that had occurred in the process of pursuing rapid economic development, improve the efficiency of the health treatment stage, and cross the U-shaped turning point, so as to achieve sustainable economic development.

Introduction

Kraft and Kraft[1] put forward economic development was always accompanied by energy consumption. Energy supplies power for human production and life and was an indispensable and important support for economic development. However, Chow et al[2] pointed out the mainly energy resources used by humans were non-renewable resources, and the exploitation and use of coal and oil would also cause a series of ecological environmental problems, such as air pollution. Clancy et al[3] believed that one of the important reasons why the air problems were attached importance to by human beings was that the environment was closely related to human health. No one could not breathe unless he was dead. The impact of air quality on human health was also obvious. The Great Smog of 1952 was a typical example. And the production of air pollutants was closely related to energy consumption. Therefore, there was an input-output relationship between energy consumption, air pollution and human health, and this input-output relationship was divided into 2 stages. In the first stage, the input of labor, energy and capital would promote economic development, but at the same time, air pollutants would be generated after energy consumption. In the second stage, the emission of air pollutants would have a negative impact on the environment and human body, so the government needed to increase health expenditure to alleviate human health problems.

Based on this logic, this paper uses undesirable two-stage meta-frontier DDF data envelopment analysis model to analyze the input-output relationship between energy consumption, environmental pollution, and human health. Among them, energy consumption is divided into renewable energy consumption and non-renewable energy consumption. In terms of environmental pollution, this paper mainly concerned about air pollution, so this paper selected CO_2 emissions and PM2.5 to analyze. In terms of human health, this article useed the mortality rate of children under the age of 5, the mortality rate of people aged 15-65 and the survival rate of people over 65 to measure. Panayotou[4] proposed the concept of an Environmental Kuznets Curve (EKC), that was the relationship between environmental quality and per capita income level was inverted U-curve. Zhang et al[5] studied the total factor energy efficiency of 23 developing countries and found that energy efficiency had a relationship with per capita income. However, some of the existing literature used outdated data, and some of the classification of income levels was too simple to fit economic reality well. Feng et al[6,7] had analyzed this topic according to the grouping of EU countries and non-EU countries, as well as new EU countries and old EU countries. However, Feng's grouping method was not exactly the same as grouping by income level, and his classification was too simple, presupposing a linear relationship between economic development level and energy efficiency and health efficiency, which was far from reality. Therefore, considering that countries with different levels of economic development and living standards may have differences in the above aspects, according to the standards of the World Bank, this paper finally selects the panel data of 27 high income countries, 21 upper middle income countries and 16 lower middle income countries from 2010 to 2014 for comparative analysis.

The rest of this paper is arranged as follows: Section 2 provides literature review, Section 3 introduces research models and methods, Section 4 analyzes empirical research results, and Section 5 is conclusion and implications.

Literature Review

In the past literature on energy, there are 2 main directions. The first is to explore the energy use and environmental pollution efficiency of various countries. The second is to analyze the reduction of air pollution emissions and environmental efficiency. Table 1 summarizes the above-mentioned literature as research on energy, environmental efficiency, and air pollution issues.

The literature on environmental pollution and health mainly emphasizes the impact of air pollution on human health. It can also be divided into 2 aspects. One is the impact of environmental air pollution exposure on health and diseases. The second is the impact and harm of environmental air pollution on the health of children and the elderly. Table 2

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Table 1. Energy and Environmental Efficiency and Air Environmental Pollution.

Author	Method	Result
Zhang[8]	Directional distance function	Among China's regional industrial environmental efficiency, the cities with the highest energy efficiency values are Jiangsu Province, Zhejiang Province, Guangdong Province, and Shanghai.
Martínez[9]	Two-stage data envelopment analysis	The energy efficiency of Germany's non-energy-intensive industries will be affected by technical efficiency and cost, while changes in the energy costs of Colombiaon's energy-intensive industries have a significant impact on energy efficiency.
Wang et al[10]	Window DEA model	The energy and environmental efficiency of China's eastern region is the highest, followed by the central region, and the western region is the least efficient. The difference in efficiency may come from the imbalance of economic development.
Li et al[11]	DEA and Malmquist model	The transformation of technology into the three components of economic structure, energy consumption structure, and technological progress has different influence methods in different regions, which can be a reference for the energy intensity of different regions in China.
Wang et al[12]	Multi-directional efficiency analysis	Since the energy efficiency and emission efficiency of the eastern region are higher than the other 2 regions, the eastern region is generally more efficient than the central and western regions. It is found that Hebei, Shanxi, Inner Mongolia, Shandong, Henan, Hubei, and other provinces have higher performance of energy saving potential and emission reduction potential.
Bi et al[13]	DEA model	China's energy efficiency and environmental efficiency are relatively low. The energy and environmental efficiency of various provinces vary greatly. Environmental efficiency has an important impact on the energy efficiency of China's thermal power generation industry. Reducing the emission of major pollutants can improve energy performance and environmental efficiency.
Wu et al[14]	Two-stage DEA model	The effect of energy conservation and emission reduction in eastern China is the best, better than that in the central and western regions. The overall efficiency of energy conservation and emission reduction in China has been relatively stable over the past 5 years, and the efficiency of pollution treatment has also maintained an upward trend.
Lin and Du[15]	Directional distance function	Most regions of China have poor performance in energy and carbon dioxide emission efficiency. The provinces in the eastern region outperform the central and western regions, and the provinces in the western region have the lowest efficiency performance. The expansion of the industrial sector is negatively correlated with the efficiency of energy and carbon dioxide emissions.
Üstün[16]	DEA model	Because the rapid economic growth has brought environmental problems to Turkey and reduced environmental efficiency, the government should quickly improve the problems and determine the location of environmental pollution risk areas.
Yao et al[17]	Directional distance function	There are significant group differences in energy efficiency values in various regions of China, and there is no significant difference between total factor and single factor efficiency, which may be due to the limited substitutability between energy inputs and other production inputs.
Choi and Roberts[18]	DEA and Malmquist model	The air transportation industry did not increase production with the reduction of PM2.5, and the truck transportation industry was driven by the reduction of carbon monoxide in the air pollutant to drive business growth.
Sueyoshi et al[19]	DEA model	The Chinese government should allocate economic resources to cities in the northwestern region (including Lanzhou, Xining, Yinchuan, and Urumqi), and strengthen stricter supervision of environmental prevention energy consumption in major cities (such as Beijing, Tianjin, Shanghai, and Chongqing).
Mavi and Standing[20]	DEA model	Most OECD member countries should strengthen innovation in environmental protection and energy conservation. Energy use and ecological sustainability are more important than other inputs and outputs, and four countries, Iceland, Ireland, Luxembourg, and Switzerland, have the highest environmental efficiency.
Liu and Liu[21]	Three-stage DEA model	In cross-border negotiations to promote the reduction of carbon dioxide emissions, external environmental variables should be taken into consideration. Developed countries should help developing countries reduce carbon emissions by opening up or expanding trade, such as encouraging import and export of energy-saving and sharing emission reduction technologies.

(continued)

Table 1. (continued)

Author	Method	Result
Wen and Zhang[22]	ZSG DEA model	The Chinese government can help promote the implementation of CO_2 emission reduction regulations by allocating CO_2 emission allowances in different regions.
Yao et al[23]	Meta-Frontier Malmquist CO_2 emission index	The average carbon dioxide emissions of the industrial sectors in eastern, central, and western regions of China have successively declined, and the average annual growth rate of the EC indicator efficiency change is 2.297%. The carbon dioxide emissions efficiency of 21 provinces have shown an upward trend.
Ma et al[24]	Spatial autoregressive model	PM2.5 pollution has significant spatial agglomeration and diffusion effects, and is significantly affected by geospatial attributes and regional economic connections. Regional coordination of environmental policies and the transfer of pollution-intensive industries is required to control air pollution in China.
Li et al[25]	Multi-level frontiers DEA	China's PM2.5 and SO_2 emissions have a significant relationship with urban population and energy technology.
Wu et al[26]	ZSG DEA model	The efficiency of the allocation of PM2.5 emissions in China's provinces is affected by the province's land area and atmospheric environment, and the government should immediately reduce smog.
Halkos and Polemis[27]	Window DEA model	There is an N-shaped relationship between the environmental efficiency of the United States and regional economic growth, and attention needs to be paid to local and global pollutants and environmental efficiency.
Camioto et al[28]	Window DEA model	Among the BRIC countries, Brazil is the most energy efficient country, followed by South Africa, China, India, and Russia.
Yi[29]	Super DEA model	The carbon emissions of China's industrial sector are growing rapidly, and the average size of the industrial sector has a significant impact on the efficiency of carbon emissions.
Feng et al[30]	DEA model	Large-scale coal-fired power plants have improved efficiency of sustainable urban development. Water pollution and excessive energy consumption are main problems faced by cities and large-scale coal-fired power plants in sustainable development.
Qin et al[31]	Directional distance function	China's economic development level is positively correlated with energy efficiency. When considering poor output, energy efficiency will decline. It is also found that the Bohai Rim Economic Zone has great air emission potential.
Du et al[32]	Directional distance function	Promoting China's energy-saving technologies and reducing technical differences between regions will effectively reduce carbon dioxide emissions in regions with low technical efficiency.
Feng et al[33]	Three-hierarchy meta-Frontier DEA model	China's structural efficiency, technical efficiency, and low management efficiency have reduced the efficiency of carbon dioxide emissions. Through industrial structure adjustments, the technological gap between regions can be reduced, market-oriented reforms can be promoted, and environmental protection can be strengthened.
Hu et al[34]	Total-factor energy efficiency model	Among the 20 administrative regions in Taiwan, most cities have good energy efficiency performance, which is mainly related to the development characteristics of environmental regions, such as Taitung and Penghu, which have natural, green and environmentally friendly tourist areas.
Zhang et al[35]	DEA window model	China's energy efficiency presents an N-shaped trend, rising first, then falling, and then rising again. Energy efficiency varies greatly from region to region. The eastern region has the highest energy efficiency, followed by the western region, and the central region has the lowest energy efficiency.
Guo et al[36]	DEA model and T test	There is a large gap in the level of economic development and environmental protection between Chinese cities, and the environmental efficiency is also very unbalanced. The environmental efficiency of the Pan-Pearl River Delta region is better than that of the Pan-Yangtze River Basin region. The southern coastal economic zone and the eastern coastal comprehensive economic zone is higher than other regions.
Ren et al[37]	Meta- Frontier dynamic SBM model	The energy and emission efficiency of China's non-YREB is lower than that of YREB. YREB should strengthen its regional technical exchange and promotion to reduce regional technological differences. Non-YREB should solve environmental protection and carbon dioxide emissions issues and promote low-carbon production models to improve efficiency.

