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Energy Efficiency Measurement: A VO TFEE Approach and Its Application

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Abstract: Energy efficiency is crucial to the 2030 UN Sustainable Development Goals (SDGs), but its widely measured indicator, energy intensity, is still insufficient. For this reason, in 2006, total factor energy efficiency (TFEE) was proposed with capital, labor, and energy as inputs and GDP as the desirable output. The later TFEE approach further incorporated pollution as the undesirable output. However, it is problematic to regard GDP (the total value of final products) as the desirable output, because GDP does not include the intermediate consumption, which accounts for a large part of the production activities and may even be larger than the value of GDP. GDP is more suitable for measuring distribution, while VO (value of output) is more appropriate for sustainable production analysis. Therefore, we propose a VO TFEE approach that takes VO as the desirable output instead and correspondingly incorporates the other intermediate materials and services except energy into inputs. Finally, the empirical analysis of the textile industry of EU member states during 2011–2017 indicates that the VO TFEE approach is more stable and convergent in measuring energy efficiency, and is more suitable for helping policymakers achieve the SDGs of energy saving, emissions reduction, and sustainable economic development.

Keywords: VO TFEE model; value of output; undesirable output; System of National Accounts; Sustainable Development Goals

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1. Introduction

In order to promote sustainable economic development and environmental protection, energy efficiency has been widely acknowledged as a top priority for international organizations, governments, firms, and even households across the world. The International Energy Agency (IEA) [1] proposes that energy efficiency should be taken as the first fuel rather than a hidden fuel, and regards it as "a key tool for boosting economic and social development" [2]. Moreover, all UN member states adopt the 2030 Agenda for Sustainable Development with 17 Sustainable Development Goals (SDGs), in which SDG 7 sets a target of doubling "the global rate of improvement in energy efficiency by 2030" and SDG 12 requires decoupling environmental degradation from economic growth to achieve sustainable consumption and production [3]. Improving energy efficiency is one of the priorities for achieving these goals. It is important to understand energy consumption in the process of production and identify issues for sustainable economic development. The U.S. Energy Information Administration (EIA) [4] also stresses the importance of energy efficiency and the need to define and measure it better. Therefore, it is essential to develop an appropriate indicator and measurement for energy efficiency.

There are two main measurements for measuring energy efficiency. One is single factor energy efficiency (SFEE), which is usually represented by energy intensity with a single input and a single output, and the other is total factor energy efficiency (TFEE), which usually uses Data Envelopment Analysis (DEA) as one of its typical methods with multiple inputs and multiple outputs. Most researchers primarily focus on the methodological

development of DEA models, spend less time on the actual process, and pay little attention to ensuring that the input and output indicators they select properly reflect the process under study [5]. After reviewing and discussing the deficiencies of production sets in these two energy efficiency measurements, we propose a new VO TFEE approach from the perspective of advanced production economics and System of National Accounts (SNA). To demonstrate how the VO TFEE approach proposed in this paper performs in measuring energy efficiency, we compare the results of this approach with those of the three existing main energy efficiency approaches, utilizing data collected from the textile industry in EU member states.

This paper is organized as follows. Section 2 is a literature review on the origin and development of energy efficiency with discussion of the deficiencies of existing measurements. Section 3 presents the VO TFEE approach and describes the methodology this paper uses in calculating TFEE. Section 4 reports the empirical results of different energy efficiency measurements. Section 5 concludes this paper. In view of the large number of abbreviations in this paper, a list of nomenclature is presented in Appendix A as Table A1.

2. Literature Review

From an economic perspective, efficiency is defined as making full use of limited and scarce resources to meet people's needs [6,7]. According to production economics [8,9], a firm's technologically feasible production set $Y \subset R^n$ is made up of all production vectors that constitute feasible plans $(y_1, \ldots, y_n)$ for the firm, observing the convention of $y_j < 0$ if commodity j is an input and $y_j > 0$ if it serves as an output. In the production process, when there is no more Pareto improvement in energy consumption, the energy economic system is operating on its production possibility frontier or its optimal state. In other words, to measure energy efficiency is actually to evaluate whether there is energy wastage in the production process by comparing the minimum or optimal energy input with its actual energy input while output is unchanged [10]. Given the amount of output, the calculation of energy efficiency can be written as

$$energy\ efficiency = minimum\ energy\ input / actual\ energy\ input \quad (1)$$

This is also consistent with the expression of "using less energy to provide the same service" by Lawrence Berkeley National Laboratory of US [11].

2.1. Energy Intensity

As for the calculation and application of energy efficiency, Patterson [12] is the first to elaborate on energy efficiency and identifies the GDP-energy ratio as the indicator of energy efficiency from an economic perspective, which is the inverse of energy intensity, i.e., the units of energy consumption per unit of GDP. Energy intensity, regarded as a typical SFEE due to its single factor input, has been widely used in measuring energy efficiency and taken as a strictly binding target among many countries and international organizations. The larger the energy intensity, the lower the energy efficiency. A recent study by IEA [13] shows that although current plans and policies are expected to reduce energy intensity by nearly 50%, the resulting energy intensity value is still below the new target of an annual decrease of 2.7% set by SDG 7. Energy intensity is critical to energy policy formulation and implementation among many countries and international organizations. However, it remains questionable whether energy intensity is a proper indicator to measure energy efficiency.

Firstly, SFEE is not a measure of energy efficiency in an economy. The calculation of energy intensity is inconsistent with the original definition of energy efficiency as Expression (1) because it has no comparison between optimal and actual energy consumption, and it is not related to technological progress. Energy intensity does not conform to the nature of energy efficiency measurement because there is no meaning without comparison in economics. Therefore, it is difficult for energy intensity to measure whether the production

process is efficient or not. Energy intensity is not a well-performing measurement or proxy for energy efficiency [14].

Secondly, energy intensity may be misleading in terms of measuring the performance of overall productivity. For example, energy intensities of primary, secondary, and tertiary industries of China were 13.4, 100.6, and 19.5 tons of standard coal per million yuan respectively in 2016, but we cannot say that the energy intensity of the primary industry is better than that of the secondary industry because this is not comparable among different industries. Energy efficiency cannot be properly measured by energy intensity in an absolute sense. Proskuryakova and Kovalev [15] also argue that what energy intensity reflects is energy consumption, not energy efficiency.

