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Energy Efficiency of the Baltic Sea Countries: An Application of Stochastic Frontier Analysis

Wen-Ling Hsiao [1], Jin-Li Hu [2,*], Chan Hsiao [1] and Ming-Chung Chang [3]

1 Department of Management Science, National Chiao Tung University, Hsinchu City 300, Taiwan; d13970@tier.org.tw (W.-L.H.); hsiaochan@gmail.com (C.H.)
2 Institute of Business and Management, National Chiao Tung University, Taipei City 100, Taiwan
3 Department of Marketing, Kainan University, Taoyuan City 33857, Taiwan; changmc@mail.knu.edu.tw
* Correspondence: jinlihu@mail.nctu.edu.tw; Tel.: +886-2-2381-2386 (ext. 57641)

Received: 11 December 2018; Accepted: 24 December 2018; Published: 29 December 2018

Abstract: Using the stochastic frontier analysis (SFA) model, this research measures total-factor energy efficiency (TFEE) and disaggregate input efficiency for 10 countries across the Baltic Sea from 2004 to 2014. Real capital, labor, energy use, and carbon dioxide (CO_2) are input variables, real gross domestic product (GDP) is the output variable, and renewable energy consumption and urban population are the environmental variables. The results provide not only the TFEE scores, in which statistical noise is considered, but also the determinants of inefficiency, which show the following. (i) Norway, Sweden, Finland, and Latvia perform better with respect to energy efficiency than other countries in the Baltic Sea Region. (ii) Interestingly, the average energy use efficiency scores from 2004 to 2014 in the 10 Baltic countries exhibit a gradual upward trend except for 2009. (iii) For the inefficiency estimates, higher renewable energy consumption and urban population correspond to higher TFEE scores.

Keywords: stochastic frontier analysis (SFA); total-factor energy efficiency (TFEE); distance functions; Baltic Sea region

1. Introduction

The importance of the green economy and sustainable development in policy discussions has grown immensely in recent years [1]. From the international discourse of institutions, such as the European Union (EU), Organization for Economic Co-operation and Development (OECD), and United Nations (UN), and particularly with regard to the 2008 financial crisis, these two concepts are seen as potential ways to come out of a severe economic slowdown [2,3]. Because energy is an indispensable resource for economic development, the formulation of effective energy usage could be a solution for solving the conflict between economic development, energy conservation, and environmental sustainability. Becoming a low carbon economy is a policy goal formulated by both the European Union and the Baltic Sea Region. Thus, a proper transition towards a low carbon economy is needed in order to tackle challenges, such as climate change mitigation and adaptation, energy supply, as well as the sustainable use of resources.

The Baltic Sea countries are intimately bound up with the European Union (EU) since eight out of 11 of them are also EU members. Hence, any EU policy affects the Baltic Sea region [4], which covers highly developed countries such as Denmark, Germany, and Sweden and the emerging economies of Poland, Estonia, Lithuania, and Latvia. Countries in the Baltic Sea region vary under their social, economic, and historic contexts, while some in this region suffer the problems of energy use and environmental pollution. Different socio-economic positions and political systems present different approaches when facing sustainable development challenges. Developed countries can thus be treated as a suitable reference model for less developed ones on their way towards sustainable development. Baležentis et al. [5] indicated that a developed country has high energy efficiency, while a developing country experiences relatively low energy efficiency. They also found that regardless of developed or developing countries, their energy efficiency always declines when their economy slows down. As previous research has suggested, when energy efficiency decreases, the economic condition of a country demonstrates a slowdown [5].

Improvement of energy efficiency is a worldwide issue and naturally is very relative to energy use. Geller et al. [6] noted that if countries in the Organization for Economic Cooperation and Development (OECD) do not adopt effective policies to improve energy efficiency, then these countries will consume about 40% more energy than that consumed in 1998. An alternative way to measure energy efficiency is provided by Hu and Wang [7] who coined the measurement formula, total-factor energy efficiency (TFEE), which was initially developed under the data development analysis (DEA) approach. TFEE is defined as the ratio of target energy input over actual energy input. Since the target energy input is no more than the actual energy input, the TFEE score is always in-between zero and one, fitting the usual domain of an efficiency measure [8].