(continued)

Table 1. (continued)

Author	Method	Result
Zhou et al[38]	Super-SBM DEA model	The carbon emission efficiency of China's construction industry is low, showing a downward trend. Economic scale, energy structure, and technological progress have a significant impact on reducing emission efficiency.
Li and Cheng[39]	Meta DDF model	China's meta-frontier total-factor carbon emission efficiency of high-tech industry was the highest, followed by that of middle-tech industry, with the lowest being low-tech industry.
Malinauskaite et al[40]	DEA model	After the implementation of the new policy, the energy efficiency of Slovenia and Spain has been significantly improved.
Wang et al[41]	SBM DEA model	The static efficiency of carbon emissions in airlines showed an inverted U-shaped trend during the inspection period.
Zhang et al[42]	DEA and different methods	China's economic increases 13.6% generated by the gross industrial output value, but significantly reduces the emission (24.2%) of industrial CO_2 in all seven carbon emission trading pilots. The average DEA efficiency of the seven carbon ETMs operations in China have increased annually.

Table 2. A Summary of Research on Air Pollution and Health.

Author	Method	Result
Loomis et al[43]	Literature review	Air pollution in Chinese cities is the most serious country in the world, and there is a positive correlation between the incidence of lung cancer and air pollution indicators.
Oakes et al[44]	Literature review	Each type of exposure index is different for different research problems, and provides the results of human health impact. The research work on the error results and joint effects of multiple pollutants exposure will help to formulate and improve multiple pollution indicators, so as to promote the research on the impact of air pollution and human health risk assessment.
Pope et al[45]	Literature review	PM2.5 pollution will increase the risk of disease and death, and air pollution should be reduced in areas with serious pollution.
Chen et al[46]		The exposure of PM2.5 and PM10 is related to the decline of lung function of Chinese children, and adverse reactions of girls are greater than those of boys.
Dauchet et al[47]		The levels of PM10, NO_2, and O_3 in France are lower than or only close to the limits of the World Health Organization. The increase of O_3 is related to the increase of blood eosinophil count. Exposure to air pollution is related to the decline of lung function of healthy residents in 2 urban areas of France.
Fioravanti et al[48]	Regression model	The prevalence of obesity among children in Rome is 9.3% and 36.9%, respectively, and there is no relationship between vehicle traffic air pollution and obesity.
Kasdagli et al[49]	Systematic review and meta analysis	The relative risk of Parkinson's disease and PD is 1.06 after long-term exposure to PM10, and the risk of exposure to NO_2 is 1.01.
Knibbs et al[50]	Regression model	Exposure to NO_2 has a significant relationship with the prevalence of asthma in Australian children.
Zhao et al[51]		The concentration of PM2.5 in Chinese cities is seriously out of range, and most people who are exposed to air pollution have the most serious impact on their health are male cyclists.
Chen et al[52]		Higher exposure to air pollution is related to the increased prevalence of respiratory diseases among Chinese students, especially allergic rhinitis. It is also found that the increase of lung function damage related to exposure to higher air pollution may be as high as 171.5%.
Bayat et al[53]	Environmental benefits mapping and analysis	In 2017, 7146 adults in Tehran died of PM2.5 due to is chemic heart disease, stroke, lower respiratory tract infection, chronic obstructive pulmonary disease, and lung cancer.
Lua et al[54]	Mortality calculation method	PM2.5 in most provinces remained stable, and the premature death rate caused by PM2.5 decreased from 1 078 800 in 2014 to 962 900 in 2017.
Luo et al[55]	AirQ2.2.3 model and air quality index	PM10 pollution is mainly caused by sandstorms in spring and winter, and 20% of the urban population in Northwest China is exposed to polluted air, which leads to an increase in respiratory and cardiovascular diseases.
Pierangeli et al[56]	Quantitative health impact assessment approach	Under the influence of air pollution, Barcelona estimated that as many as 1230 (48%) children had asthma cases, and found that less socially dependent groups could be more affected by asthma-related to air pollution than those more socially dependent.

summarizes the above literature as research on air pollution and health.

Because the above studies mostly use traditional DEA methods and focus on static analysis, ignoring changes in dynamic time and of the studies that have used Malmquist DEA to dynamically analyze efficiency, such as Li et al[11], Choi and Roberts[18], Yao et al[17], etc., used the Malmquist productivity index to analyze the country's energy and environmental efficiency. Although the Malmquist productivity index can compare the changes in productivity between years, the model cannot explain the impact of technological progress between years. And most studies focus on energy use and environmental efficiency, but still neglect to consider important air pollution indicators such as PM2.5. Although some scholars discuss the impact of exposure to air pollution on human health, such as Pope et al[45], Chen et al,[46] and others, all researchers point out that the occurrence of human diseases is related to the impact of air pollution, but there are still few studies that simultaneously discuss the 3 aspects of economy, energy, and health. Feng et al[6] divided the sample into EU countries and non-EU countries, and compared the energy consumption efficiency, environmental efficiency, and health efficiency of the 2 categories of countries. That paper takes into account the impact of income on the above 3 efficiency differences to some extent, but ignores some high-income countries that exist in non-EU countries. Although Feng et al[7] divided the EU countries into new countries and old countries and also discussed energy consumption efficiency, environmental efficiency, and health efficiency, they did not consider the impact of different countries' income levels on overall efficiency. Besides, the grouping method of Feng et al[7] is too simple, presupposing a linear relationship between economic development level and energy efficiency and health efficiency, which is far from reality. In order to solve the lack of Malmquist index and consider the continuous change of time, this paper uses the undesirable two-stage meta-frontier DDF data envelopment analysis model, using the dynamic concept proposed by Tone,[57] which has the characteristics of inter-period continuation, and the important characteristics of carry-over as a link between different periods, it can explain the reasons for the changes between different years. At the same time, using the DDF model proposed by Färe et al.,[58] this model can not only use the direction to produce the distance function, but also analyze the increase of good output and reduction of bad output, and considered the dynamic effect of a carry-over, to break through the problem of static analysis in the past research, and to consider the continuous problems of different periods at the same time, to better reflect the changes in different periods. This model can be more suitable for analyzing the input-output relationships and differences in energy consumption efficiency, environmental efficiency, and health efficiency in different countries at different income levels.

Research Method

Introduction to the DEA Model

Charnes et al[59] proposed the CCR model in 1978 to evaluate the performance of multiple inputs and multiple outputs with fixed returns to scale. Banker et al revised the assumption of fixed returns to scale to Variable Return to Scale (VRS) in 1984 and proposed the BCC model. CCR and BCC are non-radial estimation methods; Tone[60] proposed the Slacks-Based Measure (SBM) based on the balance variable model, and used non-radial estimation method to present efficiency. DDF (Direction Distance Function) is a commonly used efficiency measurement tool. Because DDF can deal with input reduction and increase output at the same time. Chung et al[61] proposed the output-oriented distance function concept, which was an extended orientation output distance function (RDF). The traditional DDF is a ray measurement mode, and the efficiency calculation fails to include all non-zero differences and all sources of inefficiency. Therefore, the efficiency value of the institute is overestimated. In order to solve this type of problem, Färe and Grosskopf[58] and Chen et al[62] established a non-directed direction distance function. Compared with other methods, this function is better because it provides a more reasonable and accurate estimate result.