Thirdly, energy intensity may misstate both the level and growth rate of productivity for lack of total factor information. It only focuses on the goal of realizing energy savings and economic growth. It does not consider labor, capital, and other factors in production, nor pollution emissions caused by energy consumption. Energy intensity may decrease solely due to its substitution by labor rather than to any underlying advancement in technological energy efficiency [16]. EIA [4] also states that energy intensity might not reflect energy efficiency accurately because there are many other factors that affect energy intensity. Moreover, it is also misleading for managers and policy makers as it ignores the possibility of achieving its goal, such as the organization and structure of the economy [17], as well as negative externalities, such as environmental pollution. It is well known that reducing energy consumption can lead to a low-carbon society, but energy intensity cannot analyze this relationship systematically and directly, thereby undermining the integrity of economic analysis.

What is more, energy intensity does not conform to any actual production process. A firm cannot produce any output with energy only. In other words, it is not feasible to form a production set with only GDP and energy consumption without any other inputs. SFEE cannot measure potential energy efficiency [18].

Finally, energy intensity does not reveal the cost and revenue of production processes. For example, energy intensity would be substantially reduced if more manual labor was employed in freight transport instead of vehicles. However, this is neither economical nor practical in the real world. Actually, energy intensity is often taken as a measure of an economy's dependence on energy, which indicates the decoupling of energy consumption from economic growth [19].

2.2. The Existing TFEE

In order to overcome the deficiencies of SFEE, Hu and Wang [20] put forward TFEE by taking into account the contribution of capital, labor, and energy consumption to GDP. They calculate TFEE as the ratio of target energy input to its actual energy input with DEA. The difference between the actual energy input and the target energy input is the total adjustment (inefficiency) of energy input. In DEA, the total energy adjustment refers to radial adjustment at first, conforming to Farrell efficiency [21], and later incorporates slack reduction, making TFEE further satisfy Pareto efficiency [22]. Hu and Wang [20] calculate the total energy adjustment including both radial adjustments and slack reduction, which is defined later as the energy saving target [23]. Total energy reduction can be achieved by improving the level of technology, thereby resulting in production optimization. The more the total adjustment is, the less the optimal energy input will be, and the smaller the value of TFEE is as a result. TFEE can achieve energy savings and output growth with technical efficiency progress.

As a compound indicator of energy efficiency measurement, TFEE has enjoyed widespread application, with capital, labor, and energy as the common inputs and GDP as the output. The production set can be expressed as (Y_1, K, L, E), where Y_1, K, L and E stand for the desirable output usually measured by GDP, capital, labor, and energy consumption, respectively.

With pollution becoming one of the most concerns in recent years, energy saving and pollution reduction have become essential parts of energy research. One of the main contributions of existing TFEE studies is that environment pollution, such as CO_2 emissions, is incorporated into output as an undesirable component, thereby improving the production set to (Y_1, Y_2, K, L, E) where Y_2 denotes the undesirable output. This production set helps to analyze energy saving and pollution reduction performance and realize sustainable production.

So far, these two production sets with and without pollution are the two main forms of TFEE analysis. Table 1 provides a theoretical comparison of energy intensity and TFEE, and Table A2 (see Appendix A) is a summary of some existing TFEE indicator selections.

Table 1. Summary of energy intensity and total factor energy efficiency (TFEE).

	Energy Intensity	**TFEE**
Definition	Energy consumption per unit of output	Ratio of target energy input to the actual energy input
Expression	$\frac{Energy}{GDP}$	$\frac{optimal\ energy\ input}{acutal\ energy\ input}$
Value	$[0, +\infty)$	$[0, 1]$
Production set	$(GDP, Energy)$	(Y_1, K, L, E) or (Y_1, Y_2, K, L, E)

Note: Energy intensity is taken as the representative of SFEE.

As a measurement of energy efficiency, however, TFEE is still not perfect, although better compared to energy intensity as a measurement.

Firstly, the undesirable output is neglected in the production set (Y_1, K, L, E), which is contradictory to the fact that fossil energy consumption will inevitably lead to environmental pollution. When measuring energy efficiency, pollution should always be taken into consideration in order to achieve sustainable development.

Secondly, total energy consumption, including both production and household consumption, is often used to measure the energy efficiency of regions and nations in TFEE studies. Actually, only energy consumed in production can be taken as an input in the production set and used to measure energy efficiency. Household energy consumption should not be included in measuring TFEE.

Finally, although the production set (Y_1, Y_2, K, L, E) further perfects the production set (Y_1, K, L, E), it is still insufficient because in the production set (Y_1, Y_2, K, L, E), Y_1 (GDP) only measures the total value of final products or the gross value added of all products in the economy over a period of time. GDP excludes the value of intermediate products. As a kind of intermediate input consumed during the production process, the value of energy consumption is not included in GDP, so the inputs are not consistent with the output in this production set. It is important to choose a proper desirable output indicator to match the inputs.

Given the discussion above, both energy intensity and the production sets of existing TFEE have some deficiencies in measuring energy efficiency. Energy intensity is not in line with the definition of energy efficiency and not considering the substitution effect between factors. Furthermore, the selection of input and output variables in existing TFEE studies does not conform to the requirements of reflecting the actual production process [5]. Therefore, from the perspective of economics and SNA, this paper proposes a new VO TFEE approach in Section 3, which perfects the selection of inputs and outputs by taking pollution into account and making the inputs of the production set consistent with its outputs.

3. Materials and Methods

The new VO TFEE approach is developed in this section by using the original definition of TFEE to calculate energy efficiency and a DEA-based model, slacks-based measure (SBM), to find the optimal energy input. A new variable set with all inputs and outputs

are proposed and identified based on SNA in this paper. Therefore, the VO TFEE is in line with not only the definition of energy efficiency, but also the actual production process.

3.1. SBM with Undesirable Output

DEA attempts to gauge relative efficiency by observing radial adjustment. The CCR model proposed by Charnes, Cooper, and Rhodes [24] is the first and remains state of the art for efficiency evaluation. However, the radial measure may overestimate efficiency when there are some slacks [25] and can lead to the absence of information about neglected efficiency [26]. Slacks are a common feature in the basic CCR model. In order to have more discriminatory power in measuring efficiency and a suitable treatment of slacks, Tone [27] proposes slacks-based measure (SBM) to overcome the problem associated with the radial approach by finding the respective maximum slacks of different inputs and outputs in the production. In the presence of pollution, Tone [28] further puts forward SBM with undesirable output as follows.