Zhang et al. [9] adopted the TFEE approach to measure the energy efficiency of 23 developing countries from 1980 to 2005, concluding that the energy efficiency in almost half of them is trending downwards. Song et al. [10] also computed energy efficiency, but they used the Bootstrap-DEA approach. They took Brazil, Russia, India, and China (BRIC), i.e., four emerging countries with rapid economic growth, as the research objects and found low energy efficiency in some of them, but their energy efficiency reveals an upward direction.

The other approach to measure the TFEE scores is the stochastic frontier approach (SFA) [11]. After Farrell [12] defined overall productive efficiency as the product of technical and allocative efficiencies by considering cost-minimization in competitive input markets, many efficiency measurement approaches were subsequently released, such as Afriat [13], Richmond [14], and Schmidt [15], who utilized the deterministic frontier model, but under the corresponding maximum likelihood estimators. Ainger et al. [16] suggested the stochastic frontier production function to measure efficiency, while Cornwell et al. [17] and Battese and Coelli [18,19] proposed an advanced model that allows one to estimate the time-varying efficiency levels.

The efficiency computation by SFA also extends to energy efficiency measurement, such as Zhou et al. [9] who proposed the SFA approach with the Shephard energy distance function to measure energy efficiency. They used a single-output production frontier model that employs the reciprocal of energy use as the output and capital, labor, and CO_2 emissions as the inputs. The merit of this methodology enables us to parametrically estimate energy efficiency and take into account statistical noise on energy efficiency measurement. Honma and Hu [11] extended the cross-sectional model in Zhou et al. [20] to a panel data model for measuring Japan's regional energy efficiency. Their cross-sectional SFA model analyzed 47 regions across Japan during the period 1996–2008, expanding the panel data SFA model further by estimating TFEE. A similar work by Hu et al. [21] explored Taiwan's regional energy efficiency by using panel data stochastic frontier analysis. The metafrontier approach originally proposed by Battese et al. [22] has also been applied on energy efficiency research, such as Lin and Du [23] who expanded the work of Zhou et al. [20] to conduct a panel data SFA estimation on China's regional energy efficiency. In addition, Błażejczyk-Majka and Kala [24] found that the results of estimated efficiency via a different methodology would be different even with the same dataset. To avoid these problems, researchers should pay more attention to the assumptions of these models.

Despite a plethora of energy efficiency research utilizing the DEA approach, the model does not include environmental variables or cross-sectional data. In our SFA model, the energy efficiency measurement stands on the Shephard energy distance function, which assumes the production function of the decision making unit (DMU) is of the Cobb–Douglas form. This paper follows Zhou et al. [20] to apply the maximum likelihood estimator (MLE) to calculate the parameters and inefficiency component.

The empirical study covers Baltic Sea countries and their energy efficiency and energy technical efficiency over the estimated period of 10 years from 2004 to 2014. The observation subjects herein include 10 of the 11 countries in the Baltic Sea Region (excluding Iceland due to absent data): Germany, Denmark, Estonia, Finland, Iceland, Latvia, Lithuania, Norway, Poland, Russian Federation, and Sweden. The merit of this paper is using an improved frontier model to estimate energy technical inefficiency through the theorem of statistics. In addition, our approach has also been seldom applied on research covering the Baltic Sea Region.

The remainder of this study is organized as follows. Section 2 introduces the methodology applied herein. Section 3 includes the empirical analysis and results. Section 4 provides a discussion. The conclusion is in Section 5.

2. Methodology

This paper employs a stochastic production frontier model involving environmental variables to compute the total-factor energy efficiency (TFEE) developed by [11], who applied the single-equation, output-oriented SFA model to estimate TFEE. TFEE measures the efficiency level of the quantity of energy used in a country, which ranges from 0 to 1. Higher scores of TFEE indicate more advanced technical levels of energy inputs.

This current study adopts the stochastic frontier analysis (SFA) model to analyze the data. The main reason we use this model is that we aim to measure disaggregate input efficiency for 10 countries across the Baltic Sea from 2004 to 2014. The strength of this model is in estimating disaggregate input efficiency. For instance, Zhou et al. [20] employed a cross-sectional SFA model to analyze energy efficiency of 21 OECD countries in 2001, focusing on disaggregate input efficiency. By using the property of linear homogeneity in the distance function, Zhou et al. [20] transformed the distance function into an estimated stochastic frontier model to compute the efficiency scores of disaggregate inputs.