In the traditional DEA's efficiency evaluation, an efficiency conversion is performed between the 2 variables through input and output items. The conversion process is identified as a "black box." Färe et al[63] proposed the Network Data Envelopment Analysis (Network DEA) model, which believed that the production process was composed of many secondary production technologies, and regarded the secondary production technology as a sub-decision unit (Sub-DMU). The best solution is to use the traditional CCR and BCC models. Zhu[64] described the value chain process as a "black box" and believed that it must contain some sub-processes, which constituted the value chain system. To estimate the efficiency of a system, it is necessary to evaluate the efficiency of each of these sub-processes. In order to analyze the efficiency of each sub-process, many scholars have tried. Chen and Zhu[65], Kao and Hwang,[66] and Kao[67] divide the whole business process into sub-processes, and connect the stages through some intermediate outputs. They calculated the efficiency of each stage under different conditions and analyzed which sub-process caused the efficiency loss of the system. After Färe et al,[63] Tone and Tsutsui[68] proposed a weighted slack-based measures (SBM) network data envelope analysis model, using linkage among decision-making units as the analysis basis for the Network DEA model, and think of each department as a Sub-DMU, and then use the SBM model to find the optimal solution. In the network DEA model, in recent years, more and more literatures are devoted to the research of multi-stage production process and its efficiency evaluation. Although a large number of studies have focused on assessing the efficiency of the two-stage process, two-stage DEA also allows for a dynamic approach, in which DMUs are evaluated at different time periods and carryovers are introduced to connect the various stages that make up the DMU at different periods (Tone and Tsutsui[69]). In terms of the dynamic DEA model, window analysis was proposed by Klopp,[70] which was first used for dynamic analysis. Subsequent developments include Malmquist,[71] Färe et al[72] Malmquist index (divided into catch up and innovation effect), but these analyses did not analyze the effect of Carry-over activities in these 2 periods. Färe and Grosskopf[73] first put inter-connecting activities in dynamic DEA model. Subsequent developments include Nemoto and Goto[74] adding some important insights on dynamic DEA, and Nemoto and Goto[75] proposed a method for using dynamic DEA to adjust to the optimal level of quasi-fixed investment instantly. Later, Sueyoshi and Sekitani[76] incorporated the concept of returns to scale into a dynamic DEA model. Amirteimoori[77] defined the DEA model to assess dynamic income efficiency and was modified and extended by Färe and Grosskopf.[78] Tone and Tsutsui[69] extended the model to dynamic analysis of slacks-based measures.

The evaluation performance of DDF non-ray distance function is better, and it can provide more reasonable and accurate estimation results. However, Färe et al[58] DDF non-ray distance function failed to consider the two-stage inter-temporal persistence effect and regional differences, so this article combines Tone and Tsutsui[69] dynamic two-stage DEA and O'Donnell et al[79] meta-frontier, proposes an undesirable two-stage meta-frontier DDF data envelopment analysis model. This paper uses this model to evaluate the energy efficiency and healthy efficiency in high income countries and middle income countries from 2010 to 2014 to avoid underestimation or overestimation of efficiency values and improvement space.

Undesirable Two-Stage Meta-Frontier DDF Data Envelopment Analysis Model

Assume that due to different management types, resources, regulations, or environments, all manufacturers (N) are composed of decision-making units ($N = N_1 + N_2 + \ldots + N_g$) of g groups. Suppose there are 2 stages in each t time periods $(t = 1, \ldots, T)$. In each time period, there are 2 stages, including energy efficiency and healthy efficiency. Energy efficiency stage has m inputs $x_{ij}^{t}\,(i = 1, \ldots, m)$ to generate D intermediate products $z_{dj}^{t}\,(d = 1, \ldots, D)$ and K desirable outputs $q_{kj}^{t}\,(k = 1, \ldots, K)$. Healthy efficiency stage produces desirable S1 output $y_{rj}^{vt}\,(r = 1, \ldots, s1)$ and undesirable $s2$ output $y_{rj}^{bt}\,(r = 1, \ldots, s2)$ from D intermediate products $z_{dj}^{t}\,(d = 1, \ldots, D)$ and C inputs $w_{cj}^{t}\,(c = 1, \ldots, C)$, $c_{hj}^{d^{t-1}}\,(h = 1, \ldots, H)$ is carry-over factor.

Under the meta frontier, the decision unit k can choose the final output that is most favorable to its maximum value, so the efficiency of the decision unit k under the common boundary can be solved by the following linear programming procedure.

Overall efficiency:

The efficiency of the DMU is:

$$\max \text{MFE} = \sum_{g=1}^{G}\sum_{t=1}^{T}\gamma_{tg}\left(w_{1g}^{t}\theta_{1g}^{t} + w_{2g}^{t}\theta_{2g}^{t}\right) \tag{1}$$

S.T.

energy efficiency stage healthy efficiency stage

$$\sum_{g=1}^{G}\sum_{j}^{n}\lambda_{jg}^{t}X_{ijg}^{t} \le \theta_{1g}^{t}X_{ipg}^{t}\ \forall i\forall t \qquad \sum_{g=1}^{G}\sum_{j}^{n}\mu_{jg}^{t}Z_{djg}^{t} \le \theta_{2g}^{t}Z_{dg}^{t}\ \forall d\forall t$$

$$\sum_{g=1}^{G}\sum_{j}^{n}\lambda_{jg}^{t}z_{djg}^{t} \le \theta_{1g}^{t}z_{dpg}^{t}\ \forall d\forall t \qquad \sum_{g=1}^{G}\sum_{j}^{n}\mu_{jg}^{t}y_{rjg}^{vt} \ge \theta_{2g}^{t}y_{rg}^{vt}\ \forall r\forall t$$

$$\sum_{g=1}^{G}\sum_{j}^{n}\lambda_{jg}^{t}q_{kjg}^{t} \ge \theta_{1g}^{t}q_{kg}^{t}\ \forall k\forall t \qquad \sum_{g=1}^{G}\sum_{j}^{n}\mu_{jg}^{t}y_{rjg}^{bt} \le \theta_{2g}^{t}y_{rg}^{bt}\ \forall r\forall t$$

$$\sum_{g=1}^{G}\sum_{j}^{n}\mu_{jg}^{t}w_{cjg}^{t} \le \theta_{2g}^{t}w_{cg}^{t}\ \forall c\forall t$$

$$\sum_{g=1}^{G}\sum_{j}^{n}\lambda_{jg}^{k} \le 1\forall t \qquad \sum_{g=1}^{G}\sum_{j}^{n}\mu_{jg}^{t} = 1\forall t$$

$$\lambda_{j}^{t} \ge 0\ \forall j\forall t \qquad \mu_{j}^{t} \ge 0\ \ \forall j\forall t \tag{2}$$

The link of 2 stages

$$\sum_{g=1}^{G}\sum_{j=1}^{n}\lambda_{jg}^{t}Z_{djg}^{t} = \sum_{g=1}^{G}\sum_{j=1}^{n}\mu_{jg}^{t}Z_{djg}^{t} \quad \forall d\forall t$$

The link of 2 periods (3)

$$\sum_{g=1}^{G}\sum_{j=1}^{n}\lambda_{jg}^{t-1}c_{hjg}^{t} = \sum_{g=1}^{G}\sum_{j=1}^{n}\lambda_{jg}^{t}c_{hjg}^{t} \quad \forall h\forall t$$

Among them, γ_t is the weight assigned to the period t, and w_1^t and w_2^t are the weights assigned to the energy efficiency stage and healthy efficiency stage in time period t, respectively. Therefore, for each time period t $w_1^t, w_2^t, \gamma_t \ge 1$ *and* $\sum_{g=1}^{G}\sum_{t=1}^{T}\gamma_{tg} = 1$.

We can calculate the following 3 efficiency groups through the linear programming formula in model

(1) Stage efficiency:

The energy efficiency stage efficiency value is

The efficiency of stage L (L = 1, 2) of the DMU to be evaluated is evaluated relative to each period t $\left(t=1,\ldots,T\right)$. Stage efficiency can be expressed as:

$$\rho_1^{t^*} = 1-\theta_l^{t^*}; l = 1, 2; \mathrm{t}=1,2,\cdots,\mathrm{T} \quad (4)$$

The healthy efficiency stage efficiency value is

$$\rho_2^{t^*} = 1-\sum_{t=1}^{T}\gamma_t\theta_t^{t^*}; l=1, 2 \quad (5)$$

(2) Period efficiency value

In this group, to evaluate the overall efficiency of each period t of the DMU being evaluated, it can be expressed as follows:

$$\rho^{t^*} = w_1^t\rho_1^{t^*} + w_2^t\rho_2^{t^*}; \mathrm{t}=1,2,\cdots,\mathrm{T} \quad (6)$$

(3) The overall efficiency

In this group, the overall efficiency of the DMU being evaluated will be evaluated. The overall efficiency is given by the weighted sum of periodic efficiency on t, which can be expressed as:

$$\rho^* = \sum_{t=1}^{T}\gamma_t\rho^{t^*} \quad (7)$$

From the above, the overall efficiency, period efficiency, division efficiency, and division period efficiency can be obtained using the meta-frontier model.

Group-Frontier

As each DMU under the group frontier chooses the most favorable final weighted output, the DMU efficiencies under the group frontier are solved using the following equations:

The efficiency of the DMU is:

$$\max \mathrm{GFE} = \sum_{t=1}^{T}\gamma_t\left(w_1^t\theta_1^t + w_2^t\theta_2^t\right) \quad (8)$$

S.T.

energy efficiency stage — healthy efficiency stage

$$\sum_j^n\lambda_j^t X_{ij}^t \le \theta_1^t X_{ip}^t \ \forall i\forall t \qquad \sum_j^n\mu_j^t Z_{dj}^t \le \theta_2^t Z_d^t \ \forall d\forall t$$

$$\sum_j^n\lambda_j^t z_{dj}^t \le \theta_1^t z_{dp}^t \ \forall d\forall t \qquad \sum_j^n\mu_j^t y_{rj}^{vt} \ge \theta_2^t y_r^{vt} \ \forall r\forall t$$

$$\sum_j^n\lambda_j^t q_{kj}^t \ge \theta_1^t q_k^t \forall k\forall t \qquad \sum_j^n\mu_j^t y_{rj}^{bt} \le \theta_2^t y_r^{bt}\forall r\forall t$$

$$\sum_j^n\mu_j^t w_{cj}^t \le \theta_2^t w_c^t \ \forall c\forall t$$

$$\sum_j^n\lambda_j^k \le 1\forall t \qquad \sum_j^n\mu_j^t = 1\forall t$$

$$\lambda_j^t \ge 0 \ \forall j\forall t \quad \mu_j^t \ge 0 \ \forall j\forall t \quad (9)$$

The link of 2 stages

$$\sum_{j=1}^n\lambda_j^t Z_{dj}^t = \sum_{j=1}^n\mu_j^t Z_{dj}^t \qquad \forall d\forall t$$

The link of 2 periods (10)

$$\sum_{j=1}^n\lambda_j^{t-1}c_{hj}^t = \sum_{j=1}^n\lambda_j^t c_{hj}^t \quad \forall h\forall t$$

Among them, γ_t. is the weight assigned to the period t, and w_1^t and w_2^t are the weights assigned to the energy efficiency stage and healthy efficiency stage in time period t, respectively. Therefore, for each time period t $w_1^t, w_2^t, \gamma_t \ge 1 and \sum_{t=1}^{T}\gamma_t = 1$.We can calculate the following 3 efficiency groups through the linear programming formula in model.

