Global Energy Consumption Analysis Based on the Three-Dimensional Network Model

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ABSTRACT To comprehensively assess global sustainable energy consumption from the perspectives of economic development and environmental conservation, we propose a multidimensional structure that includes two-dimensional and three-dimensional networks. Based on the proposed methods, we empirically investigate 35 countries of the International Energy Agency. It is found that: 1) Regarding economic income, Asia ranks first, followed by America, Oceania, Europe and Africa. 2) As for sustainable development, the best-performing region is Asia, followed by Africa and Europe, Oceania and America. 3) The regions with greater development potential in energy consumption are America, Oceania, Africa and Europe, while Asia is less efficient. In consideration of the above findings, we give some recommendations for different regions to improve their energy consumption efficiency, such as countries in Asia can focus on innovative high-tech industries while countries in Europe can enhance economic vitality with market integration.

INDEX TERMS Multidimensional structure, global energy consumption, economic income, sustainable development, efficiency.

I. INTRODUCTION

A rise in concern levels about pollutions can be seen with the development of the global economy. In recent years, environmental issues such as climate change and global warming have alarmed the world to take environment conservation into account lest the situation become worse due to unreasonable energy consumption. With the convening of the United Nations conference on sustainable development in Rio de Janeiro in 2012 and the Paris agreement adopted at the Paris climate change conference in 2015, sustainable development has aroused extensive attention and gradually become one of the vital strategies guiding global development efforts. Therefore, many countries strive to effectively reduce CO2 emissions by declining coal use and increasing the use of renewable energy. As reported by the International Energy Agency,1 global energy-related to CO2 emissions flatted in 2019. However, this organization also claims that it is significant for Africa to deal with the energy needs of a rapid-growing and increasing urban population.

Improving energy consumption efficiency is the key for Africa’s economy, as well as for other continents. As a result, this paper proposes a multidimensional structure that includes the two-dimensional and three-dimensional networks, where the two-dimensional network is primarily used to analyze the performance in terms of economic income, while the three-dimensional network plays a major role in evaluating the efficiency of sustainable development. With the aims of comprehensively evaluating the world energy consumption and providing practical suggestions for the countries being evaluated which improves their efficiency of energy consumption, we conduct an empirical investigation for 35 countries in the International Energy Agency.

In many countries such as France, the United States and Turkey, the remarkable investigations on energy consumption are mainly related to economic growth and environmental issues [1]–[3]. Therefore, improving energy consumption efficiency is of great significance for environment protection and economic development. Before improving energy consumption, energy efficiency has been assessed based on diverse approaches including data envelopment analysis (DEA), benchmarking comparison and stochastic frontier analysis [4]. Specifically, Wu et al. [5] and Liu and Wang [6]
respectively utilized a two-stage data envelopment analysis model with shared inputs and adjusted network data envelopment analysis model to evaluate the energy efficiency of the Chinese industry. Cai et al. [7] pointed out that energy benchmarks should be established. This process inevitably required a reasonable indicator system, including negative indicators. Yang et al. [8] considered the undesirable output factors when measuring the regional energy efficiency in China using the super efficiency slack-based model. It can be seen that DEA has broadly utilized to analyze energy efficiency, which evaluates the corresponding efficiencies of each decision unit on the basis of multiple inputs and outputs. Traditional DEA only focuses on the initial inputs and the final outputs, rather than considering the internal activities [9], [10]. As a result, internal processes are usually overlooked. To address this issue, the above mentioned two-stage DEA has been applied to make undesirable intermediate measures of coal consumption [11] explore the impacts of energy consumption on the environment [12] and investigate the efficiency of greenhouse production [13]. Furthermore, taking air pollution as an example, it is admitted that there some undesirable intermediate outputs in energy consumption. Being different from the above investigations, we take both desirable and undesirable intermediate outputs during the process.

As aforementioned, the analyses of energy consumption often relate to economic growth and environmental issues. In industrial sectors, particularly small and medium-sized enterprises, have adopted energy efficiency as a major element of enhancing competitiveness [14]. For example, machine tools [15] and flexible job-shop scheduling [16] were treated as vital factors to improve the energy efficiency of the manufacturing industry and industrial plants, respectively. Moreover, the economic and policy variables [17] and country context [18] were also investigated. It is obvious that energy efficiency has been extensively studied. Some of the proposed methodologies can also be used for the environmental efficiency evaluation such as super-efficiency data envelopment analysis model [19], two-stage network data envelopment analysis approach [20], and new meta-frontier non-radial angle efficiency evaluation model [21]. Obviously, the above research mainly focuses on efficiency evaluation in energy or environment.

On the other hand, the efficiency evaluation of individual research object is also difficult to meet the complexity requirements of practical problems, thus the efficiency evaluation of multiple research objects is required, which mainly focuses on the researches of energy-environment, energy-economy, economy-environment and energy-environment-economy. For instance, diversified methods were adopted to the energy-environment efficiency evaluation in China [18], [22]–[24] [25]. Similarly, many approaches are also applied to investigate the performance of energy-saving technologies and emission reduction such as the modified slacks-based measure model [26] and a comprehensive model combining game theory [27]. There are also some investigations analyze energy-economic [28] and economy-environmental [29]–[35] efficiency assessments across industries. Further, in terms of energy-environment-economy, Wang and Feng [36] utilized a global data envelopment analysis method to assess the efficiency performance of energy, environment, economy (E3) and productivity in China and then explored the key factors responsible for the change in E3 productivity. As a result, it can be found that research on energy consumption mainly focuses on efficiency assessment of single or combined factors about energy, environment and economy. It focuses on taking the final output value as one of the measurement criteria.

However, considering the environmental impact of energy consumption while calculating economic benefits is also worthy of attention. In order to simultaneously evaluate economic benefits and the environmental impact of energy consumption in the world, we first propose a two-dimensional network model to evaluate economic-oriented energy consumption, a three-dimensional network model is further constructed to make the assessment of sustainable development-oriented energy consumption. Therefore, the theoretical contribution made by this paper is to develop the multidimensional model to comprehensively analyze a country’s economic benefits and environmental impact brought by energy consumption. We also make the practical contribution of conducting empirical research to investigate the performance of energy consumption in 35 major countries from the International Energy Agency based on the new multidimensional structure model. Based on the results, some suggestions are put forward for the countries being evaluated.

The remainder of this paper is composed as follows: Section 2 demonstrates the construction of a multidimensional structure and introduces the calculation of efficiency value. In section 3, we conduct an empirical investigation of global energy consumption based on the proposed multidimensional structure model. Then, Section 4 presents a comparative analysis of global energy consumption. Moreover, some suggestions based on our findings are also provided.

II. MULTIDIMENSIONAL STRUCTURE CONSTRUCTION OF ENERGY CONSUMPTION

Traditional approaches that evaluate energy consumption mainly focuses on benefits. However, with more attention paid not merely to economic income, but to sustainable development, it is reasonable to consider the pollution emissions caused by energy consumption. Based on this, we construct a multidimensional structure model that includes a two-dimensional and a three-dimensional network, and they focus on economic income and sustainable development, respectively. Further, in this section, we derive their efficiency calculation expression and present a specific description.

A. TWO-DIMENSIONAL NETWORK AND ECONOMIC INCOME

As aforementioned, DEA, which was propose by Charnes et al. [37] has been broadly used to evaluate energy
Assume that the countries being evaluated have a consumption efficiency analysis method that involves only economic income-oriented energy consumption as an energy growth process. Therefore, it contains both industrial added value and the final desired product elements of the economic product generated by energy conversion process in the second dimension. In terms of the second dimension, energy consumption in the first dimension, energy production and net energy imports, are considered as industrial production which also determines the outcome of GDP national reserve. The two yellow ellipses represent the processes of energy conversion and economic growth, which are connected from the process of energy production and energy imports to the outcome of GDP national reserve.

Then, we further define the meaning of energy resources, industrial production and economic income in the two-dimensional network. In the first dimension, energy is produced or imported to become the industrial added value through energy conversion. The term industrial added value is considered as industrial production which also determines the energy growth in the second dimension. In terms of the second dimension, namely economic income, it denotes the total desired product elements, including the intermediate desired product elements generated by the energy conversion process and the final desired product elements of the economic growth process. Therefore, it contains both industrial added value, GDP and national reserve. Further, we can define the economic income-oriented energy consumption as an energy consumption efficiency analysis method that involves only the energy resources and economic income (two dimensions) in the process of converting energy resources into industrial production and promoting economic growth.

To clearly describe the performance of the economic income-oriented energy consumption through mathematical models, we define the relevant parameters as follows. Assume that the countries being evaluated have \( m \) initial cost elements \( x \); \( s \) intermediate product elements \( z \), where the intermediate desired product elements \( z_1 \) have \( s_1 \), the intermediate undesired product elements \( z_2 \) have \( s_2 \), and they satisfy the equation \( s = s_1 + s_2 \); \( n \) final desired product elements \( y \). When the number of research objects is \( n \), we can get the following matrix expression for any one of the research objects \( i \) (1 \( \leq i \leq k \)):

\[
X = (x_1, x_2, \ldots, x_t)^T, \quad Z_1 = (z_{1,1}, z_{1,2}, \ldots, z_{1,k})^T, \quad Z_2 = (z_{2,1}, z_{2,2}, \ldots, z_{2,k})^T, \quad Y = (y_1, y_2, \ldots, y_k)^T,
\]

where

\[
x_i = (x_{i1}, x_{i2}, \ldots, x_{im}), \quad z_{1,i} = (z_{1,i1}, z_{1,i2}, \ldots, z_{1,i{s_1}}), \quad z_{2,i} = (z_{2,i1}, z_{2,i2}, \ldots, z_{2,i{s_2}}), \quad y_i = (y_{i1}, y_{i2}, \ldots, y_{in})
\]

When multidimensional structure only includes the elements of energy resources and economic income, the efficiency calculation expression of the economic income-oriented energy consumption can be obtained as follows:

\[
\max \theta_{1,i} = \max \frac{B_{1,i}z_{1,i} - A_{i}X}{A_{i}X} \times \frac{C_{i}y_{i}}{B_{1,i}z_{1,i}},
\]

subject to

\[
\begin{align*}
B_{1,i}z_{1,i} - A_{i}X &\leq 0, \\
C_{i}y_{i} - B_{1,i}z_{1,i} &\leq 0, \\
A_{i} &= (a_{i1}, a_{i2}, \ldots, a_{im})^T, \\
B_{1,i} &= (b_{i1}, b_{i2}, \ldots, b_{i{k{s_1}}})^T, \\
C_{i} &= (c_{i1}, c_{i2}, \ldots, c_{in})^T, \\
s_2 &= 0, a_{ij}, b_{ij}, c_{j} \geq 0, \\
1 \leq i \leq m, 1 \leq j \leq s_1, 1 \leq u \leq n.
\end{align*}
\]

To achieve the optimal solution of maximizing the efficiency of energy consumption, the function is set with the multiplication corresponding energy conversion process efficiency value and economic growth process efficiency value. In Equation (1): \( X, Z_1 \) and \( Y \) are matrices representations of the relevant known data for initial cost elements, intermediate desired product elements and final desired product elements of each country, respectively, and \( m, s_1 \) and \( n \) are the corresponding quantities of these parameters; \( A, B_1 \) and \( C \) are the weight coefficient vectors corresponding to \( X, Z_1 \) and \( Y \) when all countries obtain the optimal solution, which can reflect the relative importance of certain indicators.