We also measure energy technical efficiency. Since technological advancement always very closely follows economic growth and evolves over time, this paper considers technological change over time. Following Honma and Hu [11], we assume that the stochastic frontier distance function is included in the Cobb–Douglas function as:

$$\ln D_E(K_{it}, L_{it}, E_{it}, C_{it}, Y_{it}) = \beta_0 + \beta_K \ln K_{it} + \beta_L \ln L_{it} + \beta_E \ln E_{it} + \beta_C \ln C_{it} + \beta_Y \ln Y_{it} + v_{it}, \tag{1}$$

where $D_E(\cdot)$ is the distance function, K_{it} stands for real capital, L_{it} is labor, E_{it} is energy input, C_{it} is CO_2 emissions, Y_{it} is real GDP, i represents the decision making unit, t represents the time, and v_{it} is a two-sided term representing the random error assumed to be independent and identically distributed (i.i.d.) $N(0, {\sigma_v}^2)$.

Since the Shephard distance function is linearly homogeneous, we can rearrange Equation (1) as follows:

$$\ln D_E(K_{it}, L_{it}, E_{it}, C_{it}, Y_{it}) = \ln E_{it} + \beta_0 + \beta_K \ln K_{it} + \beta_L \ln L_{it} + \beta_C \ln C_{it} + \beta_Y \ln Y_{it} + \beta_t + v_{it}. \tag{2}$$

By a shift regulation, we obtain:

$$-\ln E_{it} = \beta_0 + \beta_K \ln K_{it} + \beta_L \ln L_{it} + \beta_C C_{it} + \beta_Y \ln Y_{it} + \beta_t + v_{it} - \ln D_E(K_{it}, L_{it}, E_{it}, C_{it}, Y_{it}), \tag{3}$$

and Equation (3) can be rewritten as:

$$\ln(1/E_{it}) = \beta_0 + \beta_K \ln K_{it} + \beta_L \ln L_{it} + \beta_C C_{it} + \beta_Y \ln Y_{it} + \beta_t + v_{it} - u_{it}, \tag{4}$$

where u_{it} is an inefficiency term that is assumed to be an independent distribution with a variance of ${\sigma_{it}}^2$, and $v_{it} - u_{it}$ is the error term of a stochastic production frontier. The likelihood function is expressed in terms of $\sigma^2 = {\sigma_v}^2 + {\sigma_u}^2$ and $\gamma = {\sigma_u}^2/({\sigma_v}^2 + {\sigma_u}^2)$. The parameter γ measures the contribution of variance u to the error component, where $\gamma = {\sigma_u}^2/\sigma^2$, $\sigma^2 = {\sigma_v}^2 + {\sigma_u}^2$, and $\gamma \in [0, 1]$. Therefore, the total-factor energy efficiency (TFEE) for the ith DMU at time t can be computed by:

$$TFEE_{it} = E[\exp(-u_{it})]. \tag{5}$$

Equation (5) implies using the panel data stochastic production frontier approach on the TFEE computation. Following the study by Battese and Coelli [19], we present the inefficiency equation for performing simultaneous estimates with a stochastic frontier in Equation (4) as:

$$u_{it} = \delta_0 + \delta_1 {z_{it}}^1 + \ldots + \delta_H {z_{it}}^H + \varepsilon_{it}, \tag{6}$$

where z_{it} are the exogenous variables that explain inefficiencies, superscript H means Hth environmental variables, δ stands for a vector of estimated parameters, and ε_{it} is white noise, which is an independent normal distribution. Frontier 4.1 provided by Coelli [25] is used herein to compute TFEE and energy technical efficiency by means of the maximum likelihood technique.

3. Empirical Analysis

This section uses the methodology in the previous section to engage in an empirical analysis. Section 3.1 is data description. Section 3.2 is an overview of the whole Baltic Sea Region. Section 3.3 is the investigation of individual Baltic Sea countries.