(1) Stage efficiency:

The energy efficiency stage efficiency value is

In this group, the efficiency of stage L (L= 1, 2) of the DMU to be evaluated is evaluated relative to each period t $\left(t=1,\ldots,T\right)$. Stage efficiency can be expressed as:

$$\rho_1^{tg} = 1-\theta_l^{tg^*}; l = 1, 2; \mathrm{t}=1,2,\cdots,\mathrm{T} \quad (11)$$

The healthy efficiency stage efficiency value is

$$\rho_2^{tg} = 1-\sum_{t=1}^{T}\gamma_t\theta_t^{tg^*}; l = 1, 2 \quad (12)$$

(2) Period efficiency value

In this group, to evaluate the overall efficiency of each period t of the DMU being evaluated, it can be expressed as follows:

$$\rho^{tg} = w_1^t\rho_1^{tg} + w_2^t\rho_2^{tg}; \mathrm{t}=1,2,\cdots,\mathrm{T} \quad (13)$$

(3) The overall efficiency

In this group, the overall efficiency of the DMU being evaluated will be evaluated. The overall efficiency is given by the weighted sum of periodic efficiency on t, which can be expressed as:

$$\rho^{*g} = \sum_{t=1}^{T} \gamma_t \rho^{tg} \quad (14)$$

From the above results, the overall efficiency, the period efficiency, the division efficiency, and division period efficiency are obtained.

Technology Gap Ratio

As the meta-frontier model contains g groups, the technical efficiency of the meta-frontier (MFE) is less than the technical efficiency of the group frontier (GFE). The ratio value, or the technology gap ratio (TGR), is:

$$\text{TGR} = \frac{\rho^*}{\rho^{*g}} = \frac{MFE}{GFE} \quad (15)$$

Energy and Health Efficiency

Hu and Wang's[80] total-factor energy efficiency index was used to overcome any possible biases in the traditional energy efficiency indicators, for which there were ten key efficiency models; Labor, Renewable Energy, Non-Renewable Energy, GDP, health expenditure, mortality rate of Children, mortality rate of the aged, Survival rate of 65 years old, CO_2 emissions, and PM2.5. In this study, "i" represented area and "t" represented time. The ten efficiency models are defined in the following:

$$\text{Labor efficiency} = \frac{\text{Target Labor input}(i,t)}{\text{Actual Labor input}(i,t)}$$

$$\text{Renewable Energy efficiency} = \frac{\text{Target Renewable Energy input}(i,t)}{\text{Actual Renewable Energy input}(i,t)}$$

$$\text{Non- Renewable Energy efficiency} = \frac{\text{Target Non} - \text{Renewable Energy input}(i,t)}{\text{Actual Non} - \text{Renewable Energy input}(i,t)}$$

$$\text{Health expenditure efficiency} = \frac{\text{Target Health expenditure input}(i,t)}{\text{Actual Health expenditure input}(i,t)}$$

$$\text{GDP efficiency} = \frac{\text{Target desirable GDP output}(i,t)}{\text{Actual desirable GDP output}(i,t)}$$

$$\text{mortality rate of Children efficiency} = \frac{\text{Target Undesirable mortalityrate of Children output}(i,t)}{\text{Actual Undesirable mortalityrate of Children output}(i,t)}$$

$$\text{mortality rate of the aged efficiency} = \frac{\text{Target Undesirable mortality rate of the aged output}(i,t)}{\text{Actual Undesirable mortality rate of the agedoutput}(i,t)}$$

$$\text{Survival rate of 65 years old efficiency} = \frac{\text{Target desirable Survival rate of 65year soldoutput}(i,t)}{\text{Actual desirable Survivalrate of 65year soldoutput}(i,t)}$$

$$\text{CO2 efficiency} = \frac{\text{Target Undesirable CO2 output}(i,t)}{\text{Actual Undesirable CO2 output}(i,t)}$$

$$\text{PM2.5 efficiency} = \frac{\text{Target Undesirable PM2.5 output}(i,t)}{\text{Actual Undesirable PM2.5 output}(i,t)} \quad (16)$$

If the target labor, renewable energy, non-renewable energy and health expenditure inputs equal the actual inputs, then the efficiencies are 1, which indicates overall efficiency; however, if the target labor, renewable energy, non-renewable energy and health expenditure inputs are less than the actual inputs, then the efficiencies are <1, which indicates overall inefficiency.

If the target desirable GDP and survival rate of 65 years old outputs are equal to the actual desirable outputs, then the efficiencies are 1, indicating overall efficiency; however, if the target desirable outputs are larger than the actual desirable outputs, then the efficiencies are <1, indicating overall inefficiency.

If the target undesirable mortality rate of children, mortality rate of the aged, CO_2 emissions, and PM2.5 outputs are equal to the actual undesirable outputs, then the efficiencies are 1, indicating overall efficiency; however, if the target undesirable outputs are less than the actual undesirable outputs, then the efficiencies are <1, indicating overall inefficiency.

Empirical Analysis

Data Sources and Description

This study compares the energy efficiency and healthy efficiency in high income countries, upper middle income countries, and lower middle income countries from 2010 to 2014. The data in this paper is from the World Bank database. Now, there are 27 high income countries, 21 upper middle income countries, and 16 lower middle income countries in this paper.

The first stage: Production stage. Input variables:

Labor: the number of employed people in a country over the age of 15 each year. Unit: million persons.

Renewable energy: the annual renewable energy consumption of a country. Unit: Mega Joule.

Non-renewable energy: the annual non-renewable energy consumption of a country. Unit: Mega Joule.

Output variables:

GDP (desirable output): the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. Unit: billion dollars at current price.

The second stage: The health treatment stage. Input variables:

Health Expenditure: total annual health expenditure in each country. Unit: billion dollars.

Output variables:

Mortality rate of Children (undesirable output): the annual mortality rate of children under 5 years old in each country. Unit: percent.

Mortality rate of the aged (undesirable output): the annual mortality rate of people over 65 years old in each country. Unit: percent.

Survival rate (desirable output): the annual survival rate of 65 years old in each country. Unit: percent.

Link production stage and the health treatment stage variables. CO_2: the annual CO_2 emissions in each country. Unit: million ton.

PM2.5: Population-weighted exposure to ambient PM2.5 pollution is defined as the average level of exposure of a nation's population to concentrations of suspended particles measuring <2.5 microns in aerodynamic diameter, which are capable of penetrating deep into the respiratory tract and causing severe health damage. Exposure is calculated by weighting mean annual concentrations of PM2.5 by population in both urban and rural areas. Unit: micrograms per cubic meter.

Carry over production stage and the health treatment stage variable. Fixed assets: capital stock of each country is calculated by fixed assets investment in each country by the end of each year. Unit: billion dollars.

Annual Overall Efficiency Scores

Table 3 shows the annual overall efficiency of high income countries from 2010 to 2014. The overall efficiency of countries such as Brunei Darussalam, Iceland, Singapore, Saudi Arabia, Japan, and United States were always 1 in the 5 years from 2010 to 2014. The overall efficiency of Israel and Korea Rep. had ever reached 1 from 2010 to 2014. The overall efficiency of countries such as Belgium, Canada, Chile, Czech Republic, France, Germany, Greece, Netherlands, Poland, Portugal, and Spain were below the average overall efficiency from 2010 to 2014. Overall, there are 15 of the 27 high countries having the overall efficiency above the average efficiency. Besides, the overall efficiency of most of the high income countries are above 0.8. Therefore, high income countries have good performance in the overall efficiency in general.

Table 4 shows the annual overall efficiency of upper middle income countries from 2010 to 2014. None of these countries had kept an overall efficiency of 1 during the 5 years. The overall efficiency of Cuba, Georgia, and Irap had ever reached 1 from 2010 to 2014. The overall efficiency of Belarus, Bulgaria, China, Colombia, Kazakhstan, Malaysia, Mexico, Peru, Russian Federation, Serbia, South Africa, Thailand, and Turkey were below the average overall efficiency in most time from 2010 to 2014. Overall, there are only 8 of the 21 middle countries having the overall efficiency above the average efficiency. Besides, the overall efficiency of most of the upper middle income countries are below 0.6. Therefore, upper middle income countries have bad performance in the overall efficiency in general.