Suppose there are n decision making units (DMUs), each DMU_j $(j = 1, 2, \ldots, n)$ consumes m inputs $x_j = (x_{1j}, x_{2j}, \ldots, x_{mj})'$ (a transpose vector) and produces s_1 desirable outputs $y_j^g = \left(y_{1j}^g, y_{2j}^g, \ldots, y_{s_1 j}^g\right)'$ and s_2 undesirable outputs $y_j^b = \left(y_{1j}^b, y_{2j}^b, \ldots, y_{s_2 j}^b\right)'$, then the production technology set can be specified as $T = \left\{\left(x, y^g, y^b\right) \in R : x \text{ can produce } \left(y^g, y^b\right)\right\}$, where T is assumed to satisfy the standard axioms of the production theory and properties and R includes all the feasible input and output vectors. The production possibility set is then defined as $P = \left\{\left(x, y^g, y^b\right) \middle| x \geq X\lambda, y^g \leq Y^g\,\lambda, y^b \geq Y^b\,\lambda, \lambda \geq 0\right\}$, where $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_n)$ is an $n \times 1$ nonnegative vector, $X = [x_1, x_2, \ldots, x_n]$ is an $m \times n$ matrix of input vectors, $Y^g = \left[y_1^g, y_2^g, \ldots, y_n^g\right]$ is an $s_1 \times n$ matrix of desirable output vectors, and $Y^b = \left[y_1^b, y_2^b, \ldots, y_n^b\right]$ is an $s_2 \times n$ matrix of undesirable output vectors. In accordance with these definitions, the SBM model with all inputs and outputs for measuring efficiency of a certain $DMU(x_0, y_0)$ under the constant returns to scale (CRS) is the fractional program as follows:

$$\begin{gathered} \min\rho^* = \frac{1 - \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{i0}}}{1 + \frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{r0}^g} + \sum_{r=1}^{s_2}\frac{s_r^b}{y_{r0}^b}\right)} \\ s.t.\ x_0 = X\lambda + s^- \\ y_0^g = Y^g\lambda - s^g \\ y_0^b = Y^b\lambda + s^b \\ \lambda \geq 0,\ s^- \geq 0,\ s^g \geq 0,\ s^b \geq 0 \end{gathered} \tag{2}$$

The vectors $s^- \in R^m$ and $s^b \in R^{s_2}$ are the potential reduction of inputs and undesirable output, and $s^g \in R^{s_1}$ is the potential expansion of desirable output. They are all slacks. The objective value of function (3) satisfies $0 < \rho^* \leq 1$. The closer ρ^* value is to 1, the closer the DMU is to the production frontier, that is, the higher the relative energy efficiency is. When $\rho^* = 1$, the DMU is completely efficient. With the definition of TFEE, we can calculate the TFEE as:

$$TFEE = \frac{actual\ energy\ input - s_E^-}{actual\ energy\ input} \tag{3}$$

As a non-radial DEA model that uses slacks to determine efficiency scores, SBM outperforms the traditional CCR model with CRS settings, and is even recommended as the standard DEA model [29].

3.2. The VO TFEE Approach to Measuring Energy Efficiency

Apart from the definition of TFEE and the SBM with undesirable output, it is important to select proper input and output variables to ensure the accuracy and reliability of energy efficiency measuring results. The input and output variables must be consistent with and fully reflect the production process to the greatest extent. Given that most existing TFEE

studies use GDP (value added) as the desirable output, which does not include the value of energy input, and neglect the importance of intermediate inputs, the VO TFEE is proposed on the basis of SNA in this study.

SNA, issued by the United Nations and adopted by more than 150 countries, is the core of the macroeconomic system [30]. SNA aims to fully reflect the results of the production activities of all society and the process of its distribution and use. In order to calculate TFEE correctly, we find the value of output (VO) is a more suitable proxy for desirable output based on SNA.

According to SNA, GDP is the added value created by the production process. It is the total measure of partial production activities (only final products) or the partial measure (value added, not value of output) of total production activities. Different from GDP, however, VO is the total output measure of total production activities. It refers to the value of all goods and services produced in a certain period of time and reflects the total scale and total level of production activities, which cannot be replaced by any other indicator. In this way, GDP is more suitable as an indicator of distribution, while VO is more appropriate as the output measure of all production activities. The relationship between VO and GDP is as follows:

$$VO - intermediate\ consumption = GVA \tag{4}$$

VO includes the value of intermediate consumption and is a much broader measure of the economy than GVA (gross value added), or roughly GDP. According to SNA 2008 [30], intermediate consumption consists of both the value of goods and services consumed in the production process as inputs, excluding fixed assets. Some intermediate inputs may be transformed and incorporated into the outputs, while other intermediate inputs may be completely used up, such as energy.

The value of intermediate consumption accounts for a large proportion of VO. In 2016, VO and GDP of the United States were $32.4 trillion and $18.7 trillion, respectively, as estimated by the U.S. Bureau of Economic Analysis, which means that GDP accounted for 57.5% of VO and intermediate consumption accounted for 42.5%. As for the EU, Figure 1 shows the composition of the total output of various EU countries based on the Eurostat [31]. In 2017, the proportion of intermediate consumption in most EU member states accounted for almost 50% of output and a few substantially exceeded 50%, such as Luxembourg and Malta. Intermediate consumption plays an important role in the process of production. Take Ireland as an example of EU members; according to CSO, Ireland [32], as shown in Figure 2, in 2017, Irish intermediate consumption accounted for over half of the output in all sectors, except for services. The proportion of intermediate consumption to total output even exceeds two-thirds in the agriculture, forestry and fishery, and construction sectors of the Irish economy.

As a developing country, China's GDP was almost 32.9% of its VO in 2015. The remaining 67.1% output from production activities is not included in GDP and this proportion is even larger in other developing countries. As for companies, the added value of U.S. Steel was only 18.05% of its VO in 2018, indicating that the neglected output proportion in the added value of energy-intensive companies is even greater. Therefore, for value added, GDP underestimates the scale and level of production activities by more than 50% and is not a proper proxy of total output. There is an urgent need for a better indicator as a replacement for prov GDP in order to effectively measure energy efficiency.