3.1. Data and Variables' Descriptions

Since this paper takes the 10 countries in the Baltic Sea Region as the sample, the choice of variables herein follows the work of Chang et al. [4] who also focused on Baltic Sea countries to investigate and compare their energy efficiency. There are 11 countries in the Baltic Sea countries, including Germany, Denmark, Estonia, Finland, Iceland, Lithuania, Latvia, Norway, Poland, Russian Federation, and Sweden, but we remove Iceland due to missing data. The input factors are real capital (million US$ in 2010), labor (persons), energy consumption (Mt of oil equivalent), and CO_2 emissions (Kt), and the output is real GDP (million US$ in 2004). The choice of variables also follows other environmental and energy research such as Guo et al. [26], Choi et al. [27], and Wu et al. [28]. In addition to these aforementioned research articles, the reason why we selected these input variables is that GDP is usually significantly affected by labor productivity and real capital [29], and energy is also a critical factor that influences GDP [30]. The research findings in Koop [31] suggest that "richer countries exhibit technical progress in a way that economizes on carbon dioxide emissions but that poorer countries do not". This implies that CO_2 emissions are significantly associated with economic growth. Therefore, we include CO_2 emissions as an input variable. Aside from energy efficiency measurement, this paper also concerns the effect of energy inefficiency, and hence we take renewable energy consumption and urban population as environmental variables. The data period is 10 years from 2004 to 2014. All data come from the World Bank database, and the monetary variables are shifted into real ones taking 2010 as the base year.

The data measurement for real capital follows the work of Hu et al. [32] who utilized the perpetual inventory method to measure real capital. We denote real capital as follows:

$$K_t = K_{t-1}(1 - \delta) + R_{t-1}, \tag{7}$$

where K_t and K_{t-1} are respectively real capital in the current year and previous year, δ is the depreciation rate of stock, and R_{t-1} is the capital flow in the previous year. If the capital series starts in year $t = 1$ and the pre-sample accumulation of stock is given by Equation (7) with capital growing at a fixed rate of g, then we define real capital at the beginning of the first year by the following equation:

$$\begin{aligned} K_1 &= R_0 + (1-\delta)R_{-1} + (1-\delta)^2 R_{-2} + \ldots \\ &= \sum_{t=0}^{\infty} R_{-t}(1-\delta)^t = R_0 \sum_{t=0}^{\infty} \left[\frac{1-\delta}{1+g}\right]^t = \frac{R_1}{g+\delta}. \end{aligned} \quad (8)$$

The assumed depreciation rate of real capital is 5% [33]. According to Hu and Kao [33], the depreciation rate in developed countries is different from that of developing countries, and developed countries are more likely to have a higher depreciation rate due to their greater financial capacity. Additionally, Hu and Kao mentioned that "Unless detailed data at the sector or firm level are available, it is difficult to derive a precise rate of depreciation [34]. While the potential impact of the choice of the rate of depreciation is noted, due to data constraints this paper applies a unified rate of depreciation of 5%". Therefore, following the suggestion by Hu and Kao [33], we assume a depreciation rate of real capital of 5%. The units of real GDP, labor, real capital, and energy consumption are millions of US$, persons, millions of US$, and millions of tons of oil equivalent (Mt), respectively.

Table 1 lists the descriptive statistics for all variables. It also shows that energy use in the Baltic 10 Sea countries has the lowest value of standard deviation (SD) among input variables. Hence, energy is a very valuable and important topic to discuss for these countries. However, we need to employ another study method shown in the next two subsections to accumulate more information.

Table 1. Descriptive statistics of all variables.

Variable	Unit	Mean	SD	Min	Max	Obs
Regional GDP (y)	US$ million	615,712	905,399	12,059	3,369,503	110
Real capital (x_1)	US$ million	483,771	831,338	5263	4,349,117	110
Labor (x_2)	Persons	15,205,801	23,764,131	673,834	76,961,789	110
Energy use (x_3)	Mt of oil equivalent	4157	1497	1961	7135	110
CO_2 emissions (x_4)	Kt	300,100	517,503	6975	1,830,830	110
Renewable energy consumption (δ_2)	Percentage	26	17	3	59	110
Urban population (% of total) (δ_3)	Percentage	75	8	61	88	110

Source: World Bank (World Development Indicators database).