Table 5 shows the annual overall efficiency of lower middle income countries from 2010 to 2014. Only Cambodia had kept an overall efficiency of 1 during the 5 years. The overall efficiency of Kyrgyz Republic and Mongolia had ever reached 1 from 2010 to 2014. The overall efficiency of Bangladesh, India, Kenya, Morocco, Philippines, Tunisia, Ukraine, and Vietnam were below the average overall efficiency. Overall, there are only 8 of the 16 lower middle countries having the overall efficiency above the average efficiency. Besides, the overall efficiency of most of the lower middle income countries are below 0.6. Therefore, middle income countries have bad performance in the overall efficiency in general. However,

Table 3. Overall Efficiency of High Income Countries from 2010 to 2014.

DMU	2010	2011	2012	2013	2014	Average	DMU	2010	2011	2012	2013	2014	Average
Australia	0.9447	0.9221	0.9353	0.9510	0.9551	0.9416	New Zealand	0.8688	0.9070	0.8996	0.9102	0.9123	0.8996
Belgium	0.8163	0.7818	0.7782	0.8002	0.8113	0.7976	Norway	0.9315	0.9253	0.9318	0.9424	0.9781	0.9418
Brunei Darussalam	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	Poland	0.4529	0.4826	0.4793	0.5067	0.4992	0.4841
Canada	0.8446	0.8652	0.8430	0.8451	0.8856	0.8567	Portugal	0.7581	0.7443	0.8343	0.8295	0.7883	0.7909
Chile	0.5497	0.6082	0.5392	0.5481	0.5049	0.5500	Saudi Arabia	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Czech Republic	0.5901	0.5796	0.5846	0.5882	0.5403	0.5766	Singapore	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
France	0.8346	0.8341	0.8276	0.8405	0.8527	0.8379	Spain	0.8789	0.8137	0.8242	0.9106	0.8276	0.8510
Germany	0.8516	0.8747	0.8341	0.8714	0.8816	0.8627	Sweden	0.9934	0.9897	1.0000	1.0000	0.9921	0.9950
Greece	0.7799	0.8616	0.8509	0.8650	0.8747	0.8464	Switzerland	0.9861	0.9912	0.9887	1.0000	1.0000	0.9932
Iceland	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	United Arab Emirates	0.9830	0.9817	0.9525	1.0000	1.0000	0.9834
Israel	0.8758	0.8583	0.9227	1.0000	1.0000	0.9314	United Kingdom	0.8715	0.8672	0.8791	0.8901	0.8936	0.8803
Italy	0.9811	0.9648	0.9807	1.0000	0.9543	0.9762	United States	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Japan	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	Average	0.8717	0.8741	0.8754	0.8920	0.8861	0.8799
Korea Rep.	1.0000	1.0000	1.0000	1.0000	0.9288	0.9416							
Netherlands	0.9347	0.9239	0.9249	0.9405	0.9449	0.7976							

Table 4. Overall Efficiency of Upper Middle Income Countries from 2010 to 2014.

DMU	2010	2011	2012	2013	2014	Average	DMU	2010	2011	2012	2013	2014	Average
Argentina	0.6116	0.7082	0.6430	0.6471	0.5277	0.6275	Iraq	0.6026	0.9281	1.0000	0.9806	0.5442	0.8111
Belarus	0.2675	0.2899	0.2824	0.2966	0.3028	0.2878	Kazakhstan	0.3447	0.4123	0.4423	0.5501	0.4613	0.44214
Botswana	0.5021	0.5360	0.5749	0.5456	0.5871	0.5491	Malaysia	0.3813	0.4709	0.3982	0.4127	0.3878	0.41018
Brazil	0.6161	0.6182	0.5553	0.5620	0.5023	0.5708	Mexico	0.4650	0.4584	0.4525	0.4765	0.4472	0.45992
Bulgaria	0.3862	0.3998	0.3874	0.3939	0.3653	0.3865	Peru	0.4467	0.4464	0.4859	0.4839	0.4513	0.46284
China	0.4757	0.4541	0.4947	0.5443	0.5452	0.5028	Russian Federation	0.3176	0.6104	0.4160	0.4224	0.3265	0.41858
Colombia	0.5017	0.5277	0.5261	0.5245	0.4792	0.5118	Serbia	0.4541	0.5085	0.4291	0.4311	0.4361	0.45178
Costa Rica	0.6742	0.6634	0.7172	0.7399	0.6924	0.6974	South Africa	0.3127	0.3367	0.3133	0.2331	0.1924	0.27764
Cuba	0.9823	1.0000	0.8143	1.0000	0.9651	0.9523	Thailand	0.3060	0.3180	0.2919	0.3059	0.2783	0.30002
Georgia	0.7795	1.0000	0.7055	0.5869	0.5396	0.7223	Turkey	0.4665	0.4192	0.4415	0.4682	0.4276	0.4446
Iran	0.5417	0.6091	0.6500	0.5883	0.5327	0.5844	Average	0.4969	0.5579	0.5248	0.5330	0.4758	0.5177

Table 5. Overall Efficiency of Lower Middle Income Countries from 2010 to 2014.

DMU	2010	2011	2012	2013	2014	Average	DMU	2010	2011	2012	2013	2014	Average
Algeria	0.5288	0.5672	0.5446	0.5609	0.6696	0.5742	Nigeria	0.6471	0.6505	0.6309	0.6263	0.6289	0.6367
Bangladesh	0.4802	0.4718	0.4646	0.4888	0.4864	0.4784	Pakistan	0.6619	0.7298	0.6604	0.6451	0.6081	0.6611
Cambodia	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	Philippines	0.4169	0.4649	0.5174	0.5376	0.4185	0.4711
Cameroon	0.6595	0.5870	0.7930	0.7596	0.7858	0.7170	Sri Lanka	0.5652	0.5987	0.5459	0.5417	0.5502	0.5603
India	0.2728	0.2489	0.2586	0.2751	0.2541	0.2619	Tunisia	0.4771	0.4999	0.4637	0.4683	0.4626	0.4743
Kenya	0.4263	0.4396	0.5082	0.4800	0.4432	0.4595	Ukraine	0.4457	0.5260	0.4657	0.4733	0.2504	0.4322
Kyrgyz Republic	1.0000	0.6825	0.5680	0.5230	0.5738	0.6695	Vietnam	0.2466	0.2834	0.2994	0.3319	0.3198	0.2962
Mongolia	1.0000	1.0000	0.5789	0.5966	0.5495	0.7450	Average	0.5819	0.5754	0.5482	0.5506	0.5318	0.5576
Morocco	0.4818	0.4561	0.4721	0.5009	0.5071	0.4836							

the average overall efficiency of lower middle income countries was higher than that of upper middle income countries. It demonstrated that lower middle income countries have better performance in the overall efficiency than upper income countries in general.

Through the comparison of the data in Tables 3, 4, and 5, we could find the average efficiency of high income countries was higher than that of upper and lower middle countries. Besides, there were 55.56% of high income countries, 38.09% of upper middle income countries and 50% of lower

Table 6. Average Overall Efficiency in Each Stage.

	2010-I	2011-I	2012-I	2013-I	2014-I	Average-I
High income	0.9409	0.9161	0.9163	0.9271	0.9060	0.9213
Upper middle income	0.5536	0.6422	0.5821	0.5738	0.4897	0.5683
Lower middle income	0.5919	0.5885	0.5834	0.5238	0.4749	0.5525
	2010-II	2011-II	2012-II	2013-II	2014-II	Average-II
High income countries	0.8527	0.8451	0.8473	0.8684	0.8736	0.8574
Upper middle income	0.4402	0.4734	0.4675	0.4921	0.4619	0.4670
Lower middle income	0.5718	0.5619	0.5579	0.5727	0.5885	0.5706

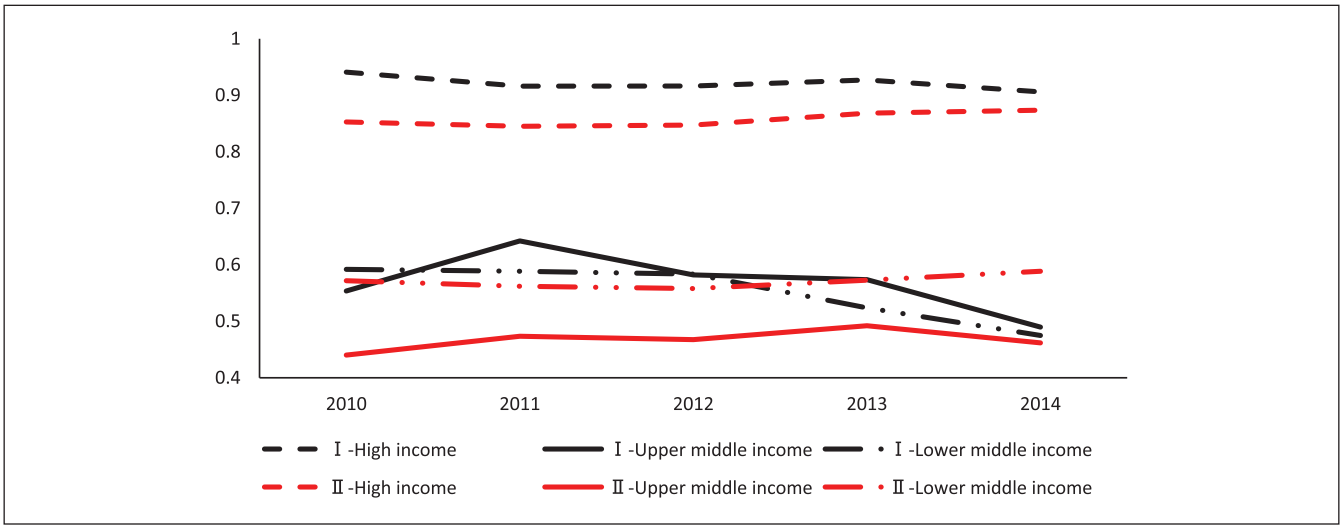

Figure 1. Average annual overall efficiency in each stage.

middle income countries having the overall efficiency above the average efficiency. Therefore, this might imply that there was a U-shaped relationship between overall efficiency and income level. This paper would discuss this phenomenon later. In addition, both high income countries and middle income countries in Eastern Europe have shown lower overall efficiency. Therefore, countries in Eastern Europe have greater room for improvement and need cooperation to improve overall efficiency. In addition, Western European countries should also pay close attention to the development of Eastern European countries and provide timely assistance to prevent negative spatial spillover effects.