Combining Figure 1 and Equation 1, the meaning of some parameters can be further obtained. \( x_1 \) and \( x_2 \) represent energy production and net energy imports, respectively, while \( z_1 \) implies industrial added value. Finally, GDP and national reserves are denoted by \( y_1 \) and \( y_2 \) respectively. These are also three parameters we are concerned with, among which \( \theta_{EEC} \) is the main observation value for assessing economic income-oriented energy consumption, while \( \theta_{ECC1} \) and \( \theta_{ECC2} \) are our references for analyzing such results. The efficiency value expression of beneficial energy consumption is \( \theta_{ECC} = \frac{X}{B_{1,i}z_{1,i}} \times \frac{C_{i}y_{i}}{B_{1,i}z_{1,i}} \). Then, under the premise that the economic income-oriented energy consumption obtains the optimal value, the efficiency value of the energy conversion process
and the economic growth process are: \( \theta_{\text{EC1}} = \frac{B_{1s1,\xi} + B_{2s2,\xi}}{A_{X1,\xi}} \) and \( \theta_{\text{EG1}} = \frac{C_{Y1,\xi}}{B_{1s1,\xi}} \), respectively.

**B. THREE-DIMENSIONAL NETWORK AND SUSTAINABLE DEVELOPMENT**

It should also be pointed out that the energy conversion process also produces pollution emissions. They can be considered as the intermediate undesired product elements in the efficiency evaluation of sustainable development-oriented energy consumption, and CO\(_2\) can be a typical example of the pollution emissions. Similarly, we can define the sustainable development-oriented energy consumption as an energy conversion efficiency analysis method that involves energy resources, pollution emission and economic benefits (three dimensions) in the process of energy conversion and economic growth. The corresponding three-dimensional network model is presented in Figure 2. Besides related pollution emission elements represented by the red rectangle, the other graphical description is similar to that in Figure 1. The practical significance of Figures 1 and 2 is that since a complete production activity always consumes energy, discharges pollution and promotes economy in practice, thus it is reasonable to integrate these elements to simulate this process and evaluate its efficiency.

Further, we use mathematical equations to make a clearer assessment of sustainable development-oriented energy consumption. The efficiency calculation expression based on the three-dimensional network can be derived as Eq. (2).

To achieve the optimal solution of maximize the efficiency of energy consumption considering CO\(_2\) emissions, the function is set with the multiplication corresponding energy conversion process efficiency value and economic growth process efficiency value. In Equation (2); in addition to the parameters already explained in Equation (1), the meaning of the remaining parameters is as follows: \( Z_2 \) is the vector of intermediate undesired product elements while \( B_2 \) and \( s_2 \) are the corresponding weight coefficient vectors and the quantity value.

\[
\max \theta_{2,\xi} = \frac{B_{1s1,\xi} + B_{2s2,\xi}}{A_{X1,\xi}} \times \frac{C_{Y1,\xi}}{B_{1s1,\xi}}
\]

\[
B_1X_1 + B_2X_2 - AX \leq 0
\]

\[
CY - B_1Z_1 \leq 0
\]

\[
A = (a_1, a_2, \ldots, a_i, \ldots, a_m),
\]

\[
B_1 = (b_{1,1}, b_{1,2}, \ldots, b_{1,i}, \ldots, b_{1,1}),
\]

\[
B_2 = (b_{2,1}, b_{2,2}, \ldots, b_{2,v}, \ldots, b_{1,1}),
\]

\[
C = (c_1, c_2, \ldots, c_u, \ldots, c_n),
\]

\[
a_1, b_{1,j}, b_{2,v}, c_u \leq 0,
\]

\[
l \leq 0i \leq 0m, l \leq 0j \leq 0s_1,
\]

\[
l \leq 0v \leq 0s_2, l \leq 0u \leq 0n.
\]

According to Figure 2 and Equation 2, \( Z_2 \) (\( Z_2 \) is only used in the sustainable development-oriented energy consumption analysis) indicates pollution emissions expressed by CO\(_2\),

Besides, \( \theta_{\text{SEC}} \), \( \theta_{\text{EC2}} \) and \( \theta_{\text{EG2}} \) are also the parameters that need to be focused on, which can analyze the performance and causes of sustainable energy consumption. The efficiency value of sustainable development-oriented energy consumption is \( \theta_{\text{SEC}} = \frac{B_{1s1,\xi} + B_{2s2,\xi}}{A_{X1,\xi}} \times \frac{C_{Y1,\xi}}{B_{1s1,\xi}} \). The efficiency value of the energy conversion process and the economic growth process are \( \theta_{\text{EC2}} = \frac{B_{1s1,\xi} + B_{2s2,\xi}}{A_{X1,\xi}} \) and \( \theta_{\text{EG2}} = \frac{C_{Y1,\xi}}{B_{1s1,\xi}} \) when a country’s sustainable development-oriented energy consumption performs best.

Besides, the description and assumption of the decision variables and parameters are listed in TABLE 9 which can be seen in the Appendix to make the proposed multidimensional networks clearer and more understandable.

**C. THE PROPERTIES ANALYSIS OF ULTIDIMENSIONAL NETWORKS**

Through the proposed multidimensional structure model and the derived expression of the efficiency value, some properties and corresponding proofs are demonstrated below:

**Property 1:** The efficiency values of economic income-oriented energy consumption and sustainable energy consumption can both be represented by the multiplication of corresponding energy conversion process efficiency value and economic growth process efficiency value, which is expressed as \( \theta_{\text{EEC}} = \theta_{\text{EC1}} \times \theta_{\text{EG1}}(\theta_{\text{SEC}} = \theta_{\text{EC2}} \times \theta_{\text{EG2}}). \)

**Proof:** The actual production activity process is often accompanied by an efficiency reduction. Based on the above equations, the efficiency values of the economic income-oriented energy consumption that involves the energy conversion process and the economic growth process are \( \theta_{\text{EEC}} = \frac{B_{1s1,\xi} + B_{2s2,\xi}}{A_{X1,\xi}} \times \frac{C_{Y1,\xi}}{B_{1s1,\xi}} \), \( \theta_{\text{EC1}} = \frac{B_{1s1,\xi} + B_{2s2,\xi}}{A_{X1,\xi}} \), and \( \theta_{\text{EG1}} = \frac{C_{Y1,\xi}}{B_{1s1,\xi}} \), respectively. Similarly, for sustainable development-oriented energy consumption, the efficiency values are \( \theta_{\text{SEC}} = \frac{B_{1s1,\xi} + B_{2s2,\xi}}{A_{X1,\xi}} \times \frac{C_{Y1,\xi}}{B_{1s1,\xi}} \), \( \theta_{\text{EG2}} = \frac{C_{Y1,\xi}}{B_{1s1,\xi}} \), and \( \theta_{\text{EC2}} = \frac{B_{1s1,\xi} + B_{2s2,\xi}}{A_{X1,\xi}} \) respectively. It is obvious that \( \theta_{\text{EEC}} = \theta_{\text{EC1}} \times \theta_{\text{EG1}}(\theta_{\text{SEC}} = \theta_{\text{EC2}} \times \theta_{\text{EG2}}) \) is established. Therefore, this property is proven.

This property indicates that both economic income-oriented energy consumption and sustainable development-oriented energy consumption are affected by the process of energy conversion and economic growth. It reflects the characteristics of multi-layer efficiency decline in actual production activities and also shows that the performance of these two sub-processes can be used to explain the results of energy consumption efficiency assessment from another perspective. This phenomenon can be reflected in the empirical analysis.

**Property 2:** The efficiency values of the economic income-oriented energy consumption and the sustainable development-oriented energy consumption are both less than or equal to 1, and the efficiency values of the corresponding energy conversion process and economic growth process
TABLE 1. The indicator description of energy consumption.

| Stage         | Classification             | Indicator           | Unit               | Data Sources       |
|---------------|----------------------------|---------------------|--------------------|--------------------|
| I             | Energy resources           | Energy production   | Mtoe               | International Energy Agency |
| I             | Energy resources           | Net energy imports  | Mtoe               | International Energy Agency |
| I, II         | Desired industrial production | Industrial added value | Dollar            | World Bank          |
| I, II         | Undesired industrial production | CO₂                | Mt of CO₂          | International Energy Agency |
| II            | Economic benefits          | GDP                 | Dollar             | World Bank          |
| II            | Economic benefits          | National reserve    | Dollar             | World Bank          |

(Note: Million tons of oil equivalents.)

share some similarities, which can be indicated by $\theta_{\text{BEC}} \leq 1(\theta_{\text{SEC}} \leq 1), \theta_{\text{EC1}} \leq 1(\theta_{\text{EC2}} \leq 1), \theta_{\text{EG1}} \leq 1(\theta_{\text{EG2}} \leq 1)$.