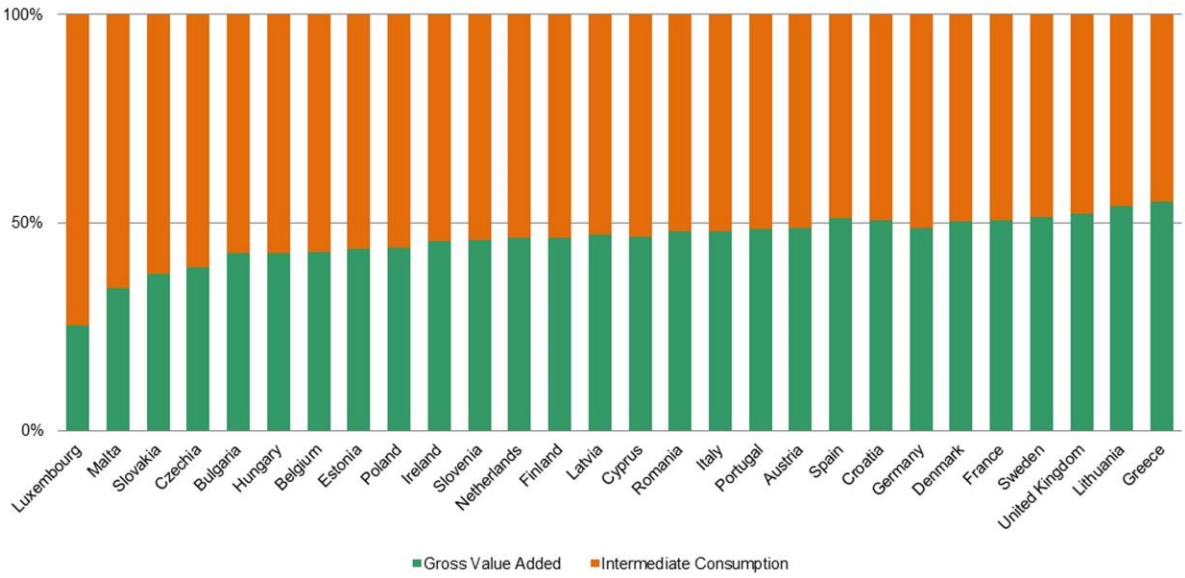

Figure 1. The percentage of gross value added and intermediate consumption in the total output value of EU member states in 2017. Source: Eurostat.

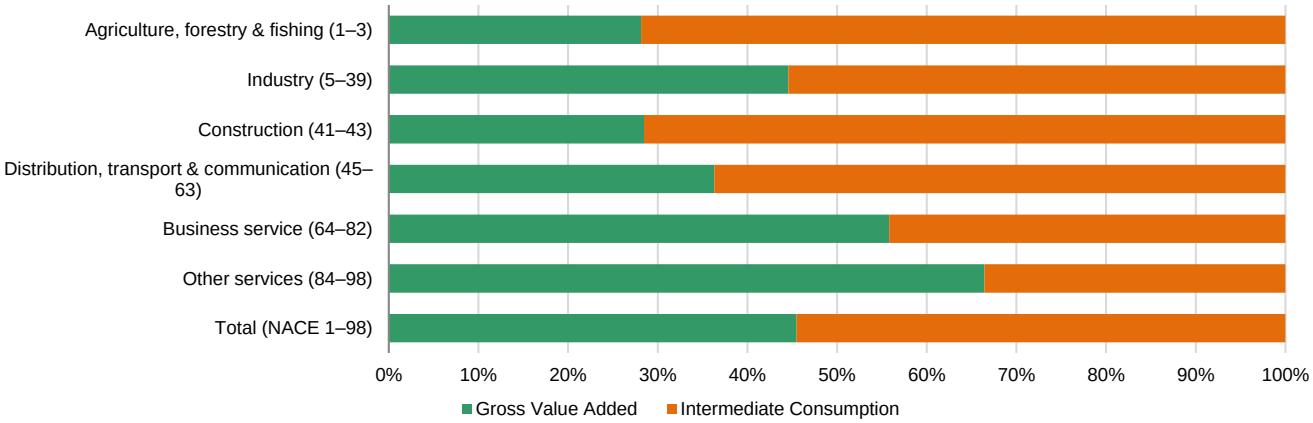

Figure 2. The percentage of gross value added and intermediate consumption in the total output value of Ireland in 2017. Source: CSO, Ireland.

Some scholars have recently adopted VO rather than GDP as the desirable output, but their understanding of the production set is still insufficient. Li and Li [33] consider the matching of inputs and outputs in production by taking capital, labor, energy consumption, and other intermediate materials as the inputs, and VO and industrial wastes as outputs to measure the industrial TFEE in 30 Chinese provinces. However, intermediate services, such as purchasing, sales, marketing, accounting, data processing, transportation, storage, maintenance, security, etc., are also quite important in the production process. When taking VO as the desirable output, its corresponding inputs should include capital, labor, and energy consumption, together with other intermediate materials and services, as VO is the total value produced in industrial production activities during a certain period of time. Here, we denote VO as Y_3.

By replacing Y_1 with Y_3 as the desirable output and incorporating the other intermediate materials M and services S into inputs, this paper proposes a VO TFEE with feasible production set $(Y_3, Y_2, K, L, E, M, S)$ in accordance with SNA and makes the production set closer to the reality of the production process in an economy. Compared with the two main production sets of TFEE in previous studies, the new VO TFEE production set is a superior and more comprehensive approach in measuring energy efficiency. Here we denote the

production sets (Y_1, K, L, E), (Y_1, Y_2, K, L, E) and $(Y_3, Y_2, K, L, E, M, S)$ as Model 1, Model 2, and Model 3, respectively, and summarize them in Table 2.

Table 2. The production sets of three TFEE models.

	Output			Input				
	Y_1 (GDP)	Y_2 (Undesirable Output)	Y_3 (VO)	K	L	E	M	S
Model 1	√	×	×	√	√	√	×	×
Model 2	√	√	×	√	√	√	×	×
Model 3	√	√	√	√	√	√	√	√

Note: As Y_3 consists of both intermediate consumption and GVA as Equation (2) expressed, GDP, as a part of VO, is also included in Model 3.

4. Empirical Results and Comparisons

With the VO TFEE indicators and input-oriented SBM with undesirable output, this section conducts an empirical analysis, for the period 2011 to 2017, on energy efficiency measurements for the textile industry in EU member states by examining and comparing empirical results for energy intensity with the three TFEE models.

4.1. Data

The EU textile industry includes the manufacture of textiles, wearing apparel, leather, and related products. For consistency, all input and output data used in this study are extracted from the database corresponding to Eurostat, and the depreciation rate of the textile industry is set as 0.109 according to the EU KLEMS database, which is the depreciation rate of machinery and equipment in the textile industry. The dataset covers 19 EU countries for the period 2011 to 2017 due to the availability of the data source. All monetary variables are converted at constant prices in 2011.

Capital stock in the base year is obtained by dividing the consumption of fixed assets by the depreciation rate, and the subsequent capital stock is calculated with the gross investment in tangible goods using the perpetual inventory method (PIM) proposed by Goldsmith [34]. All the capital stock values are deflated by the price index of fixed capital consumption. Labor is the numbers employed in textile enterprises. Energy consumption refers to final energy consumption in the textile industry. Intermediate materials and services, excluding energy, are calculated by subtracting energy value from intermediate consumption. The three output variables VO, VA, and greenhouse gases are obtained directly from Eurostat. Other intermediate materials and services, excluding energy, VA and VO, are deflated by a GDP deflator.