3.2. *An Investigation on Energy Consumption*

Table 2 presents the results using Equation (4) to investigate energy consumption in the Baltic Sea countries in which the factors of real capital, labor, CO_2 emissions, renewable energy consumption, and urban population have significant effects on the region. Since energy consumption is not only a reciprocal, but also an explained variable in Equation (4), such a variable with a positive (negative) coefficient implies that this variable is a factor reducing (inducing) energy consumption, and an environmental variable with a positive (negative) coefficient implies that this variable is a factor reducing (inducing) energy consumption. Hence, it is reasonable to see in Table 2 that increases in labor and renewable energy consumption induce energy consumption to rise, implying that labor and energy consumption are complementary factors in the production process of Baltic Sea countries. There is also an interesting result that CO_2 emissions and energy consumption have a positive relationship, which means that both of them increase or decrease at the same time, which means that energy consumption and CO_2 emissions have a close relationship.

In terms of the other three environmental factors, renewable energy consumption and urban population have significantly negative influences on the inefficiency of energy consumption, suggesting that an increase in renewable energy use causes fossil fuel energy consumption to fall. Chien and Hu [35] noted that renewable and traditional energies are complementary goods, such that both of them increase or decrease at the same time. Their finding is different from our finding that renewable and traditional energies are substitute goods in which an increase in renewable energy consumption causes traditional energy consumption to fall. The other interesting point is that an increase in urban population also reduces energy consumption, indicating that urbanization is helpful for saving energy. The urbanization process in the Baltic Sea countries is very different from China, because some studies about China's urbanization claimed that urbanization raises energy consumption [36,37]. The parameter γ measures the contribution of variance u to the error component. In Table 2, γ is 0.304, which means that the inefficiency variance accounts for 30.4% of the total variance of error components.

Table 2. Maximum likelihood estimation on the parameters.

Variable	Inefficiency of TFEE	Standard-Error	t-Ratio
Constant (β_0)	10.732 ***	1.062	10.101
Log real capital (x_1)	−0.219	0.116	−1.891
Log labor (x_2)	−0.723 ***	0.071	−10.206
Log CO_2 emissions (x_4)	−0.968 ***	0.100	−9.640
Log real GDP (y)	−0.125	0.059	−2.132
Renewable energy consumption (δ_1)	−0.038 ***	0.008	−4.914
Urban population (% of total) (δ_2)	−0.009 *	0.005	−1.724
$\sigma^2 = {\sigma_v}^2 + {\sigma_u}^2$	0.037	0.014	2.665
$\gamma = {\sigma_u}^2/\sigma^2$	0.304	0.269	1.130
Log likelihood	23.801	-	-
Number of observations	110	-	-
Number of countries	10	-	-

Notes: 1. The maximum likelihood method is used for the parameter estimation. 2. *: p-value $\leq$ 0.5; **: p-value $\leq$ 0.05; ***: p-value $\leq$ 0.01. 3. $\sigma^2 = {\sigma_v}^2 + {\sigma_u}^2$. Setting γ to be 0 implies that u_{it} should be removed.

3.3. Total-Factor Energy Efficiency Scores

Table 3 shows the energy use efficiency scores of the 10 Baltic Sea countries over the period 2004–2014. It presents in order the top four energy use scores during the data period. The countries above average (0.620) are Norway (0.986), Sweden (0.975), Finland (0.873), and Latvia (0.850) in order. Those with energy use efficiency scores below average are Denmark (0.591), Lithuania (0.541), Estonia (0.501), Germany (0.343), Poland (0.276), and the Russian Federation (0.268).

Table 3. Energy use efficiency scores of the 10 Baltic Sea countries between 2004 and 2014.

Country	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Average
Germany	0.301	0.311	0.322	0.339	0.334	0.341	0.350	0.364	0.366	0.368	0.383	0.343
Denmark	0.473	0.503	0.483	0.529	0.549	0.551	0.579	0.634	0.707	0.700	0.773	0.591
Estonia	0.465	0.454	0.446	0.462	0.482	0.525	0.527	0.530	0.539	0.527	0.541	0.501
Finland	0.786	0.829	0.800	0.824	0.896	0.849	0.852	0.895	0.943	0.942	0.958	0.873
Lithuania	0.514	0.494	0.494	0.503	0.523	0.533	0.521	0.553	0.568	0.614	0.636	0.541
Latvia	0.832	0.846	0.811	0.805	0.819	0.883	0.749	0.827	0.920	0.906	0.914	0.850
Norway	0.985	0.986	0.985	0.986	0.986	0.985	0.984	0.985	0.986	0.986	0.986	0.986
Poland	0.253	0.256	0.257	0.263	0.271	0.274	0.281	0.290	0.294	0.296	0.301	0.276
Russian Federation	0.257	0.260	0.262	0.269	0.270	0.266	0.269	0.272	0.273	0.276	0.273	0.268
Sweden	0.945	0.967	0.971	0.976	0.979	0.981	0.979	0.980	0.985	0.984	0.985	0.975
Average	0.581	0.591	5.831	0.596	0.611	0.619	0.609	0.633	0.658	0.660	0.675	0.620