**Proof:** According to the input-oriented multidimensional structure, we can draw that $B_{1,\xi}Z_1 - A_{\xi}X \leq 0$, $C_{\xi}Y_{\xi} - B_{1,\xi}Z_1 \leq 0; B_{1,\xi}Z_1 + B_{2,\xi}Z_2 = A_{\xi}X \leq 0$, $C_{\xi}Y_{\xi} - B_{1,\xi}Z_1 \leq 0$ always exist, thus $B_{1,\xi}Z_1 \leq 1$, $C_{\xi}Y_{\xi} \leq 1; B_{1,\xi}Z_1 + B_{2,\xi}Z_2 \leq 1, C_{\xi}Y_{\xi} \leq 1$ are obviously established. There are also expressions for a specific research subject $\xi$, which leads to the fact that $\theta_{\text{EC1}} \leq 1(\theta_{\text{EC2}} \leq 1), \theta_{\text{EG1}} \leq 1(\theta_{\text{EG2}} \leq 1).$ In addition, $\theta_{\text{SEC}} = \theta_{\text{EC1}} \times \theta_{\text{EG1}}(\theta_{\text{SEC}} = \theta_{\text{EC2}} \times \theta_{\text{EG2}})$ is derived from Property 1, thus we can conclude that $\theta_{\text{SEC}} \leq 1(\theta_{\text{SEC}} \leq 1).$ The proof is completed.

This property demonstrates that both the economic income-oriented energy consumption and sustainable development-oriented energy consumption are accord with the principle of energy conservation. Besides, it shows the phenomenon that resource losses exist both in the energy conversion process and the economic growth process in actual production activities, which is also reflected in the following empirical results.

**Property 3:** The efficiency values of the energy conversion process and the economic growth process are both greater than or equal to the corresponding beneficial energy consumption efficiency value and sustainable energy consumption efficiency value, which can be represented by $\theta_{\text{BEC}}(\theta_{\text{EC2}} \geq \theta_{\text{SEC}})$, $\theta_{\text{EGI}} \geq \theta_{\text{BEC}}(\theta_{\text{EG2}} \geq \theta_{\text{SEC}})$.

**Proof:** According to Properties 1 and 2, we can gain that $\theta_{\text{BEC}} = \theta_{\text{EC1}} \times \theta_{\text{EG1}}(\theta_{\text{SEC}} = \theta_{\text{EC2}} \times \theta_{\text{EG2}}), \theta_{\text{EC1}} \leq 1(\theta_{\text{EC2}} \leq 1)$ and $\theta_{\text{EG1}} \leq 1(\theta_{\text{EG2}} \leq 1)$, which result in the establishment of $\theta_{\text{BEC}} \geq \theta_{\text{BEC}}(\theta_{\text{EC2}} \geq \theta_{\text{SEC}})$ and $\theta_{\text{EG1}} \geq \theta_{\text{BEC}}(\theta_{\text{EG2}} \geq \theta_{\text{SEC}}).$ Thus, we complete the proof.

This property integrates the phenomena exhibited by properties 1 and 2, and further demonstrates the incomplete conversion of resources in the efficiency assessment of both the economic income-oriented energy consumption and the sustainable development-oriented energy consumption, which provides a reference for preventing resource waste by reducing intermediate links in actual production activities.

Based on these properties, it can be found that when $\theta_{\text{BEC}} = 1$ or $\theta_{\text{SEC}} = 1$, the economic income-oriented energy consumption or the sustainable development-oriented energy consumption of the country being evaluated is efficient, otherwise there is potential space for improvement. The corresponding processes of energy conversion and economic growth can be elaborated similarly.

### III. EMPIRICAL STUDY OF GLOBAL ENERGY CONSUMPTION

In order to measure global energy consumption performance and further provide suggestions for specific countries or regions to improve their energy consumption performance, the multidimensional structure model is employed to evaluate the energy consumption efficiency of the member countries of the International Energy Agency in terms of economic income and sustainable development. The research background, the data and indicator selection and analysis of the empirical results are presented below.

### A. BACKGROUND AND DATA

To improve the global energy supply, demand structure and the regulations for relevant energy policies, the International Energy Agency was established by the Organization for Economic Co-operation and Development in November 1974. It is an intergovernmental energy agency in the world. Since its establishment, the International Energy Agency has expanded its membership for several times. Until now, it has 30 member countries and 8 association countries, covering approximately 75% of the total global energy consumption. Therefore, researching on the energy consumption performance of the major countries of the International Energy Agency can provide a general understanding of the current status of energy utilization in the world. Among them, Canada, South Korea and New Zealand are excluded due to the lack of partial data. Then, we obtain the data of 35 major countries between 2012 and 2016 from the International Energy Agency and the World Bank.

With respect to the data availability, three categories of representative indicators, namely energy resources, industrial production and economic benefits, are selected and their descriptive statistics are summarized in Table 1. The indicators in this study are on the basis of some existing investigations and practical situations. For the economic income-oriented energy consumption, energy production and net energy imports are used to measure the total amount
of energy owned by a country. Obviously, many industries, especially heavy industries have a large demand for energy and the desired industrial production greatly affects on promoting the national economy, thus we choose the industrial added value to connect the energy conversion process and economic growth process. Moreover, GDP and national reserves are selected to reflect a country's economic development level. Relevant studies also utilize GDP as the economic output in the evaluation of energy consumption efficiency [10], [38]. In terms of sustainable development-oriented energy consumption, the environmental impacts associated with the energy conversion process need to be further considered. Also, prior investigations in this field proved a unidirectional Granger causality from energy consumption to carbon emissions or use CO₂ emissions as the environment pollution effects brought by energy consumption [12], [39]. Therefore, we use CO₂ emissions to represent the pollution emissions as the undesired industrial production when evaluating the efficiency of a country's sustainable development-oriented energy consumption. Finally, it should be noted that we have normalized the data to be dimensionless in the calculation process.

### B. RESULT ANALYSIS FROM THE PERSPECTIVE OF ECONOMIC INCOME

Based on the two-dimensional network model, the efficiency values of the economic income-oriented energy consumption are calculated using the software Matlab (R2016b) which are shown in Table 2. Obviously, the economic income-oriented energy consumption efficiency values of Singapore are all above 0.9049 in the 5 years and remain at 1 between 2012 and 2015. However, other countries have

#### TABLE 2. Economic income-oriented energy consumption efficiency values.

| Country           | 2012     | 2013     | 2014     | 2015     | 2016     | Mean   | Rank (M) |
|-------------------|----------|----------|----------|----------|----------|--------|----------|
| Singapore         | 1.0000   | 1.0000   | 1.0000   | 1.0000   | 0.9049   | 0.9810 | 1        |
| Switzerland       | 0.2193   | 0.2381   | 0.2814   | 0.3381   | 0.3391   | 0.2832 | 2        |
| Japan             | 0.1978   | 0.2314   | 0.3014   | 0.3362   | 0.2995   | 0.2733 | 3        |
| Luxembourg        | 0.0814   | 0.1295   | 0.2787   | 0.3138   | 0.4635   | 0.2534 | 4        |
| China             | 0.2133   | 0.2115   | 0.2472   | 0.2498   | 0.2237   | 0.2291 | 5        |
| Brazil            | 0.1118   | 0.1121   | 0.1511   | 0.1602   | 0.1527   | 0.1376 | 6        |
| United States     | 0.0569   | 0.0650   | 0.1344   | 0.1811   | 0.2238   | 0.1322 | 7        |
| Australia         | 0.0400   | 0.0583   | 0.1184   | 0.1626   | 0.2109   | 0.1180 | 8        |
| Germany           | 0.0604   | 0.0680   | 0.1209   | 0.1443   | 0.1483   | 0.1084 | 9        |
| United Kingdom    | 0.0402   | 0.0568   | 0.1139   | 0.1619   | 0.1497   | 0.1045 | 10       |
| France            | 0.0525   | 0.0582   | 0.1034   | 0.1230   | 0.1260   | 0.0926 | 11       |
| Italy             | 0.0546   | 0.0616   | 0.1047   | 0.1162   | 0.1136   | 0.0901 | 12       |
| Indonesia         | 0.0759   | 0.0743   | 0.0926   | 0.0948   | 0.1089   | 0.0893 | 13       |
| Mexico            | 0.0623   | 0.0705   | 0.1023   | 0.1092   | 0.0951   | 0.0879 | 14       |
| India             | 0.0474   | 0.0491   | 0.0674   | 0.0851   | 0.0826   | 0.0663 | 15       |
| Thailand          | 0.0596   | 0.0584   | 0.0633   | 0.0713   | 0.0626   | 0.0630 | 16       |
| Turkey            | 0.0390   | 0.0519   | 0.0708   | 0.0737   | 0.0648   | 0.0600 | 17       |
| Morocco           | 0.0370   | 0.0423   | 0.0584   | 0.0745   | 0.0790   | 0.0582 | 18       |
| Norway            | 0.0434   | 0.0431   | 0.0660   | 0.0615   | 0.0589   | 0.0546 | 19       |
| Poland            | 0.0400   | 0.0443   | 0.0548   | 0.0599   | 0.0572   | 0.0512 | 20       |
| Spain             | 0.0189   | 0.0281   | 0.0575   | 0.0704   | 0.0737   | 0.0497 | 21       |
| Denmark           | 0.0399   | 0.0439   | 0.0500   | 0.0487   | 0.0411   | 0.0447 | 22       |
| Ireland           | 0.0168   | 0.0179   | 0.0450   | 0.0822   | 0.0603   | 0.0444 | 23       |
| Sweden            | 0.0225   | 0.0334   | 0.0475   | 0.0525   | 0.0484   | 0.0409 | 24       |
| The Netherlands   | 0.0225   | 0.0265   | 0.0450   | 0.0509   | 0.0512   | 0.0392 | 25       |
| Portugal          | 0.0214   | 0.0182   | 0.0292   | 0.0426   | 0.0451   | 0.0313 | 26       |
| Czech Republic    | 0.0187   | 0.0257   | 0.0309   | 0.0384   | 0.0387   | 0.0305 | 27       |
| Belgium           | 0.0128   | 0.0159   | 0.0288   | 0.0430   | 0.0343   | 0.0270 | 28       |
| South Africa      | 0.0205   | 0.0216   | 0.0279   | 0.0313   | 0.0276   | 0.0258 | 29       |
| Austria           | 0.0123   | 0.0149   | 0.0278   | 0.0336   | 0.0365   | 0.0250 | 30       |
| Hungary           | 0.0187   | 0.0216   | 0.0241   | 0.0240   | 0.0191   | 0.0215 | 31       |
| Greece            | 0.0039   | 0.0060   | 0.0135   | 0.0189   | 0.0266   | 0.0138 | 32       |
| Finland           | 0.0053   | 0.0078   | 0.0145   | 0.0167   | 0.0168   | 0.0122 | 33       |
| Slovak Republic   | 0.0019   | 0.0028   | 0.0064   | 0.0092   | 0.0108   | 0.0062 | 34       |
| Estonia           | 0.0000   | 0.0000   | 0.0000   | 0.0001   | 0.0001   | 0.0000 | 35       |
TABLE 3. Energy conversion process efficiency values.