Table 3 provides three interesting concerns. Firstly, all the input and output data have more or less decreased during the sample period. Secondly, in terms of VA and VO, the value-added rate (VA/VO) of the largest-scale textile industry increases from 0.2750 to 0.3020, which is always less than one-third, while the rate of the smallest-scale textile industry ranges from 0.3686 to 0.4276, which is always larger than one-third. The economic benefits of some large-scale textile industries in the EU are not as good as those of some small-scale textile industries. Finally, in terms of the mean value, the value-added rate of the textile industry is around 0.35, much lower than the 0.5 of total industries shown in Figure 1. Compared with other industries, the EU textile industry is a lower-end industry in the value chain, faces greater competitive pressure and needs to be greatly improved.

Table 3. The descriptive statistics of all inputs and outputs of all EU countries each year.

Variable	Year	Mean	Std. Dev.	Maximum	Minimum
Capital stock (million euro in 2011 constant price)	2011	3453.4781	7423.7787	32,491.2794	28.4215
	2012	3223.2817	6833.8923	29,924.6587	25.6215
	2013	3064.7756	6340.6949	27,755.3726	22.4527
	2014	2912.6722	5856.4242	25,625.1090	20.3401
	2015	2727.2914	5327.3256	23,221.0915	17.1161
	2016	2664.8664	5077.9500	22,101.6250	16.3665
	2017	2582.6287	4865.3463	21,173.1128	15.2973
Labor (number)	2011	10,330.9474	14,571.6624	64,464	350
	2012	10,100.6316	14,253.3114	63,359	323
	2013	9883.4211	13,694.4961	61,062	319
	2014	9851.2632	13,362.3141	59,237	300
	2015	9892.3684	13,112.3126	57,966	301
	2016	10,029.2105	13,026.2877	57,333	297
	2017	10,061.6842	13,173.5549	57,946	292
Energy consumption (gigawatt-hour)	2011	2563.9073	3639.3322	13,854.6110	7
	2012	2442.7075	3616.6730	13,966.5560	6
	2013	2359.7405	3470.9314	13,568.2780	6
	2014	2295.3536	3372.2446	13,230.2500	5
	2015	2206.1046	3213.9547	12,868.2220	5
	2016	2198.7072	3167.9340	12,776.4170	5
	2017	2197.9739	3288.8097	13,528.4290	5.1990
Intermediate materials and services except energy (million euro in 2011 constant price)	2011	6157.8244	14,090.9352	61,712.4470	25.2765
	2012	5707.8845	13,025.8529	57,306.2758	22.4154
	2013	5590.2348	12,726.0652	55,955.4625	17.2142
	2014	5712.8812	12,765.0353	56,061.5849	17.5662
	2015	5712.5177	12,496.6908	54,955.9977	20.8218
	2016	5552.3837	12,029.4338	52,830.7348	21.7496
	2017	5638.1871	12,210.8510	53,656.9266	23.0158
Value added (million euro in 2011 constant price)	2011	3219.4526	5638.6789	24,015.5000	19.8000
	2012	3060.2258	5299.9012	22,453.9019	14.9453
	2013	3045.5897	5320.9381	22,560.5364	11.3442
	2014	3112.3434	5406.1415	22,873.9963	11.6339
	2015	3135.9951	5439.6331	22,974.3233	12.4878
	2016	3171.4093	5484.7226	23,105.5088	13.5916
	2017	3213.1149	5617.6459	23,674.6272	15.2851
Value of output (million euro in 2011 constant price)	2011	9633.5263	20,004.3888	87,314.4000	46.3000
	2012	9023.7522	18,600.7112	81,403.7046	38.6414
	2013	8874.5489	18,280.0911	79,999.6538	29.7538
	2014	9052.4330	18,393.4531	80,314.8931	30.0458
	2015	9046.5775	18,116.4941	79,090.8805	33.8808
	2016	8904.7753	17,652.7959	76,952.1779	35.8324
	2017	9017.9260	17,972.7684	78,386.3512	38.9719
Greenhouse gases (tonnes in CO_2 equivalent)	2011	406,554.7321	667,948.9286	2,458,099.8800	1611.5900
	2012	371,783.6905	579,871.4227	2,022,994.3700	1432.0400
	2013	400,717.0995	671,627.1423	2,558,221.7100	1271.9300
	2014	377,705.1632	621,028.9253	2,307,487.3500	1157.7900
	2015	392,675.9005	703,096.2549	2,871,121.3600	1254.1300
	2016	383,712.2342	658,729.9127	2,644,937.0000	1272.9000
	2017	370,583.2774	627,648.5870	2,509,165.5200	1408.1200

Note: 19 EU countries included in this study are Bulgaria, Czechia, Germany, Estonia, Ireland, Greece, Spain, Italy, Cyprus, Latvia, Lithuania, Hungary, Netherlands, Austria, Poland, Portugal, Romania, Slovakia, and United Kingdom.

4.2. Results and Comparisons

This section reports on, and compares, the empirical results of the three existing energy efficiency measurements (energy intensity, Model 1 and Model 2) and the VO TFEE approach (Model 3) proposed in this paper, which measures SBM efficiency according to the fractional program (3) and then measures TFEE according to Equation (1). Figure 3 demonstrates the results and trends of average energy efficiency in the textile industry in 19 EU countries during the period 2011–2017. Figure 3a shows the annual average energy efficiency results of the four measures. Figure 3b displays the annual average TFEE trend with three-year SBM-window analysis.

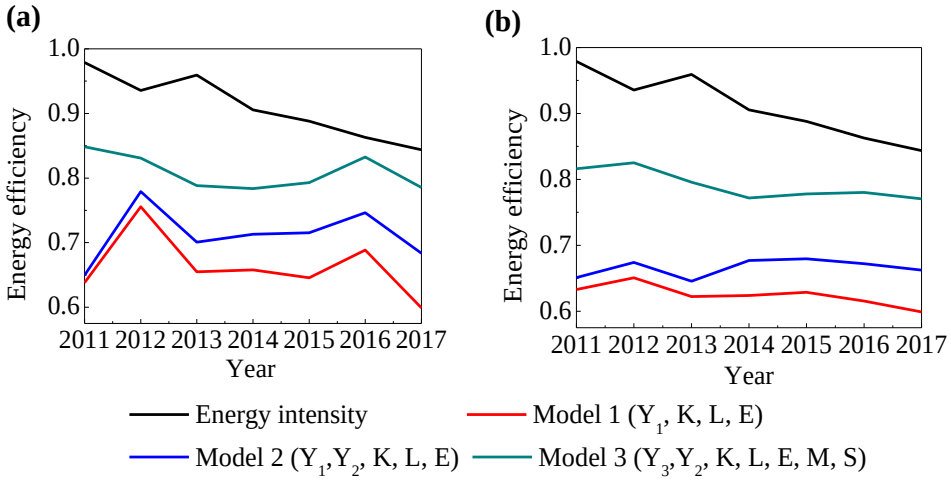

Figure 3. Average energy efficiency results and trends in textile industry of EU, 2011–2017. (**a**) The annual average energy efficiency results of the four measures; (**b**) the annual average TFEE trend with three-year slacks-based measure (SBM)-window analysis.