Total Average Efficiency Scores Analysis in Each Stage

In order to specifically analyzed the differences in the overall efficiency of countries with different income levels, Table 6 showed the efficiency values at different stages. In the first stage, the efficiency of high income countries was above 0.9, and the efficiency value of middle income countries was around 0.5. The average efficiency of upper income countries is higher than that of lower middle income countries in general. In the second stage, the efficiency of high income countries was above 0.8, the efficiency value of upper middle income countries was around 0.45, and the efficiency value of lower middle income countries was around 0.56.

Figure 1 showed more clearly the difference of trends and gaps in efficiency between the high income countries and middle income countries in 2 stages. The efficiency of the first stage of high income countries showed a steady trend of fluctuations, with no obvious upward or downward trend. However, the efficiency of upper middle income countries and lower middle income countries showed significant differences in the 2 stages. This phenomenon would help explain the U-shaped relationship mentioned above. Though the efficiency of upper middle income countries and lower middle income countries were not much different in the first stage, the efficiency of lower middle income countries was significantly higher than that of upper middle income countries in the second stage. The reason for this phenomenon might be that upper income countries were in the stage of accelerating industrialization and rapid economic development, and a large number of environmental and medical

Table 7. Average TGRs of High Income and Middle Income Countries.

	2010	2011	2012	2013	2014	Average
High income	0.9941	0.9972	0.9909	0.9958	0.9948	0.9946
Upper middle income	0.5429	0.6068	0.5752	0.5806	0.5200	0.5651
Lower middle income	0.6244	0.6226	0.5981	0.6079	0.5814	0.6069
	2010-I	2011-I	2012-I	2013-I	2014-I	Average-I
High income	0.9971	1.0000	0.9910	0.9969	0.9957	0.9977
Upper middle income	0.6132	0.6230	0.5628	0.5607	0.5002	0.5720
Lower middle income	0.5856	0.6822	0.6237	0.6147	0.5257	0.6064
	2010-II	2011-II	2012-II	2013-II	2014-II	Average-II
High income	0.9911	0.9859	0.9903	0.9948	0.9933	0.9911
Upper middle income	0.4960	0.5206	0.5234	0.5558	0.5176	0.5227
Lower middle income	0.6271	0.6178	0.6242	0.6506	0.6566	0.6353

problems had been accumulated in the early stage. Therefore, the efficiency of upper income countries in the second stage was lower than that of lower income countries.

The Technical Efficiency of the Group Frontier for High Income and Middle Income Countries

Table 7 showed the technology gap ratio (TGR) of high income and middle income countries from 2010 to 2014. Due to space limitations, this article did not list the TGR for each country. Table 5 showed the average overall TGRs of high income countries were higher obviously than that of middle income countries. However, the average overall TGRs of lower income countries was higher than that of upper middle income countries. In the first stage, the TGRs of high income countries were above 0.9, while the TGRs of middle income countries were below 0.7. In the second stage, the TGRs of high income countries were also above 0.9 while the TGRs of middle income countries were below 0.66. Besides, the TGRs of upper middle income countries was lower than that of lower income countries in each stage, and it was more significant in the second stage. Therefore, compared with high-income countries, middle income countries had a bigger gap between group frontier (GF) and meta-frontier (MF) in the energy efficiency and health efficiency. The phenomenon that the TGRs of upper income countries was lower than the TGRs of lower income countries implied that there was also a U-shaped relationship in terms of income levels and TGR.

The Efficiency of the Input and Output Variables

Table 8 contained the data of annual average efficiency of each variable in the production stage. Labor, renewable energy and non-renewable energy were the input variables and GDP, CO_2 and PM2.5 were the output variables. The data reflected the input and output efficiency of energy.

Firstly, from the perspective of energy input, non-renewable energy was more efficient than renewable energy in general. However, there was some difference between high income countries and middle income countries. Firstly, high income countries had higher efficiency of renewable energy and non-renewable energy than middle income countries. Secondly, the gaps between renewable efficiency and non-renewable energy efficiency in high income countries and lower income countries were greater than in upper middle income countries. Thirdly, the renewable efficiency of upper middle income countries was higher than that of lower income countries. Therefore, there were much room for upper middle income countries to improve renewable energy and non-renewable energy efficiency. Besides, lower income countries should also improve renewable energy efficiency.

Secondly, from the perspective of energy output, GDP is the desirable output, CO_2 and PM2.5 are undesirable outputs. It was obvious that high income countries had higher efficiency in GDP, CO_2 and PM2.5 than middle income countries. However, there was some difference in the efficiency of middle income countries. The efficiencies of GDP in upper middle income countries and lower middle income countries were roughly equal from 2010 to 2014. But the efficiency of CO_2 and PM2.5 in upper middle income countries and lower middle income countries were opposite. Upper middle income performed better in PM2.5, while lower middle income countries performed $CO_{2.}$

Table 9 contains the data of annual average efficiency of each variable in the health treatment stage. Health expenditure is the input variable. Mortality rate of children, mortality rate of the aged and survival rate of 65 years old are the output variables. The data also reflects the input and output efficiency of health treatment.

Firstly, from the perspective of health treatment input, high income countries performed better than middle income countries, and lower middle income countries performed better than upper middle income countries. Secondly, from the

Table 8. Comparison of Energy Efficiency.

Year	Countries	Labor	Renewable energy	Non-renewable energy	GDP	CO_2	PM2.5
2010	High income	0.8996	0.8497	0.9121	0.9596	0.9149	0.8810
	Upper middle income	0.4182	0.5672	0.5713	0.8225	0.5348	0.4961
	Lower middle income	0.3765	0.5743	0.6592	0.8425	0.6604	0.5698
2011	High income	0.9350	0.8502	0.9299	0.9641	0.9199	0.8762
	Upper middle income	0.5399	0.6536	0.6555	0.8587	0.6275	0.5943
	Lower middle income	0.3811	0.6324	0.6486	0.8402	0.6843	0.5345
2012	High income	0.9332	0.8887	0.9264	0.9648	0.9159	0.9115
	Upper middle income	0.4683	0.5995	0.6059	0.8351	0.5989	0.5466
	Lower middle income	0.3416	0.5024	0.6034	0.8205	0.6192	0.4565
2013	High income	0.9418	0.9245	0.9340	0.9696	0.9379	0.9408
	Upper middle income	0.4675	0.6363	0.6037	0.8330	0.5992	0.5850
	Lower middle income	0.3125	0.6319	0.5939	0.8184	0.6239	0.4617
2014	High income	0.9170	0.8397	0.8794	0.9596	0.8762	0.9339
	Upper middle income	0.4612	0.5754	0.5842	0.8017	0.5301	0.6123
	Lower middle income	0.3283	0.5559	0.5819	0.8009	0.6068	0.4362
Annual average	High income	0.9253	0.8706	0.9164	0.9635	0.9130	0.9087
	Upper middle income	0.4710	0.6064	0.6041	0.8302	0.5781	0.5669
	Lower middle income	0.3480	0.5794	0.6174	0.8245	0.6389	0.4917

Table 9. Comparison of Health Efficiency.

Year	Countries	Health expenditure	Mortality rate of children	Mortality rate of the aged	Survival rate of 65 years old
2010	High income	0.6939	0.8407	0.8859	0.9311
	Upper middle income	0.4743	0.3479	0.4888	0.7732
	Lower middle income	0.6647	0.4591	0.6498	0.8269
2011	High income	0.6744	0.8289	0.8770	0.9275
	Upper middle income	0.5333	0.4002	0.5261	0.7869
	Lower middle income	0.6544	0.4161	0.6133	0.8231
2012	High income	0.5777	0.8083	0.8834	0.9283
	Upper middle income	0.4496	0.3651	0.5035	0.7894
	Lower middle income	0.6501	0.3394	0.5537	0.8197
2013	High income	0.7738	0.8528	0.9024	0.9383
	Upper middle income	0.5901	0.3989	0.5413	0.7866
	Lower middle income	0.6617	0.3476	0.5453	0.8254
2014	High income	0.8710	0.8818	0.9127	0.9405
	Upper middle income	0.5592	0.3853	0.5310	0.7838
	Lower middle income	0.6860	0.3522	0.5510	0.8311
Annual average	High income	0.7182	0.8425	0.8923	0.9331
	Upper middle income	0.5213	0.3795	0.5181	0.7840
	Lower middle income	0.6634	0.3829	0.5826	0.8252

perspective of health treatment output, survival rate of 65 years old is the desirable output, mortality rate of children and mortality rate of the aged are undesirable outputs. It is obvious that high income countries have higher efficiency in mortality rate of children, mortality rate of the aged and survival rate of 65 years old than middle income countries, especially in mortality rate of children. Lower middle income countries performed better than upper middle income countries in mortality rate of children, mortality rate of the aged and survival rate of 65 years, especially in mortality rate of the aged.