| Country        | 2012  | 2013  | 2014  | 2015  | 2016  | Mean | Rank (M) |
|----------------|-------|-------|-------|-------|-------|------|----------|
| Australia      | 1.0000| 1.0000| 1.0000| 1.0000| 1.0000| 1.0000| 1        |
| Japan          | 1.0000| 1.0000| 1.0000| 1.0000| 1.0000| 1.0000| 1        |
| Singapore      | 1.0000| 1.0000| 1.0000| 1.0000| 1.0000| 1.0000| 1        |
| United States  | 0.9988| 0.9529| 0.9686| 0.9886| 0.9500| 0.9655| 4        |
| China          | 0.9676| 0.9742| 0.9352| 0.8393| 0.9170| 0.8149| 7        |
| Germany        | 0.8362| 0.7563| 0.6388| 0.6793| 0.6066| 0.5864| 8        |
| Indonesia      | 1.0000| 0.6507| 0.6792| 0.5573| 0.5981| 0.5270| 9        |
| United Kingdom | 0.5332| 0.4102| 0.4789| 1.0000| 0.3408| 0.3227| 10       |
| Ireland        | 0.4803| 0.5828| 0.5904| 0.5197| 0.4619| 0.5177| 11       |
| Mexico         | 0.5664| 0.5745| 0.5644| 0.4921| 0.3912| 0.5044| 12       |
| France         | 0.4770| 0.5588| 0.5482| 0.4958| 0.4421| 0.5007| 13       |
| Brazil         | 0.6169| 0.5963| 0.5427| 0.3977| 0.3498| 0.3961| 14       |
| Norway         | 0.5678| 0.4709| 0.4238| 0.2861| 0.2318| 0.3287| 15       |
| Spain          | 0.3463| 0.4043| 0.4019| 0.3699| 0.3247| 0.3287| 16       |
| Turkey         | 0.2834| 0.3724| 0.3672| 0.3361| 0.2899| 0.3277| 17       |
| Switzerland    | 0.2754| 0.3234| 0.3349| 0.3408| 0.3391| 0.3227| 18       |
| India          | 0.3218| 0.3218| 0.3127| 0.3288| 0.3125| 0.3195| 19       |
| Luxembourg     | 0.0814| 0.1295| 0.2787| 0.3138| 0.4635| 0.2534| 20       |
| The Netherlands| 0.2331| 0.2636| 0.2484| 0.2171| 0.1923| 0.2309| 21       |
| Poland         | 0.2050| 0.2338| 0.2420| 0.2302| 0.1915| 0.2205| 22       |
| Sweden         | 0.1970| 0.2298| 0.2235| 0.1917| 0.1684| 0.2021| 23       |
| Thailand       | 0.1878| 0.2166| 0.1998| 0.2055| 0.1797| 0.1979| 24       |
| Morocco        | 0.1726| 0.1942| 0.2031| 0.2035| 0.2110| 0.1969| 25       |
| Austria        | 0.1603| 0.1934| 0.2000| 0.1889| 0.1795| 0.1844| 26       |
| Belgium        | 0.1382| 0.1637| 0.1691| 0.1954| 0.1393| 0.1611| 27       |
| South Africa   | 0.1536| 0.1467| 0.1307| 0.1226| 0.0998| 0.1307| 28       |
| Portugal       | 0.1267| 0.1253| 0.1211| 0.1451| 0.1303| 0.1297| 29       |
| Denmark        | 0.1069| 0.1246| 0.1276| 0.1101| 0.0991| 0.1137| 30       |
| Czech Republic | 0.1030| 0.1159| 0.1195| 0.1103| 0.0987| 0.1095| 31       |
| Finland        | 0.0888| 0.1059| 0.1064| 0.0945| 0.0829| 0.0957| 32       |
| Slovak Republic| 0.0653| 0.0705| 0.0757| 0.0789| 0.0817| 0.0744| 33       |
| Greece         | 0.0498| 0.0637| 0.0621| 0.0621| 0.0758| 0.0627| 34       |
| Hungary        | 0.0445| 0.0537| 0.0579| 0.0607| 0.0573| 0.0548| 35       |
| Estonia        | 0.0001| 0.0001| 0.0002| 0.0002| 0.0002| 0.0002|          |

not reached the frontier state during this period. Its average efficiency value is 0.9810, ranking first among the listed countries and far exceeding Switzerland (0.2832), which is at the top of the second rank. Except for these two countries, other countries that rank at the top 10 have the economic income-oriented energy consumption efficiency value of more than 0.1, they are Japan (0.2733), Luxembourg (0.2534), China (0.2291), Brazil (0.1376), United States (0.1322), Australia (0.1180), Germany (0.1084) and United Kingdom (0.1045). The remaining countries are relatively inefficient in terms of economic income-oriented energy consumption over the 5 years. It should be pointed out that Estonia is the most inefficient and the average value is almost 0.

Thus, we can conclude that there exist extreme phenomena in the economic income-oriented energy consumption performance, with a significant difference between each other.

In order to further investigate the reasons that affect the economic income-oriented energy consumption performance, the efficiency values of the corresponding sub-processes are also calculated.

As shown in Table 3, the energy conversion process efficiency values based on the two-dimensional network are presented. Australia, Japan and Singapore achieve the optimal performance for 5 years in the energy conversion process. Other countries such as the United States, Germany, Indonesia and Ireland also obtain an efficiency value of 1 in some years, and they generally rank ahead of other countries based on average efficiency values.

Furthermore, among the 10 top-ranked countries, some of them are efficient in neither of the five years such as the United Kingdom, China and Italy. China also has better performance in the energy conversion process. Nevertheless, the efficiency values of Italy and Japan are generally
The economic growth process efficiency values based on the two-dimensional network are listed in Table 4. Obviously, Luxembourg maintains the best performance in the economic growth process. Other countries that have the efficiency values of 1 in some years are Singapore and Switzerland. Except for the countries mentioned above, others are not as efficient with the values that are less than 0.5 in each year. For example, the last-ranked 2 countries, Slovak Republic and Ireland, their average efficiency values are below 0.1. Then, the average economic growth process efficiency values of remaining countries shown in Table 4 are mainly distributed around 0.2 to 0.4, which is similar to the results presented in Table 2.

### C. RESULTS ANALYSIS FROM THE PERSPECTIVE OF SUSTAINABLE DEVELOPMENT

Similarly, the efficiency values of sustainable development-oriented energy consumption and the corresponding sub-processes based on the three-dimensional network are shown in Tables 5-7. Table 5 reflects the countries’ efficiency values of sustainable development-oriented energy consumption. It can be found that Singapore, Switzerland and Luxembourg are efficient in some years with the average efficiency values of 0.7095, 0.5630 and 0.5295, respectively. It should be noted that the United States is more efficient in the economic income-oriented energy consumption, whereas its sustainable development-oriented energy consumption is not that efficient, and it ranks in the bottom. Besides, Japan also experiences a similar situation. It is top-ranked in terms of economic income-oriented energy consumption, but it falls to 27th when considering the performance of...
TABLE 5. Sustainable energy consumption efficiency values based on the three-dimensional network.