According to Figure 3, there are two observations. On the one hand, the energy efficiency values measured by energy intensity and TFEE are quite different. Among the four approaches, the results of Model 3 have the smallest variance illustrated in Figure 3a, which indicates that Model 3 is more stable and suitable for policy analysis, and in Figure 3b, Model 3 has the most convergent trend since 2013, which reflects the improvement in energy efficiency and learning effects of energy saving and emission reduction in these EU member states.

On the other hand, the TFEE value of Model 2 has similar fluctuations and trends as Model 1, but its value is larger than that of Model 1, which indicates that under the heavy pressure of environmental pollution, the EU textile industry has made certain achievements in environmental governance over the period. In comparison with these two models, Model 3 has the largest TFEE value and fluctuates differently from Models 1 and Model 2. When taking intermediate consumption into account, energy efficiency scores perform better and fluctuate less.

As for the energy efficiency results among countries, it is clearly shown in Table A3 in Appendix B that the ranking of energy intensity is different from that of Model 3 for most countries. For example, Germany and the United Kingdom both rank 1st in Model 3, while in terms of energy intensity Germany ranks 9th and the United Kingdom ranks 17th. According to labor productivity calculated as the ratio of VA to labor in Table A4 (see Appendix B), we can see that the average labor productivity for the German textile industry is 0.8927, ranking first among 19 EU countries, and for the British textile industry it is 0.7321, ranking it second. Therefore, in view of the fact that the level of labor productivity mainly depends on various economic and technological factors in production, it can be considered that the textile industries in Germany and the United Kingdom are more developed, so their energy efficiency ranking should be among the best. The labor productivity ranking

of the textile industry in the remaining EU countries also illustrates this view. In terms of ranking energy efficiency values, Model 3 is more convincing than energy intensity.

Furthermore, taking two single countries, Figure 4 shows the energy efficiency results of Bulgaria and Hungary, respectively, from 2011 to 2017, where the TFEE values of Model 1 are almost the same as those of Model 2. Energy intensity in Bulgaria fluctuates and rises while in Hungary continues to rise substantially during the sample period. Considering technical progress and economic development, the value added in the textile industry should gradually increase and energy intensity should gradually decrease throughout the sample period. These confusing results in energy intensity might be due to the deficiency of the single factor energy efficiency measurement rather than poor performance in achieving energy saving goals set by the SDGs.

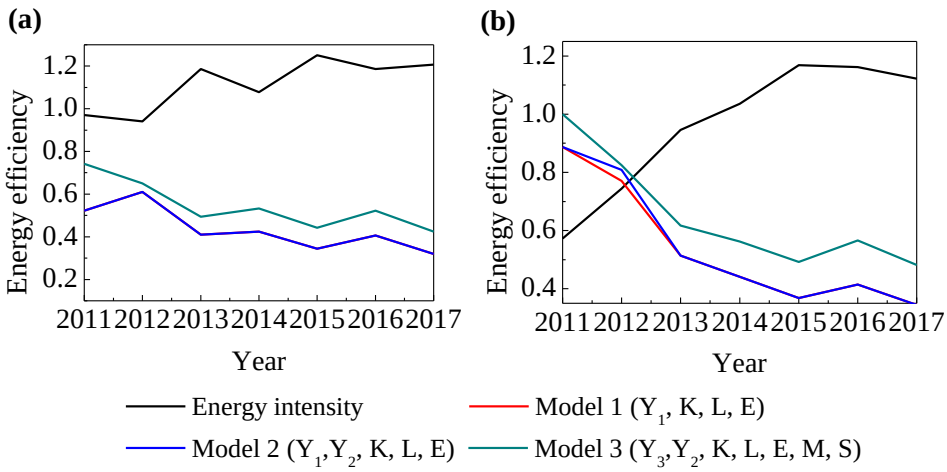

Figure 4. Energy efficiency results of textile industry in Bulgaria and Hungary, 2011–2017. (**a**) Energy efficiency results of textile industry in Bulgaria; (**b**) energy efficiency results of textile industry in Hungary.

Based on the discussion above, it can be concluded that energy intensity as a measurement for energy efficiency is also problematic in empirical estimation. In terms of reflecting the reality of energy efficiency, both the values and rankings measured by energy intensity are not as good as those of Model 3, which may mislead policy makers in decision making for national policy development and implementation because energy intensity is widely used in different countries. Filippini and Hunt [35] also state that energy intensity does not always reasonably indicate relative energy efficiency, which could result in a misleading picture for policy makers and misguided decisions in allocating funds. As a new measurement for energy efficiency, Model 3 provides better and more reliable energy efficiency results than energy intensity for policy making around sustainable development.

Figure 5 shows the empirical results of the textile industry in the United Kingdom, where the TFEE values of Model 1 are almost the same as those of Model 2. In Figure 5, the United Kingdom is always efficient in Model 3, but not in Model 1 and Model 2. In fact, in the actual production process, it is impossible for energy efficiency calculated by Model 1 and Model 2 to change from 0.29 to 1 within one year, because the improvement in efficiency is mainly driven by technical progress, which cannot be made so dramatically in just one year. The estimated results of energy efficiency from both Model 1 and Model 2 are also problematic in reflecting reality and are inconsistent with technical progress and practice. Therefore, Model 3 also performs better and more credibly than Model 1 and Model 2.

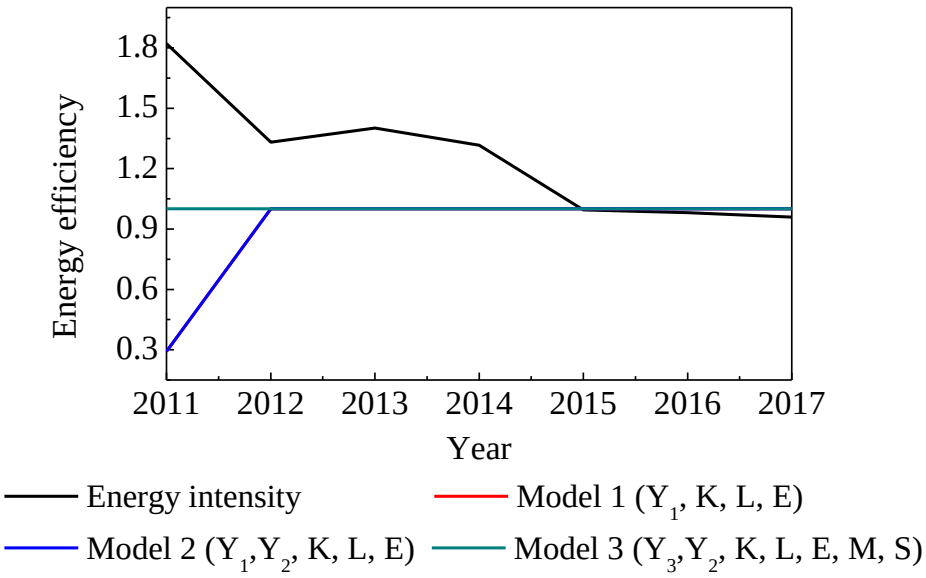

Figure 5. Energy efficiency results of textile industry in the United Kingdom, 2011–2017.