Conclusions and Implications

This paper focused on the energy efficiency and health efficiency in high income countries and middle countries from

2010 to 2014. Furthermore, in order to better understand the health and energy efficiency performance of various countries at different income levels, this paper further refined the income level, which was divided into 2 categories: upper middle income countries and lower middle income countries. This paper calculated the efficiency for the inputs and outputs of the production stage and health treatment stage in high income countries and middle countries using undesirable two-stage meta-frontier DDF data envelopment analysis model. The efficiency we calculated included the efficiency of non-renewable energy, renewable energy, PM2.5, CO_2, labor, GDP, health expenditure, mortality rate of children, mortality rate of the aged, and survival rate of 65 years old. This paper drew some conclusions by comparing and analyzing the efficiency of high income countries, upper middle income countries, and lower middle income countries. The detail conclusions were as follows:

(1) The overall efficiency of high income countries was higher than middle income countries in general from 2010 to 2014. The average overall efficiency of high income countries was about 0.87 while the average overall efficiency of upper middle income countries was only about 0.50 and the average overall efficiency of lower middle income countries was about 0.55. Besides, there were 55.56% of high income countries, 38.09% of upper middle income countries, and 50% of lower middle income countries having the overall efficiency above the average efficiency.
(2) There was a U-shaped relationship between health efficiency and income level. As the data showed, the efficiency performance of upper middle income countries in the health treatment was worse than that of high income countries and lower middle income countries. Specifically, the performance of upper middle income countries in health expenditure, mortality rate of children, mortality rate of the aged and survival rate of 65 years old was worse than the others.
(3) In the production stage, the efficiency of high income countries is higher than middle income country and the gap between high income countries and middle income countries was widening. Besides, the efficiency of upper middle income countries was higher than that of lower middle income countries but the gap between upper middle income countries and lower middle income countries was small. Thus, there is much room for middle income countries to improve the efficiency of the first stage, namely energy efficiency.
(4) Non-renewable energy was more efficient than renewable energy in general. Whether in high income or middle income countries, the efficiency of non-renewable energy was higher than renewable energy. High income countries should improve renewable energy efficiency because the gaps between renewable energy efficiency and non-renewable energy efficiency in high income countries are greater than in middle income countries.
(5) Middle income countries produced more air pollutants than high income countries under the same conditions of economic growth from 2010 to 2014. The gaps between high income countries and middle income countries in the efficiency of GDP were about 0.1 from 2010 to 2014. But the gaps between high income countries and middle income countries in the efficiency of CO_2 and PM2.5 were about 0.3 from 2010 to 2014.
(6) There were much more room for middle income countries to reduce the mortality rate of children and mortality rate of the aged. The efficiency of mortality rate of children and mortality rate of the aged are only 0.5 and 0.8, respectively, which were very lower than high income countries.

Based on the above discussions, this paper puts forward the following practical and positive suggestions for improving the efficiency for high income countries and middle income countries.

(1) Middle income countries should increase the efficiency of non-renewable energy, increase supervision of environmental pollution problems, promote the progress of energy-saving and emission-reduction technologies, and reduce pollutant emissions per unit of GDP.
(2) High income countries should take advantage of economic development and technological bases to increase investment in research and development of renewable energy technologies and improve the efficiency of renewable energy. In addition, high income countries should take the initiative to help the surrounding middle income countries to improve efficiency, because efficiency might have spatial autocorrelation and there would be spillover effects.
(3) Middle income countries should increase their fiscal expenditures to meet the medical needs of residents, popularize medical common sense, strengthen the construction of basic medical systems, improve the health conditions of children, and reduce mortality rate of children.
(4) Upper income countries should pay attention to the environmental and health problems that had occurred in the process of pursuing rapid economic development, improve the efficiency of the health treatment stage, and cross the U-shaped turning point, so as to achieve sustainable economic development.

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References

1. Kraft J, Kraft A. Relationship between energy and GNP. *J Energy Dev*. 1978;3:401-403.
2. Chow J, Kopp RJ, Portney PR. Energy resources and global development. *Science*. 2003;302:1528-1531.
3. Clancy L, Goodman P, Sinclair H, Dockery DW. Effect of air-pollution control on death rates in Dublin, Ireland: an intervention study. *Lancet*. 2002;360:1210-1214.
4. Panayotou T. Empirical tests and policy analysis of environmental degradation at different stages of economic development. Working paper WP238. 1993.
5. Zhang XP, Cheng XM, Yuan JH, Gao XJ. Total-factor energy efficiency in developing countries. *Energy Policy*. 2011;39:644-650.
6. Feng Y, Yu X, Chiu Y-H, Chang T-H. Dynamic linkages among economic development, energy consumption, environment and health sustainable in EU and Non-EU Countries. *Healthcare*. 2019;7:138.
7. Feng Y, Yu X, Chiu Y-H, Lin T-Y. Energy efficiency and health efficiency of old and new EU Member States. *Front Publ Health*. 2020;8:168.
8. Zhang T. Frame work of data envelopment analysis-A model to evaluate the environmental efficiency of China's industrial sectors. *Biomed Environ Sci*. 2009;22(1):8-13.
9. Martínez CIP. Energy efficiency development in German and Colombian non-energy-intensive sectors: a non-parametric analysis. *Energy Effic*. 2010;4(1):115-131.
10. Wang K, Wei YM, Zhang X. Energy and emissions efficiency patterns of Chinese regions: a multi-directional efficiency analysis. *Appl Energy*. 2013;104:105–116.
11. Li Y, Sun L, Feng T, Zhu C. How to reduce energy intensity in China: a regional comparison perspective. *Energy Policy*. 2013;61:513-522.
12. Wang K, Yu S, Zhang W. China's regional energy and environmental efficiency: a DEA window analysis based dynamic evaluation. *Math Comput Modell*. 2013;58(6):1117-1127.
13. Bi GB, Song W, Zhou P, Liang L. Does environmental regulation affect energy efficiency in China's thermal power generation? Empirical evidence from a slacks-based DEA model. *Energy Policy*. 2014;66:537-546.
14. Wu J, Lin L, Sun J, Xiang J. A comprehensive analysis of China's regional energy saving and emission reduction efficiency: from production and treatment perspectives. *Energy Policy*. 2015;84:166-176.
15. Lin B, Du K. Energy and CO_2 emissions performance in China's regional economies: do market-oriented reforms matter?. *Energy Policy*. 2015;78:113-124.
16. Üstün AK. Evaluating environmental efficiency of Turkish cities by data envelopment analysis. *Global NEST J*. 2015;17(2):281-290.
17. Yao X, Zhou H, Zhang A, Li A. Regional energy efficiency, carbon emission performance and technology gaps in China: a meta-frontier non-radial directional distance function analysis. *Energy Policy*. 2015;84:142-154.
18. Choi J, Roberts DC. Impacts of air pollution on productivity growth in the air and truck transportation industries in the US: an application of the data envelopment analysis malmquist environmental productivity index. *Open J Soc Sci*. 2015;3:120-129.
19. Sueyoshi T, Yuan Y. China's regional sustainability and diversified resource allocation: DEA environmental assessment on economic development and air pollution. *Energy Econ*. 2015;49:239-256.
20. Mavi RK, Standing C. Evaluating eco-innovation of OECD countries with data envelopment analysis. Paper presented at: The International Conferences on Internet Technologies & Society (ITS), Education Technologies (ICEduTECH), and Sustainability, Technology and Education (STE), Melbourne, Australia, Dec 6–8, 2016. http://www.iadisportal.org
21. Liu X, Liu J. Measurement of low carbon economy efficiency with a three-stage data envelopment analysis: a comparison of the largest twenty CO_2 emitting countries. *Int J Environ Res Publ Health*. 2016;13(11):11-16.
22. Wen L, Zhang E. Allocation of CO_2 emissions with zero sum gains data envelopment analysis models. *Nat Environ Pollut Technol*. 2016;15(3):1065-1069.
23. Yao X, Guo C, Shao S, Jiang Z. Total-factor CO_2 emission performance of China's provincial industrial sector: a meta-frontier non-radial Malmquist index approach. *Appl Energy*. 2016;184:1142-1153.
24. Ma YR, Ji Q, Fan Y. Spatial linkage analysis of the impact of regional economic activities on PM2.5 pollution in China. *J Cleaner Prod*. 2016;139:1157-1167.
25. Li J, Gong L, Chen Z, Zeng L, Yang G, Zhang J. The hierarchy and transition of China's urban energy efficiency. *Energy Procedia*. 2016; 104: 110-117.
26. Wu X, Tan L, Guo J, Wang Y, Liu H, Zhu W. A study of allocative efficiency of PM2.5 emission rights based on a zero sum gains data envelopment model. *J Cleaner Prod*. 2016;113(1):1024-1031.
27. Halkos GE, Polemis ML. The good, the bad and the ugly? Balancing environmental and economic impacts towards efficiency. *MPRA*. 2016;2016:72-132.
28. Camioto FDC, Moralles H, Fernando M, Enzo B, Rebelatto DADN. Energy efficiency analysis of G7 and BRICS considering total-factor structure. *J Cleaner Prod*. 2016;122(20):67-77.
29. Yi J. Study on carbon emission efficiency of China's industrial industry and analysis of its influencing factors. *Low Carbon Econ*. 2017;8:20-30.
30. Feng Q, Qiu Q, Quan Y, Tang L. Sustainability efficiency of Chinese cities involving coal-fired power plants with data envelopment analysis. *Int J Sustainable Dev World Ecol*. 2017;24(5):395-400.