| Country            | 2012    | 2013    | 2014    | 2015    | 2016    | Mean    | Rank (M) |
|--------------------|---------|---------|---------|---------|---------|---------|----------|
| Singapore          | 0.7746  | 0.8365  | 0.0316  | 1.0060  | 0.9049  | 0.7095  | 1        |
| Switzerland        | 0.7356  | 0.0804  | 0.8067  | 0.1925  | 1.0000  | 0.5630  | 2        |
| Luxembourg         | 0.4533  | 1.0000  | 0.2120  | 0.0002  | 1.0000  | 0.5295  | 3        |
| Denmark            | 0.3539  | 0.0058  | 0.3826  | 0.3835  | 0.2986  | 0.2849  | 4        |
| Czech Republic     | 0.1162  | 0.1964  | 0.2294  | 0.3084  | 0.3508  | 0.2402  | 5        |
| Morocco            | 0.2016  | 0.1429  | 0.0034  | 0.3241  | 0.3541  | 0.2052  | 6        |
| Portugal           | 0.0387  | 0.1299  | 0.2255  | 0.2129  | 0.3253  | 0.1865  | 7        |
| Thailand           | 0.0017  | 0.1680  | 0.2146  | 0.2380  | 0.2272  | 0.1699  | 8        |
| Hungary            | 0.0168  | 0.0828  | 0.0246  | 0.3696  | 0.3105  | 0.1609  | 9        |
| China              | 0.2115  | 0.0073  | 0.2460  | 0.2498  | 0.0354  | 0.1500  | 10       |
| Brazil             | 0.1281  | 0.1375  | 0.1896  | 0.0662  | 0.2558  | 0.1434  | 11       |
| Poland             | 0.0016  | 0.1448  | 0.1392  | 0.1983  | 0.2304  | 0.1429  | 12       |
| Sweden             | 0.0992  | 0.1121  | 0.0022  | 0.2439  | 0.2549  | 0.1425  | 13       |
| Greece             | 0.0014  | 0.0040  | 0.1980  | 0.2738  | 0.0933  | 0.1141  | 14       |
| Belgium            | 0.0014  | 0.0542  | 0.1374  | 0.1818  | 0.1911  | 0.1132  | 15       |
| South Africa       | 0.0836  | 0.0020  | 0.1306  | 0.1688  | 0.1778  | 0.1126  | 16       |
| Norway             | 0.0582  | 0.0871  | 0.1557  | 0.0033  | 0.2543  | 0.1117  | 17       |
| France             | 0.0172  | 0.0798  | 0.1125  | 0.1105  | 0.1958  | 0.1032  | 18       |
| Turkey             | 0.0695  | 0.0020  | 0.1067  | 0.1586  | 0.1699  | 0.1013  | 19       |
| Australia          | 0.0031  | 0.0032  | 0.1184  | 0.1626  | 0.2093  | 0.0993  | 20       |
| United Kingdom     | 0.0589  | 0.0139  | 0.1532  | 0.2238  | 0.0397  | 0.0979  | 21       |
| The Netherlands    | 0.0018  | 0.0368  | 0.1433  | 0.1001  | 0.1471  | 0.0858  | 22       |
| Italy              | 0.0756  | 0.0114  | 0.1623  | 0.0042  | 0.1666  | 0.0840  | 23       |
| Indonesia          | 0.0759  | 0.0743  | 0.0488  | 0.1163  | 0.0995  | 0.0830  | 24       |
| Austria            | 0.0717  | 0.0263  | 0.1074  | 0.1247  | 0.0428  | 0.0746  | 25       |
| Spain              | 0.0380  | 0.0076  | 0.0641  | 0.0744  | 0.1841  | 0.0376  | 26       |
| Japan              | 0.0045  | 0.0054  | 0.0058  | 0.3362  | 0.0070  | 0.0718  | 27       |
| Slovak Republic    | 0.0007  | 0.0382  | 0.0801  | 0.1006  | 0.1276  | 0.0694  | 28       |
| Mexico             | 0.0515  | 0.0968  | 0.0033  | 0.0048  | 0.1844  | 0.0682  | 29       |
| Estonia            | 0.2243  | 0.0157  | 0.0040  | 0.0905  | 0.0001  | 0.0669  | 30       |
| Finland            | 0.0538  | 0.0676  | 0.0032  | 0.0053  | 0.1651  | 0.0590  | 31       |
| Germany            | 0.0084  | 0.0698  | 0.0208  | 0.1132  | 0.0784  | 0.0581  | 32       |
| Ireland            | 0.0011  | 0.0243  | 0.0518  | 0.0572  | 0.1077  | 0.0484  | 33       |
| India              | 0.0419  | 0.0457  | 0.0025  | 0.0141  | 0.0208  | 0.0250  | 34       |
| United States      | 0.0109  | 0.0116  | 0.0040  | 0.0055  | 0.0089  | 0.0082  | 35       |

sustainable development-oriented energy consumption. The Czech Republic, Portugal and Hungary also share some similarities.

The calculation results of the energy conversion process for the economic income-oriented energy consumption are presented in Table 6. We can find that there are 8 countries have the efficiency value 1 in the years, namely Indonesia, Norway, Singapore, Australia, Switzerland, Germany, Luxembourg and Japan. These countries rank respectively the 3rd, 4th, 6th, 10th, 11th, 20th, 24th and 32nd in all the studied countries. Thus, there is no sure relationship between the ranking situation and the energy conversion frontier, which can be regarded as an accidental phenomenon caused by an unexpected events. In addition, the last-ranked 10 countries are Spain, Italy, The Netherlands, Mexico, Greece, Hungary, Japan, Estonia, the United States and India. Among them, except for Greece, Hungary and Estonia, the remaining countries are top-ranked in Table 3, especially Japan (ranking first) and the United States (ranking third), indicating that environmental elements have a significant impact. Then, the average efficiency values for all countries are evenly distributed in the interval of 0.1841 to 0.8399 and the fluctuation is not obvious.

Table 7 shows the economic growth process efficiency values based on the three-dimensional network. It can be found that the average efficiency values of the first 3 countries, namely Luxembourg, Singapore and Switzerland are more distinct from those of other countries and their performance in the economic growth process is effective in some years. This phenomenon is similar to the efficiency value distribution of the economic growth process compared with which of the economic income-oriented energy consumption in Table 4. The remaining countries listed in Table 7 show unsatisfactory performance. For example, Germany (0.0975), Finland (0.0822), Slovak Republic (0.0767), Ireland (0.0681) and the United States (0.0426) have the efficiency values that are less than 0.1.
TABLE 6. The energy conversion process efficiency values based on the three-dimensional network.

| Country            | 2012   | 2013     | 2014     | 2015     | 2016     | Mean   | Rank (M) |
|--------------------|--------|----------|----------|----------|----------|--------|----------|
| Czech Republic     | 0.6454 | 0.8874   | 0.8857   | 0.8868   | 0.8941   | 0.8399 | 1        |
| Portugal           | 0.5774 | 0.8964   | 0.9359   | 0.7316   | 0.9405   | 0.8164 | 2        |
| Indonesia          | 1.0000 | 1.0000   | 0.4211   | 0.7836   | 0.6436   | 0.7697 | 3        |
| Norway             | 0.8111 | 0.9693   | 1.0000   | 0.0610   | 1.0000   | 0.7683 | 4        |
| Slovak Republic    | 0.0702 | 0.9619   | 0.9529   | 0.8630   | 0.9632   | 0.7622 | 5        |
| Singapore          | 0.7748 | 0.8387   | 0.0683   | 1.0000   | 1.0000   | 0.7364 | 6        |
| Denmark            | 0.9495 | 0.1035   | 0.9763   | 0.8682   | 0.7211   | 0.7373 | 7        |
| Morocco            | 0.9397 | 0.6570   | 0.0845   | 0.8889   | 0.9453   | 0.7031 | 8        |
| Sweden             | 0.8681 | 0.7772   | 0.0496   | 0.8912   | 0.8868   | 0.6946 | 9        |
| Australia          | 0.1718 | 0.2029   | 1.0000   | 1.0000   | 0.9933   | 0.6736 | 10       |
| Switzerland        | 0.9319 | 0.1557   | 0.9728   | 0.2622   | 1.0000   | 0.6645 | 11       |
| China              | 0.9608 | 0.1577   | 0.9654   | 0.9886   | 0.1511   | 0.6447 | 12       |
| Belgium            | 0.0649 | 0.5600   | 0.8079   | 0.8280   | 0.7826   | 0.6087 | 13       |
| United Kingdom     | 0.7803 | 0.2206   | 0.8753   | 0.9388   | 0.1976   | 0.6025 | 14       |
| Poland             | 0.0946 | 0.7642   | 0.6152   | 0.7654   | 0.7719   | 0.6023 | 15       |
| Austria            | 0.9346 | 0.3424   | 0.7833   | 0.7097   | 0.2196   | 0.5979 | 16       |
| Ireland            | 0.0955 | 0.5656   | 0.5528   | 0.6979   | 0.9763   | 0.5776 | 17       |
| Finland            | 0.8595 | 0.9148   | 0.1168   | 0.1099   | 0.8209   | 0.5717 | 18       |
| Brazil             | 0.7094 | 0.7313   | 0.6810   | 0.1397   | 0.5898   | 0.5702 | 19       |
| Germany            | 0.2122 | 1.0000   | 0.2528   | 0.7988   | 0.5088   | 0.5545 | 20       |
| Thailand           | 0.0994 | 0.6295   | 0.6777   | 0.6863   | 0.6527   | 0.5473 | 21       |
| France             | 0.2140 | 0.7658   | 0.6004   | 0.4554   | 0.6934   | 0.5458 | 22       |
| Turkey             | 0.5182 | 0.1132   | 0.5614   | 0.7345   | 0.7607   | 0.5376 | 23       |
| Luxembourg         | 0.4353 | 1.0000   | 0.2120   | 0.0002   | 1.0000   | 0.5295 | 24       |
| South Africa       | 0.6290 | 0.0811   | 0.6130   | 0.6618   | 0.6443   | 0.5258 | 25       |
| Spain              | 0.7028 | 0.1597   | 0.4608   | 0.4901   | 0.8106   | 0.5248 | 26       |
| Italy              | 0.6681 | 0.1595   | 0.9147   | 0.1651   | 0.6850   | 0.5185 | 27       |
| The Netherlands    | 0.1026 | 0.5314   | 0.7904   | 0.4811   | 0.5603   | 0.4952 | 28       |
| Mexico             | 0.4749 | 0.7886   | 0.1615   | 0.2100   | 0.7580   | 0.4786 | 29       |
| Greece             | 0.0630 | 0.0954   | 0.9140   | 0.9025   | 0.2988   | 0.4547 | 30       |
| Hungary            | 0.0451 | 0.2085   | 0.0675   | 0.9338   | 0.9305   | 0.4371 | 31       |
| Japan              | 0.1319 | 0.1213   | 0.1114   | 1.0000   | 0.1461   | 0.3021 | 32       |
| Estonia            | 0.9945 | 0.0695   | 0.0140   | 0.3033   | 0.0005   | 0.2764 | 33       |
| United States      | 0.2224 | 0.2007   | 0.1363   | 0.1608   | 0.2054   | 0.1851 | 34       |
| India              | 0.2853 | 0.3006   | 0.0911   | 0.1133   | 0.1301   | 0.1841 | 35       |