In summary, from both the perspectives of a theoretical framework and an empirical analysis, the new VO TFEE approach, i.e., Model 3, performs better and is more reliable as an energy efficiency indicator compared with the other three approaches in measuring energy efficiency.

5. Discussion and Conclusions

5.1. Discussion

Sustainable development has become the main trend of world development, and energy efficiency is one of the main standards to measure sustainable development. Improving energy efficiency is crucial for the whole world, especially when considering pollutant emissions. On this basis, many scholars have conducted a lot of research on energy efficiency measurement through energy intensity and TFEE, and evaluate the impact of various factors on energy efficiency. However, energy intensity and the existing two frequently used TFEE approaches have many deficiencies, which do not conform to the foundation of production economics and the practice of economic theory. Therefore, they are insufficient to investigate practical problems and are not conductive to formulating sustainable development policies.

In view of the shortcomings of the three main approaches, this paper proposes a VO TFEE approach (Model 3) for the measurement of energy efficiency, which takes VO instead of GDP as the desirable output and correspondingly incorporates capital, labor, energy, and the other intermediate materials and services except energy into inputs, thereby making the production possibility set include all inputs and outputs in conformity with production economics and SNA. The research results show that Model 3, the VO TFEE, has the smallest variance and is a more stable and convergent approach in measuring energy efficiency compared with the existing approaches, i.e., energy intensity, Model 1 and Model 2 of TFEE, so it is most suitable to provide reference for policy making and analysis.

For VO TFEE, it is essential to have the price of energy. Based on the available data, future research can further analyze energy efficiency of different countries, regions, and cities, as well as its dynamic changes and influencing factors.

5.2. Conclusions

As a comprehensive indicator, energy efficiency includes the three policy objectives of energy saving, pollution reduction, and economic growth. As a traditional and widely used energy efficiency proxy, however, energy intensity only focuses on energy saving and economic growth without considering the feasibility of actual production practice

and the substitution between different production factors. The new VO TFEE approach (Model 3) with total factor analysis is more in line with the essence of energy efficiency and production economics as it can simultaneously achieve the policy goals of energy saving, pollution reduction, and sustainable economics. The empirical results indicate that the ranking of energy intensity in Germany and the United Kingdom are less accurate and less reliable compared with that of Model 3. Moreover, the continuous increase of energy intensity in Bulgaria and Hungary does not conform to the energy saving goals set by the SDGs, which may mislead policy makers in decision making and implementation of sustainable development at both industrial and national levels.

Among existing TFEE studies, Model 2 has been improved from Model 1 to incorporate undesirable output into the production possibilities set in the presence of pollution. However, the problem with Model 2 is that GDP is employed as the desirable output and does not include the value of intermediate consumption, which accounts for over half of the total output value of all production activities. In the VO TFEE approach (Model 3), we take VO instead of GDP as the desirable output and incorporate other intermediate consumption and services, excluding energy, into inputs as well in the measurement of energy efficiency. It has been proven by empirical results that Model 3 performs better and more reliably than both Model 1 and Model 2 in measuring energy efficiency of the textile industry in the EU.

According to the theoretical framework developed and the empirical evidence presented in this study, we conclude that the new VO TFEE approach, Model 3, is the best among the existing energy efficiency measurements. Energy intensity should not be regarded as the only binding target for policy making and implementation, and Model 3 should be introduced as a measurement of energy efficiency and put into practice. For policy makers, the VO TFEE approach includes the total input and output of all production activities as well as the optimal allocation efficiency, and its smaller fluctuations are more consistent with actual energy consumption. It can provide more information about sustainable production and help realize the SDGs of energy saving, pollution reduction, and sustainable economic development with the improvement of efficiency.

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Appendix A

Table A1. List of nomenclature.

IEA	International Energy Agency
EIA	Energy Information Administration
SDG	Sustainable Development Goal
SFEE	Single factor energy efficiency
TFEE	Total factor energy efficiency
SNA	System of National Accounts
DEA	Data Envelopment Analysis
SBM	Slacks-based Measure
$(y_1, \ldots, y_n)$	Production feasible plans
VO, Y_3	Value of output
GVA	Gross value added
DMU	Decision making unit
CRS	Constant returns to scale
PIM	Perpetual inventory method
K	Capital
L	Labor
E	Energy consumption
M	Intermediate materials
S	Intermediate services
VA, Y_1	Value added such as GDP
Y_2	Undesirable output
$(GDP, Energy)$	The production set of energy intensity
(Y_1, K, L, E)	Model 1, a production set of TFEE
(Y_1, Y_2, K, L, E)	Model 2, a production set of TFEE
$(Y_3, Y_2, K, L, E, M, S)$	Model 3, the production set of VO TFEE
$x_j = \left(x_{1j}, x_{2j}, \ldots, x_{mj}\right)'$	Input vectors
$y_j^g = \left(y_{1j}^g, y_{2j}^g, \ldots, y_{s_1 j}^g\right)'$	Desirable output vectors
$y_j^b = \left(y_{1j}^b, y_{2j}^b, \ldots, y_{s_2 j}^b\right)'$	Undesirable output vectors
$\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_n)$	Nonnegative vector
$X = [x_1, x_2, \ldots, x_n]$	$m \times n$ matrix of input vectors
$Y^g = \left[y_1^g, y_2^g, \ldots, y_n^g\right]$	$s_1 \times n$ matrix of desirable output vectors
$Y^b = \left[y_1^b, y_2^b, \ldots, y_n^b\right]$	$s_2 \times n$ matrix of undesirable output vectors
s^-	Potential reduction of inputs
s_E^-	Potential reduction of energy consumption
s^b	Potential reduction of undesirable output
s^g	Potential expansion of desirable output
ρ^*	The objective value of SBM

Table A2. Summary of some existing TFEE indicator selections.