31. Qin Q, Li X, Li L, Zhen W, Wei YM. Air emissions perspective on energy efficiency: an empirical analysis of China's coastal areas. *Appl Energy*. 2017;185:604-614.
32. Du K, Xie C, Ouyang X. A comparison of carbon dioxide (CO2) emission trends among provinces in China. *Renew Sustainable Energy Rev*. 2017;73:19-25.
33. Feng C, Zhang H, Huang JB. The approach to realizing the potential of emissions reduction in China: an implication from data envelopment analysis. *Renew Sustainable Energy Rev*. 2017;71:859-872.
34. Hu JL, Chang MC, Tsay HW. The congestion total-factor energy efficiency of regions in Taiwan. *Energy Policy*. 2017;110:710-718.
35. Zhang S, Li D, Li S, Jiang H, Shen Y. Analysis of regional total factor energy efficiency in China under environmental constraints: based on undesirable-minds and DEA window model. *IOP Conf Ser Earth Environ Sci*. 2017;69:01204.
36. Guo J, Zhu D, Wu X, Yan Y. Study on environment performance evaluation and regional differences of strictly-environmental-monitored fare cities in China. *Sustainability*. 2017;9(12):2094.
37. Ren F, Tian Z, Shen Y, Chiu YH, Lin TY. Energy, CO_2 and AQI efficiency and improvement of the Yangtze river economic belt. *Energies*. 2019;12(4):647.
38. Zhou Y, Liu W, Lv X, Chen X, Shen M. Investigating interior driving factors and cross-industrial linkages of carbon emission efficiency in China's construction industry: based on Super-SBM DEA and GVAR model. *J Cleaner Prod*. 2019;241(20):118322.
39. Li J, Cheng Z. Study on total-factor carbon emission efficiency of China's manufacturing industry when considering technology heterogeneity. *J Cleaner Prod*. 2020;260:121021.
40. Malinauskaite J, Jouhara H, Egilegor B, Al-Mansour F, Ahmad L, Pusnik M. Energy efficiency in the industrial sector in the EU, Slovenia, and Spain. *Energy*, 2020;208:118398.
41. Wang Z, Xu X, Zhu Y, Gan T. Evaluation of carbon emission efficiency in China's airlines. *J Cleaner Prod*. 2020;243:118500.
42. Zhang W, Li J, Li G, Guo S. Emission reduction effect and carbon market efficiency of carbon emissions trading policy in China. *Energy*. 2020;196:117117.
43. Loomis D, Huang W, Chen G. The International Agency for Research on Cancer (IARC) evaluation of the carcinogenicity of outdoor air pollution: focus on China. *Chin J Cancer*. 2014;33(4):189.
44. Oakes M, Baxter L, Long TC. Evaluating the application of multipollutant exposure metrics in air pollution health studies. *Environ Int*. 2014;69:90-99.
45. Pope III CA, Cropper M, Coggins J, Cohen A. Health benefits of air pollution abatement policy: role of the shape of the concentration–response function. *J Air Waste Manage Assoc*. 2015;65(5):516-522.
46. Chen C, Li C, Li Y, Liua J, Meng C, Han J, Zhang Y, Xua D. Short-term effects of ambient air pollution exposure on lung function: a longitudinal study among healthy primary school children in China. *Sci Total Environ*. 2018;645:1014-1020.
47. Dauchet L, Hulo S, Cherot-Kornobis N, Matran R, Amouyel P, Edmé JL, Giovannelli J. Short-term exposure to air pollution: associations with lung function and inflammatory markers in non-smoking, healthy adults. *Environ Int*. 2018;121:610-619.
48. Fioravanti S, Cesaroni G, Badaloni C, Michelozzi P, Forastiere F, Porta D. Traffic-related air pollution and childhood obesity in an Italian birth cohort. *Environ Res*. 2018;160:479-486.
49. Kasdagli MI, Katsouyanni K, Dimakopoulou K, Samoli E. Air pollution and Parkinson's disease: a systematic review and meta-analysis up to 2018. *Int J Hyg Environ Health*. 2019;222(3):402-409.
50. Knibbs LD, Cortés de Waterman AM, Toelle BG, et al. The Australian Child Health and Air Pollution Study (ACHAPS): a national population-based cross-sectional study of long-term exposure to outdoor air pollution, asthma, and lung function. *Environ Int*. 2018;120:394-403.
51. Zhao PL, Shengxiao L, Peilin LJ, Long K. How does air pollution influence cycling behavior? Evidence from Beijing. *Transp Res Part D Transp Environ*. 2018;63:826-838.
52. Chen Z, Cui L, Cui X, et al. The association between high ambient air pollution exposure and respiratory health of young children: a cross sectional study in Jinan, China. *Sci Total Environ*. 2019;656:740-749.
53. Bayat R, Ashrafi K, Motlagh MS, et al. Health impact and related cost of ambient air pollution in Tehran. *Environ Res*. 2019;176:108547.
54. Lua X, Lin C, Li W, et al. Analysis of the adverse health effects of PM2.5 from 2001 to 2017 in China and the role of urbanization in aggravating the health burden. *Sci Total Environ*. 2019;652(20):683-695.
55. Luo H, Guan Q, Lin J, et al. Air pollution characteristics and human health risks in key cities of northwest China. *J Environ Manage*. 2020;269:110791.
56. Pierangeli I, Nieuwenhuijsen MJ, Cirach M, Rojas-Rueda D. Health equity and burden of childhood asthma-related to air pollution in Barcelona. *Environ Res*. 2020;186:109067.
57. Tone K, Tsutsui M. Dynamic DEA with network structure: a slacks-based measure approach. *Omega*. 2014;42(1):124-131.
58. Färe R, Grosskopf S. Directional distance functions and slacks-based measures of efficiency. *Eur J Oper Res*. 2010;200(1):320-322.
59. Charnes AC, Cooper WW, Rhodes EL. Measuring the efficiency of decision making units. *Eur J Oper Res*. 1978;2:429-444.
60. Tone K. A slacks-based measure of efficiency in data envelopment analysis. *Eur J Oper Res*. 2001;130(3):498-509.
61. Chung YH, Fare R, Grosskopf S. Productivity and undesirable outputs: a directional distance function approach. *J Environ Manage*. 1997;51:229–240.
62. Chen PC, Yu MM, Chang CC, Hsu SH, Managi S. The enhanced Russell-based directional distance measure with undesirable outputs: numerical example considering CO_2 emissions. *Omega*. 2015;53:30-40.
63. Färe R, Grosskopf S, Whittaker G. Network DEA. *Model Data Irregularities Struct Complexities Data Envelop Anal*. 2007:209-240.
64. Zhu J. Efficiency evaluation with strong ordinal input and output measures. *Eur J Oper Res*. 2003;146:477-485.
65. Chen Y, Zhu J. Measuring information technology's indirect impact on firm performance. *Inf Technol Manage*. 2004;5(1):9-22.
66. Kao C, Hwang S. Efficiency decomposition in two-stage data envelopment analysis: an application to non-life insurance companies in Taiwan. *Eur J Oper Res*. 2008;185(1):418-429.

67. Kao C. Efficiency decomposition in network data envelopment analysis: a relational model. *Eur J Oper Res*. 2009;192(3):949-962.
68. Tone K, Tsutsui M. Network DEA: a slacks based measurement approach. *Eur J Oper Res*. 2009;197:243-252.
69. Tone K, Tsutsui M. Dynamic DEA: a slacks-based measure approach. *Omega*. 2010;38:145-156.
70. Klopp GA. *The Analysis of the Efficiency of Production System with Multiple Inputs and Outputs*. PhD dissertation. University of Illinois, Industrial and System Engineering College, Chicago; 1985.
71. Malmquist S. Index numbers and indifference surfaces. *Trabajos Estadística*. 1953;4(2):209-242.
72. Färe R, Grosskopf S, Norris M, Zhang Z. Productivity growth, technical progress, and efficiency change in industrialized countries. *Am Econ Rev*. 1994;84(1):66-83.
73. Färe R, Grosskopf S. Productivity and intermediate products: a frontier approach. *Econ Lett*. 1996;50(1):65-70.
74. Nemoto J, Goto M. Dynamic data envelopment analysis: modeling intertemporal behavior of a firm in the presence of productive inefficiencies. *Econ Lett*. 1999;64(1):51-56.
75. Nemoto J, Goto M. Measurement of dynamic efficiency in production: an application of data envelopment analysis. *J Prod Anal*. 2003;19(2-3):191-210.
76. Sueyoshi T, Sekitani K. Returns to scale in dynamic DEA. *Eur J Oper Res*. 2005;161(2):536-544.
77. Amirteimoori A. Data envelopment analysis in dynamic framework. *Appl Math Comput*. 2006;181(1):21-28.
78. Färe R, Grosskopf S. A comment on dynamic DEA. *Appl Math Comput*. 2009;213(1):275-276.
79. O'Donnell CJ, Prasada Rao DS, Battese GE. Metafrontier frameworks for the study of firm-level efficiencies and technology ratios. *Empirical Econ*. 2008;34(2):231-255.
80. Hu JL, Wang SC. Total-factor energy efficiency of regions in China. *Energy Policy*. 2006;34:3206-3217.