D. FURTHER DISCUSSION
The annual efficiency value fluctuation is shown in Figure 2 and Figure 3 by comparing the efficiency differences of the current year and the previous year on the aspects of the economic income-oriented energy consumption, the sustainable development-oriented energy consumption and their subprocesses. Each individual large rectangle represents a country’s efficiency value change, which is divided into 3 small rectangles. The blue histogram denotes the efficiency change of the economic income-oriented energy consumption and the sustainable development-oriented energy consumption in Figure 2 and Figure 3, respectively. The red histogram and the green histogram represent the efficiency change of the energy conversion process and the economic growth process, respectively. Then, the height of a histogram implies the magnitude of increase or decrease in efficiency value compared with the previous year. In Figure 2, except for the individual rectangles, the height of most histograms is relatively small. Then, we can summarize that:

- When assessing the economic income-oriented energy consumption efficiency values, the majority of countries’ performance tends to be stable.
- Overall, the efficiency values of the energy conversion process and the economic growth process in each country do not fluctuate significantly, thus we further verify that the performance of the economic income-oriented energy consumption is affected by the two subprocesses simultaneously.
- Luxembourg’s efficiency values change exceed 0.1 in terms of economic income-oriented energy consumption. The energy conversion process of Germany, Ireland, Italy, Luxembourg, Norway, Indonesia, Mexico and Brazil, and the economic growth process of Greece, Switzerland and Brazil also have similar performance in the five years. Among them, Ireland shows the most obvious change in the energy conversion process. In addition, the countries whose the efficiency values of economic income-oriented energy consumption, energy conversion process and economic growth process

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TABLE 7. The economic growth process efficiency values based on the three-dimensional network.

| Country          | 2012  | 2013  | 2014  | 2015  | 2016  | Mean  | Rank (M) |
|------------------|-------|-------|-------|-------|-------|-------|----------|
| Luxembourg       | 1.0000| 1.0000| 0.9999| 0.9555| 1.0000| 0.9911| 1        |
| Singapore        | 0.9997| 0.9973| 0.4631| 1.0000| 0.9049| 0.8730| 2        |
| Switzerland      | 0.7894| 0.5168| 0.8293| 0.7340| 1.0000| 0.7739| 3        |
| Hungary          | 0.3726| 0.3972| 0.3641| 0.3958| 0.3338| 0.3727| 4        |
| Denmark          | 0.3728| 0.0559| 0.3919| 0.4418| 0.4141| 0.3353| 5        |
| Czech Republic   | 0.1801| 0.2213| 0.2590| 0.3477| 0.3923| 0.2801| 6        |
| Thailand         | 0.0191| 0.2670| 0.3167| 0.3467| 0.3481| 0.2595| 7        |
| Estonia          | 0.2255| 0.2254| 0.2868| 0.2985| 0.2129| 0.2498| 8        |
| Morocco          | 0.2146| 0.2175| 0.0401| 0.3646| 0.3746| 0.2423| 9        |
| Brazil           | 0.1806| 0.1880| 0.2784| 0.0445| 0.4337| 0.2250| 10       |
| Portugal         | 0.0670| 0.1449| 0.2409| 0.2910| 0.3459| 0.2179| 11       |
| China            | 0.2201| 0.0465| 0.2548| 0.2527| 0.2346| 0.2017| 12       |
| Poland           | 0.0167| 0.1895| 0.2263| 0.2590| 0.2985| 0.1980| 13       |
| South Africa     | 0.1329| 0.0245| 0.2130| 0.2551| 0.2760| 0.1803| 14       |
| France           | 0.0802| 0.1042| 0.1874| 0.2426| 0.2824| 0.1794| 15       |
| Greece           | 0.0222| 0.0418| 0.2166| 0.3033| 0.3122| 0.1792| 16       |
| Sweden           | 0.1142| 0.1443| 0.0434| 0.2736| 0.2874| 0.1726| 17       |
| Turkey           | 0.1340| 0.0180| 0.1901| 0.2159| 0.2234| 0.1563| 18       |
| United Kingdom   | 0.0755| 0.0631| 0.1751| 0.2383| 0.2006| 0.1505| 19       |
| Belgium          | 0.0214| 0.0968| 0.1701| 0.2195| 0.2442| 0.1504| 20       |
| The Netherlands  | 0.0172| 0.0692| 0.1813| 0.2080| 0.2625| 0.1476| 21       |
| Austria          | 0.0767| 0.0769| 0.1371| 0.1758| 0.1951| 0.1323| 22       |
| Italy            | 0.1132| 0.0715| 0.1774| 0.0255| 0.2432| 0.1262| 23       |
| Norway           | 0.0717| 0.0899| 0.1557| 0.0548| 0.2543| 0.1253| 24       |
| Spain            | 0.0541| 0.0474| 0.1392| 0.1517| 0.2271| 0.1239| 25       |
| India            | 0.1469| 0.1520| 0.0276| 0.1244| 0.1601| 0.1222| 26       |
| Indonesia        | 0.0759| 0.0743| 0.1159| 0.1484| 0.1546| 0.1138| 27       |
| Australia        | 0.0180| 0.0159| 0.1184| 0.1626| 0.2107| 0.1051| 28       |
| Mexico           | 0.1085| 0.1228| 0.0203| 0.0227| 0.2432| 0.1035| 29       |
| Japan            | 0.0342| 0.0441| 0.0525| 0.3362| 0.0477| 0.1029| 30       |
| Germany          | 0.0397| 0.0698| 0.0823| 0.1417| 0.1540| 0.0975| 31       |
| Finland          | 0.0601| 0.0739| 0.0277| 0.0482| 0.2011| 0.0822| 32       |
| Slovak Republic  | 0.0105| 0.0397| 0.0840| 0.1166| 0.1325| 0.0767| 33       |
| Ireland          | 0.0113| 0.0430| 0.0938| 0.0820| 0.1103| 0.0681| 34       |
| United States    | 0.0491| 0.0577| 0.0292| 0.0340| 0.0431| 0.0426| 35       |

have been increasing over time are Australia, Estonia, Greece, Luxembourg, Slovak Republic, United States and Morocco, suggesting that they have a strong development potential in transforming energy resources into industrial products and promote the country’s economic development.

Further, the annual efficiency change in sustainable development-oriented energy consumption can be clearly seen from Figure 3. Compared with the economic income-oriented energy consumption, more fluctuations occur in the majority of countries. Similarly, the efficiency values of the energy conversion process in most countries also show great variation. It can be found that the efficiency value fluctuation in most countries is more obvious in the energy conversion process than that in the economic growth process. Hence, we can further speculate that the energy conversion process significantly impacts the overall efficiency in these countries. It should be pointed out that the United States presents a relatively stable performance in terms of the annual sustainable energy consumption, the energy conversion process and the economic growth process. Therefore, we believe that the United States is not sensitive to carbon dioxide emissions when converting energy resources into economic benefits. However, Switzerland’s efficiency fluctuations are negative in 2013 and 2015 but positive in 2014 and 2016. A similar situation also occurs in Italy, while Hungary shows the opposite trend. The extremely unstable performance suggests that carbon dioxide has a significant effect on the process of energy conversion and the economic growth in these countries.

Then, the countries where carbon dioxide has only brought positive effects in the past 5 years are Australia, Belgium, Czech Republic, Ireland and Thailand. It indicates that these countries have performed well in environmental management, thus various efficiency value in
FIGURE 3. The efficiency values fluctuation based on two-dimensional network.

response to sustainable energy consumption increases when the environmental factors are involved in the assessment. Through the above analysis, we can further summarize as follows:

- In most countries, the efficiency value of sustainable energy consumption fluctuates more dramatically than that of beneficial energy consumption.
- The energy conversion process in the majority of countries is more sensitive to CO₂ emissions than the economic growth process.

For the impact of CO₂ emissions, the United States performs stably, whereas Switzerland and Italy are not stable, and the countries that are positively affected are Australia, Belgium, Czech Republic, Ireland and Thailand.

IV. COMPARATIVE ANALYSIS OF GLOBAL ENERGY CONSUMPTION

To investigate the overall performance of global energy consumption, efficiency values of beneficial and sustainable energy consumption and their corresponding subprocesses in various regions are evaluated. Based on our analyses, some policy recommendations are given.

A. COMPARATIVE ANALYSIS BASED ON THE CROSS-COUNTRY DATA

As shown in Table 8, 35 major member countries of the International Energy Agency are classified into 5 regions. Australia is a country in Oceania. Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Luxembourg, Mexico, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Netherlands and the United Kingdom are in Europe. Japan, Turkey, China, India, Indonesia, Singapore and Thailand are in Asia. Moreover, Mexico, the United States and Brazil belong to America. Morocco and South Africa are in Africa.

Based on the multidimensional (two-dimensional network and three-dimensional network) structure, the regional comparisons of average efficiency values calculated by the
two-dimensional network and the three-dimensional network are presented in Figure 4. The blue line represents the average efficiency value of the economic income-oriented and the sustainable development-oriented energy consumption in the left and the right figure, respectively. The red line and the green line indicate the corresponding efficiency values of the energy conversion process and economic growth process. In general, the average efficiency value of the energy conversion process is always the largest, followed by the economic growth process. The efficiency value of economic income-oriented or sustainable development-oriented energy consumption is the smallest, which is consistent with the properties described in Section 2. It indicates that energy utilization generally performs better than industrial production in many regions. This pheromone is not affected by environmental emissions. However, Africa is different.
Its average efficiency value of the economic growth process is greater than that of the energy conversion process when CO₂ emissions are not involved. Similarity, the efficiency value of the energy conversion process in Europe also increases relative to (comparing with?) the economic income-oriented energy consumption, while the performance of Oceania, Asia and America is poor, especially Oceania, whose performance changes from effective to ineffective. Compared with the dramatic change in the average efficiency value of the energy conversion process, the fluctuations of the economic growth are slow. Further, since the efficiency value of both the economic income-oriented and the sustainable development-oriented energy consumption are expressed by multiplying the efficiency values of two subprocesses, their efficiency variation range is smaller. Through the above analysis, we derive that:

• In the economic income-oriented energy consumption assessment, Asia is the region with the highest efficiency, followed by America, Oceania, Europe, and Africa. In the sustainable development-oriented energy consumption assessment, Asia is also the best-performing region, followed by Africa, Europe, Oceania and America.