	Input	Output
	TFEE without pollution	
Hu and Wang [20]	(1) Capital; (2) Labor; (3) Energy consumption; (4) Total sown area of farm crops	GDP
Hu and Kao [23]	(1) Capital; (2) Labor; (3) Energy consumption	GDP
Zhang et al. [36]	(1) Capital;(2) Labor;(3) Energy consumption	GDP
Song et al. [37]	(1) Capital formulation; (2) Labor; (3) Energy consumption	GDP
Lin and Du [38]	(1) Capital; (2) Labor; (3) Energy consumption	GDP
Bian et al. [39]	(1) Capital; (2) Labor; (3) Energy consumption	GDP
Borozan [40]	(1) Capital; (2) Employment; (3) Energy consumption	GDP
Jebali et al. [41]	(1) Capital; (2) Labor; (3) Energy consumption	GDP
Eguchi et al. [42]	(1) Capital; (2) Coal consumption	(1) Net electricity production; (2) sample size
Haider et al. [43]	(1) Capital; (2) Labor; (3) Energy consumption; (4) Material	output

Table A2. *Cont.*

	Input	Output
	TFEE with pollution	
Zhou and Ang [44]	(1) Capital; (2) Labor; (3) Coal consumption; (4) Oil consumption; (5) Gas consumption; (6) Other energy consumption	(1) GDP; (2) CO_2
Li and Hu [45]	(1) Capital; (2) Labor; (3) Energy consumption	(1) GDP; (2) SO_2; (3) CO_2
Wang et al. [46]	(1) Capital; (2) Labor; (3) Energy consumption	(1) GDP; (2) CO_2
Wang et al. [47]	(1) Capital stock; (2) Labor; (3) Energy consumption	(1) GDP; (2) CO_2
Apergis et al. [48]	(1) Capital; (2) Labor; (3) Energy consumption	(1) GDP; (2) CO_2
Wang and Feng [49]	(1) Capital; (2) Labor; (3) Energy consumption	(1) GDP; (2) COD; (3) SO_2; (4) Ammonia nitrogen
Wang et al. [50]	(1) Capital; (2) Labor; (3) Energy consumption	(1) GDP; (2) CO_2
Wang and Wei [51]	(1) Capital; (2) Labor; (3) Total energy (Coal, Oil, Natural gas, Electricity)	(1) GDP;(2) CO_2
Li and Lin [52]	(1) Capital; (2) Labor; (3) Energy consumption	(1) GDP; (2) CO_2; (3) SO_2; (4) COD
Zhou et al. [53]	(1) Capital; (2) Labor; (3) Energy consumption	(1) GDP; (2) CO_2
Zhou et al. [54]	(1) Capital stock; (2) Labor force; (3) Oil; (4) Natural gas; (5) Coal; (6) Non-fossil energy	(1) GDP; (2) CO_2
Sueyoshi et al. [55]	(1) Capital; (2) Labor; (3) Energy consumption	(1) Gross regional product; (2) SO_2; (3) soot (dust); (4) waste water; (5) COD; (6) Ammonia nitrogen
Yang et al. [56]	(1) Capital; (2) Labor; (3) Energy consumption (4) SO_2; (5) NO_X	GDP
Yang and Wei [57]	(1) Capital; (2) Labor; (3) Energy consumption	(1) GDP; (2) Waste water; (3) SO_2; (4) Smoke and dust
Özkara and Atak [58]	(1) Capital; (2) Employment; (3) Electricity	(1) Production value; (2) CO_2
Camioto et al. [59]	(1) Capital; (2) Labor; (3) Energy consumption	(1) GDP; (2) CO_2
Fathi et al. [60]	(1) Capital; (2) Labor; (3) Energy consumption	(1) GDP; (2) CO_2
Iftikhar et al. [61]	(1) Capital; (2) Labor; (3) Energy consumption	(1) GDP; (2) CO_2
Moon and Min [62]	(1) Capital; (2) Employee; (3) Energy consumption	(1) Cost of goods sold; (2) GHG
Moutinho et al. [63]	(1) Population density; (2) labor productivity; (3) municipal waste; (4) number of registered cars; (5) number of companies	(1) GDP/PM10; (2) GDP/CO_2
Mohsin et al. [64]	(1) Labor; (2) Energy consumption	(1) GDP; (2) CO_2 per capita

Appendix B

Table A3. Comparison of the four energy efficiency results and rankings of each country.

Country	Energy Intensity		TFEE with Model 1		TFEE with Model 2		TFEE with Model 3	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Bulgaria	1.1169	16	0.4337	17	0.4337	17	0.5439	17
Czechia	1.7034	19	0.2781	19	0.2781	19	0.3980	19
Germany	0.8435	9	1	1	1	1	1	1
Estonia	1.0272	13	0.4770	15	0.4770	15	0.6542	13
Ireland	1.3714	18	0.3512	18	0.3512	18	0.4801	18
Greece	0.8285	8	0.5809	11	0.9026	6	1	1
Spain	0.4811	2	0.9880	3	0.9880	5	1	1
Italy	0.5805	3	0.8162	6	0.8192	10	1	1
Cyprus	0.4032	1	0.9883	2	0.9883	4	1	1
Latvia	0.9509	10	0.5062	13	0.5062	13	0.5813	16
Lithuania	0.7652	7	0.6208	10	0.8270	9	0.9519	10
Hungary	0.9644	11	0.5341	12	0.5394	12	0.6492	14
Netherlands	1.0597	15	0.4475	16	0.4475	16	0.6556	12
Austria	1.0442	14	0.7967	8	1	1	1	1
Poland	0.5953	4	0.7980	7	0.8421	8	1	1
Portugal	0.9743	12	0.4901	14	0.4901	14	0.6081	15
Romania	0.6764	6	0.8385	5	1	1	1	1
Slovakia	0.6569	5	0.7492	9	0.7492	11	0.8470	11
United Kingdom	1.2579	17	0.8989	4	0.8989	7	1	1

Table A4. The average labor productivity of textile industry in EU countries.

Country	Labor Productivity	Rank	Country	Labor Productivity	Rank
Bulgaria	0.1270	12	Lithuania	0.1355	11
Czechia	0.0594	18	Hungary	0.0928	15
Germany	0.8927	1	Netherlands	0.2319	8
Estonia	0.1962	9	Austria	0.6727	3
Ireland	0.1759	10	Poland	0.1125	13
Greece	0.0737	16	Portugal	0.2386	7
Spain	0.4407	4	Romania	0.3982	5
Italy	0.3844	6	Slovakia	0.1091	14
Cyprus	0.0453	19	United Kingdom	0.7321	2
Latvia	0.0736	17			

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