• In general, the energy conversion process performs better than the economic growth process in most regions, except for Africa with respect to the economic income-oriented energy consumption.

• Compared with the performance of the economic income-oriented energy consumption, the efficiency value of the energy conversion process in Africa and Europe increases under the evaluation of the sustainable development-oriented energy consumption.

However, the performance of Oceania, Asia and America become poor implying that some environmental elements have a negative impact on the energy conversion process in these regions. The performance of the economic growth process in each region is worse in the sustainable development-oriented energy consumption than that of the economic income-oriented energy consumption.

B. COMPARATIVE ANALYSIS BASED ON THE CROSS-COUNTRY-TIME DATA

To further investigate the historical performance of each region, their efficiency values in different time periods are compared. Figures 5-6 show the efficiency trends in the past 5 years. The graphs on the left, middle and right represent the changes in efficiency values of the economic income-oriented or the sustainable development-oriented energy consumption, the energy conversion process and the economic growth process, respectively. The broken lines show the efficiency value trends over the past 5 years and the column indicates the average efficiency values of the 5 regions. In Figure 5, the trends of the broken lines are generally similar in slight fluctuations over time. As for the annual performance of the economic income-oriented energy consumption, Asia ranks first, followed by America. Oceania occupies the 3rd place while Europe and Africa are in the bottom 2, at 4th and 5th respectively. Then, the efficiency value of Oceania increases rapidly in 2015 while America takes the opposite position, which leads to Oceania’s ranking begins to be higher than that of America, and it continues to maintain this trend in 2016. Regarding the regional average efficiency, Asia has a prominent performance over the
past 5 years. Oceania and America have a gradual upward trend, whose efficiency values exceed the regional average efficiency in 2015 while Europe and Africa are below the average. It may be related to the adoption and the signing of “The Paris Agreement” in 2015 and 2016. Various countries hold different attitudes towards this agreement, the majority of countries accept and commit to reinforce the management in response to the global threat brought by climate change, but some reject it. For the energy conversion process, the overall efficiency of the past 5 years shows an upward trend firstly but then a downward trend. Among these regions, Oceania is efficient in the 5 years, whereas the other 4 regions have the potential to be improved. The efficiency value of Asia rises first in 2013 and then decline slightly in 2014, after which it resumes the upward trend in 2015 and 2016. The energy conversion level of America declines in 2015, causing its efficiency value to be lower compared with that of Asia. Then, the efficiency value of Europe gradually falls from an upward trend in 2016 while Africa starts to decline in 2014. Hence, it is believed that 2015 and 2016 are two important years that are worthy of attention for these regions. Furthermore, it is obvious that the efficiency values of the energy conversion process in Asia and the Americas are greater than the average during the period studied, while Europe and Africa are both less efficient than average, which is consistent with the results obtained in Section 3. It suggests that Asia and the Americas can effectively control energy conversion. Europe and Africa need to further strengthen the ability to convert energy resources into industrial products. The industrial structures make these regions have such effect. For instance, most of the African member countries are less-developed. They are experiencing the industrialization and some of them are still in the agricultural era. Therefore, their production equipment is not cutting edge, which can be the main reason for these African member countries to be inefficient. The composition of European is dominated by developed countries, most of which are in the post-industrial era, and the service industry is also an important component. Hence, heavy industries may not be an important target of state support, which can lead to management negligence in the conversion of energy resources. For the economic growth process, the variation trend of efficiency value over the past 5 years is similar in several regions. It can be seen that the efficiency values of 4 regions increase rapidly during the period from 2014 to 2015 and then the rate slows down in 2016, while Asia shows a downward trend in 2016. Among them, Oceania shows the largest increase in 2016, followed by America. The conditions of Europe and Africa are similar, both slowly increasing, while Asia’s development is not particularly ideal.

For sustainable energy consumption, the performance of each region over the years is revealed in Figure 6. Overall, they are unstable and at a lower level. For example, the efficiency values of sustainable energy consumption in Oceania are almost 0 both in 2012 and 2013, and then increase suddenly in 2014 and remain steady growth in 2015 and 2016. In addition, the region with large efficiency value fluctuation in 2014 is also Europe. Asia, America and Africa all reached the maximum fluctuation in 2015. The difference is that the efficiency value of America shows a downward trend in 2015 while that of Asia and Africa dramatically increases. Then, Oceania, Europe, America and Africa all present their development potential in the future, but Asia shows a sluggish state in 2016. The characteristics and trends of efficiency values in these regions over the past 5 years also occur in the corresponding two subprocesses. Oceania’s efficiency value grows slowly in 2013 and then reaches its efficiency front in 2014 and maintains this status in 2015 and 2016. Then, the annual efficiency value of Europe has been rising, except for a slight decline in 2015. Asia is in a downward trend for the first 3 years and then declines in 2016 after a sudden rise in 2015. The efficiency of America increases in 2013 and 2016. However, the efficiency of Africa decreases in 2013 and 2014. For the economic growth process, the trend of efficiency values in the 5 regions is similar to that of sustainable development-oriented energy consumption. Among these regions, the annual efficiency values of Asia and Europe are significantly higher than the average, while those of America and Oceania are lower than the average. Then, America, Oceania, Europe and Africa present a positive state in 2016, among which the overall trend of Oceania and Europe show an upward curve in the past 5 years. Therefore, we believe that they have the potential to get improved with respect to the economic growth process. Through the above longitudinal comparison, some important results can be seen as follows:

* The efficiency value of economic income-oriented energy consumption of America, Oceania, Europe and Africa is increasing year by year, among which Oceania has the greatest development potential. Asia is relatively stable, higher than the overall level, but its development momentum is insufficient.

* Small fluctuations in the energy conversion process in these regions can be observed. Among them, Oceania maintains the performance forefront. The annual efficiency values of America and Asia are higher than the average while Europe and Africa are lower than the average.

* As for economic income-oriented energy consumption, the efficiency values of the economic growth process in America, Oceania, Europe and Africa increase every year. Asia has a slight decline in 2016, which is similar to the performance of economic income-oriented energy consumption. Therefore, we believe that the economic growth process has a more profound driving effect on economic income-oriented energy consumption.

* The efficiency values of the regions’ sustainable development-oriented energy consumption are lower than that of the overall level in each year. The performance of the 5 regions in sustainable development-oriented energy consumption over the past 5 years is unstable, among which Europe is the least volatile, while the other 4 regions all experience significant
fluctuations, further illustrating that America, Oceania, Asia and Africa are sensitive to CO₂ emissions. In addition, we find that the future trend of sustainable development-oriented energy consumption in Asia is relatively negative, while the other 4 regions are positive.

Regarding sustainable development-oriented energy consumption, the annual performance of the energy conversion process in each region is also unstable, and Oceania presents the largest efficiency variation. The efficiency fluctuations of the economic growth process in the regions are similar to those of sustainable development-oriented energy consumption. The regions with better performance are Asia and Europe, while Oceania and America perform poor, but both show strong development potential.

C. POLICY RECOMMENDATIONS FOR SUSTAINABLE ECONOMIC DEVELOPMENT

Through the above analysis, we propose different policy recommendations for each region. Oceania’s efficiency of economic income-oriented energy consumption is at an average level and its sustainable development-oriented energy consumption is lower than the global overall level, but it has great development potential. It is sensitive to CO₂ emissions in the processes of energy conversion and economic growth. Asia has a good performance in both economic income-oriented and sustainable development-oriented energy consumption. The energy conversion process and economic process are negatively affected by CO₂ emissions. Therefore, the countries in this region should focus on innovative high-tech industries, which not only meets the requirements of green development, but also serves as a direction of industrial transformation of each country in the future, and has great development potential. America’s economic income-oriented energy consumption efficiency is high and growing year by year, but it has the worst performance in sustainable development-oriented energy consumption. Environmental factors have a great inhibitory effect on the process of energy conversion and economic growth. Therefore, countries in this region should take advantage of their prominent economic advantages to strengthen the management of pollution emissions from production activities and promote further economic growth. For the similar negative effects of environmental factors on these regions, except the composition of individual countries with abnormal performance, we put forward the following recommendations to improve the performance of sustainable development-oriented energy consumption.

1) TRANSFORMING INDUSTRIAL STRUCTURE WITH SCIENTIFIC AND INNOVATIVE TECHNOLOGIES
The government can establish various welfare policies and increase the investment in scientific research to encourage the development of knowledge-based, high-tech and innovative industries, making these intelligent industries become the main support of national economic development.

2) PROMOTE GREEN ECONOMIES WITH CLEAN ENERGY
A large amount of energy resources is involved in production activities, especially in traditional heavy industry. Therefore, the choice of energy type has a direct impact on the pollution emission. Selecting clean and sustainable energy can be helpful to cope with the problem of primary energy exhaustion and pollution emissions.

3) DEVELOP SPECIAL INDUSTRIES IN CONSIDERATION OF LOCAL CONDITIONS
Developing other special industries such as tourism and service industry with local characteristics and making good control can not only stimulate the country’s economic growth, but also strengthen the communication between countries, which is conducive to improving the country’s international visibility.

Europe’s performance is in contrast to Oceania’s. Its economic income-oriented energy consumption efficiency is below the average and its sustainable development-oriented energy consumption is at the average level. In addition, its overall performance of energy resource utilization is low, but the environmental impact of this process is well controlled. Environmental factors have a positive effect on its energy conversion process and a negative effect on its economic growth process, but it is not obvious. Therefore, countries in the region should focus on controlling the production processes in which industrial products contribute to economic growth. Some specific measures are proposed as follows:

4) ENHANCE ECONOMIC VITALITY WITH MARKET INTEGRATION
Regulating market rules can promote commodity circulation, which further stimulates a country’s economic growth and makes the market more dynamic.

Economic income-oriented energy consumption in Africa is the worst, but its sustainable development-oriented energy consumption ranks second. Its energy conversion process has performed poorly while the economic growth process has grown every year and still has great potential for improvement. Environmental factors positively impact its energy conversion process, but negatively influence the economic growth process, which shows its effective management of environmental emissions in the energy conversion process. However, the conversion efficiency of energy resources still needs to be improved. Thus, some suggestions are given below.

5) PROMOTE PRODUCT TRADE FREQUENTLY WITH INFRASTRUCTURE CONSTRUCTION
Short-term investment in infrastructure can bring long-term economic returns. Convenient transportation can increase the technical exchange between countries and expand the flow of industrial products, which can not only communicate advanced technology but also further drive a country’s economic growth.
FIGURE 7. The regional efficiency values correspond to sustainable energy consumption.

TABLE 9. Description and assumptions of the decision variables and parameters.

| Symbol | Description | Symbol | Description | Symbol | Description |
|--------|-------------|--------|-------------|--------|-------------|
| X      | initial cost elements matrix | $z_{iA}$ | intermediate undesired product elements vector of $i$ th object | $k$ | number of research objects |
| Z      | intermediate product elements matrix | $y_k$ | final desired product elements vector of $k$ th object | $\xi$ | any research objects |
| $Z_1$  | intermediate desired product elements matrix | $\eta$ | efficiency value | $C$ | weight assigned to $Y$ |
| $Z_2$  | intermediate undesired product elements matrix | $a_i$ | weight assigned to $x_{ci}$ | $x_{cm}$ | $m$ th initial cost element of $\xi$ th object |
| $Y$    | final desired product elements matrix | $c_o$ | weight assigned to $y_{co}$ | $z_{1,\xi}$ | $s_1$ th intermediate desired product element of $\xi$ th object |
| A      | weight assigned to $X$ | $m$ | amount of initial cost elements $X$ | $z_{2,\xi}$ | $s_2$ th intermediate undesired product element of $\xi$ th object |
| $B_1$  | weight assigned to $Z_1$ | $s$ | amount of intermediate product elements $Z_1$ | $y_{co}$ | $n$ th final desired product element of $\xi$ th object |
| $B_2$  | weight assigned to $Z_2$ | $s_1$ | amount of intermediate desired product elements $Z_1$ | $b_{1,i}$ | weight assigned to $z_{1,\xi}$ |
| $x_k$  | initial cost elements vector of $k$ th object | $s_2$ | amount of intermediate undesired product elements $Z_2$ | $b_{2,v}$ | weight assigned to $z_{2,\xi}$ |
| $z_{1,k}$ | intermediate desired product elements vector of $k$ th object | $n$ | amount of final desired product elements $Y$ | | |

6) IMPROVE TECHNOLOGY INNOVATIONS BY EDUCATION

Technology innovations are the key in the processes of converting energy resources into industrial products and promoting economic growth by industrial products. Therefore, it is necessary to focus on cultivating personnel, especially researchers in energy-related industries. To do so, more professional training, research inputs and academic communications should be considered as an important proportion of government investment.

7) FINDING COMPARISON WITH THE EXISTING LITERATURE

As for the comparison between our findings and the existing literature on the same issue, it can be found that other energy or resources are also taken into considerations such as population, capital and land. Specifically, Australia’s production department efficiency is low due to the low utilization rate of land [5]. The USA and China are the large users of excess energy because of economic inefficiency and distributional inefficiency, respectively, [40]. The findings are different with which presented in this paper as the research time period, methods and indicators are different. There are also some research related to energy consumption evaluation mainly concern about energy industries in one country [41]–[43]. Furthermore, we compare the efficiency values calculated by the proposed models in this paper with the investigation of World Energy Outlook 2018 released by the International Energy Agency. The details are shown in TABLE 10 in the Appendix.

TABLE 10 shows the economic income-oriented and sustainable development-oriented efficiency values and the energy intensity values in 2016 released on the World Energy Outlook 2018. Firstly, it should be note that energy intensity is also an indicator reflecting energy efficiency, which is the amount of energy consumed per unit of GDP produced. In general, the higher the energy efficiency value, the better the country’s performance. Conversely, the greater the energy intensity, the poorer the country’s energy performance.

In addition, to compare the energy consumption performance between the results given in this paper and the data reported by the International Energy Agency, we further provide energy consumption performance ranks among the counties being evaluated. According to the comparison, the performance of energy consumption in many countries is quite different from that reported by the International Energy Agency because of the elements considered in the
two investigations. Energy intensity only involve two indicators namely GDP and total energy consumption, while the research in this paper considers more including industrial added value and CO\textsubscript{2} emissions. Therefore, both of the two studies analyze global energy consumption performance. However, due to the differences in terms of indicators and evaluating methods, the results can be different.

V. CONCLUSION

In order to achieve the aims of comprehensively evaluating the world energy consumption and providing practical suggestions for the countries being evaluated which improves their efficiency of energy consumption, this paper has first discussed the concepts of economic income-oriented energy consumption and sustainable development-oriented energy consumption. The economic income-oriented energy consumption only involves 2 dimensions, namely energy and economy, while sustainable development-oriented energy consumption includes 3 dimensions, namely energy, environment and economy. In addition, the multidimensional structure has been presented to measure the efficiency values of both economic income-oriented and sustainable development-oriented energy consumption. In order to further analyze the performance of the 2 types of energy consumptions, the efficiency values of the subprocesses, the energy conversion process and the economic development process have also been assessed. Finally, an empirical study has been conducted based on 35 major countries from the International Energy Agency and some useful conclusions have been obtained.

| Country          | Economic income-oriented | Sustainable development-oriented | World Energy Outlook |
|------------------|--------------------------|---------------------------------|----------------------|
|                  | Efficiency value | Rank    | Efficiency value | Rank    | Energy intensity | Rank    |
| Singapore        | 0.9049        | 1       | 0.9049          | 3       | 0.0600          | 3       |
| Switzerland      | 0.3391        | 3       | 1.0000          | 1       | 0.0500          | 1       |
| Japan            | 0.2995        | 4       | 0.0070          | 34      | 0.0900          | 13      |
| Luxembourg       | 0.4635        | 2       | 1.0000          | 1       | 0.0700          | 5       |
| China            | 0.2237        | 6       | 0.0354          | 31      | 0.1500          | 32      |
| Brazil           | 0.1527        | 8       | 0.2558          | 9       | 0.1000          | 20      |
| United States    | 0.2238        | 5       | 0.0089          | 33      | 0.1300          | 29      |
| Australia        | 0.2109        | 7       | 0.2093          | 14      | 0.1200          | 27      |
| Germany          | 0.1483        | 10      | 0.0784          | 28      | 0.0900          | 13      |
| United Kingdom   | 0.1497        | 9       | 0.0397          | 30      | 0.0700          | 5       |
| France           | 0.1260        | 11      | 0.1958          | 15      | 0.1000          | 20      |
| Italy            | 0.1136        | 12      | 0.1666          | 21      | 0.0700          | 5       |
| Indonesia        | 0.1089        | 13      | 0.0995          | 26      | 0.0800          | 9       |
| Mexico           | 0.0951        | 14      | 0.1844          | 17      | 0.0900          | 13      |
| India            | 0.0826        | 15      | 0.0208          | 32      | 0.1100          | 24      |
| Thailand         | 0.0626        | 19      | 0.2272          | 13      | 0.1300          | 29      |
| Turkey           | 0.0648        | 18      | 0.1699          | 20      | 0.0700          | 5       |
| Morocco          | 0.0790        | 16      | 0.3541          | 4       | 0.0800          | 9       |
| Norway           | 0.0589        | 21      | 0.2543          | 11      | 0.0900          | 13      |
| Poland           | 0.0572        | 22      | 0.2304          | 12      | 0.1000          | 20      |
| Spain            | 0.0737        | 17      | 0.1841          | 18      | 0.0800          | 9       |
| Denmark          | 0.0411        | 26      | 0.2986          | 8       | 0.0600          | 3       |
| Ireland          | 0.0603        | 20      | 0.1077          | 25      | 0.0500          | 1       |
| Sweden           | 0.0484        | 24      | 0.2549          | 10      | 0.1100          | 24      |
| The Netherlands  | 0.0512        | 23      | 0.1471          | 23      | 0.0900          | 13      |
| Portugal         | 0.0451        | 25      | 0.3253          | 6       | 0.0800          | 9       |
| Czech Republic   | 0.0387        | 27      | 0.3508          | 5       | 0.1300          | 29      |
| Belgium          | 0.0343        | 29      | 0.1911          | 16      | 0.1200          | 27      |
| South Africa     | 0.0276        | 30      | 0.1778          | 19      | 0.2100          | 35      |
| Austria          | 0.0365        | 28      | 0.0428          | 29      | 0.0900          | 13      |
| Hungary          | 0.0191        | 32      | 0.3105          | 7       | 0.1100          | 24      |
| Greece           | 0.0266        | 31      | 0.0933          | 27      | 0.0900          | 13      |
| Finland          | 0.0168        | 33      | 0.1651          | 22      | 0.1600          | 33      |
| Slovak Republic  | 0.0108        | 34      | 0.1276          | 24      | 0.1000          | 20      |
| Estonia          | 0.0001        | 35      | 0.0001          | 35      | 0.1600          | 33      |
The theoretical contribution made by this paper is to develop the multidimensional model to comprehensively analyze a country’s energy consumption, economic benefits, and environmental impact brought by energy consumption. We also make the practical contribution of conducting empirical research to investigate the performance of energy consumption in 35 major countries from the International Energy Agency based on the new multidimensional structure model. Based on the results, some suggestions are put forward for the countries being evaluated. It is believed that both the proposed multidimensional and the empirical investigation results could be of great help for many countries to improve their consumption efficiency and sustainable development. Admittedly, there are still some limitations in this paper. For example, the research objects for empirical analysis are in a small scope, which may lead to the inaccuracy of the result. Secondly, the selection of indicators also requires more objective criteria to judge the rationality. The questions raised above will be the direction of our future research. Nevertheless, this paper has certain reference values for government departments of various countries in energy consumption assessment and policy formulation.

APPENDIX
See Tables 9 and 10.

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