Latvia is in fourth place in the ranking of energy use efficiency, only performing worse than Norway, Sweden, and Finland and achieving the highest energy use efficiency score of this group of countries (see Figure 1). On the other hand, Germany is third from last in the ranking of energy use efficiency (0.343), demonstrating that Germany has a relatively lower score on energy use efficiency. This phenomenon could be due to the fact that over 50% of Germany's energy was produced from traditional material (e.g., coal and lignite) up until 2010 as indicated by Renn and Marshall [38]. Although Germany performs relatively worse than most of the sample countries, there is a gradual upward trend in its energy use efficiency from 2004 to 2014. The improvement in its energy use efficiency might result from the massive consumption of renewable energy since 2010 [39]. With a large hydro-power input, Latvia has the highest share of renewable energy in the European Union, as 36.2% of its energy is produced from renewables. In Estonia and Lithuania, the use of renewable energy sources also shows an increasing trend since 1990, as 13.6% and 10.5% of energy is consumed from renewable material, respectively.

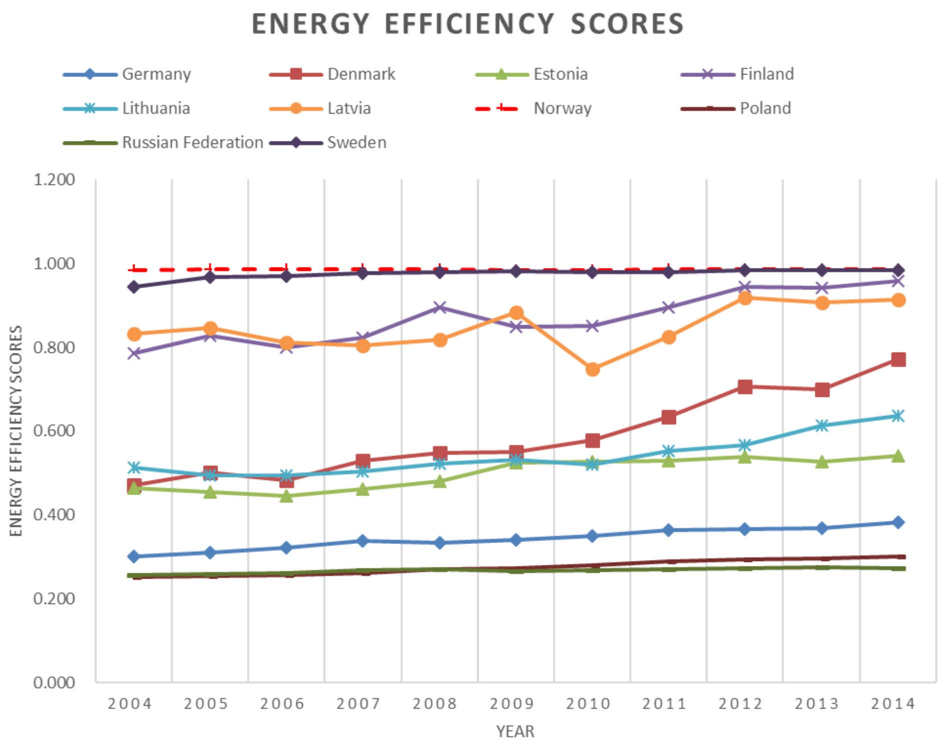

Figure 1. Energy efficiency scores in the Baltic Sea region.

As shown in Figure 2, the average energy use efficiency scores from 2004 to 2014 in the 10 Baltic countries show a gradual upward trend except for 2009. It is interesting to see a gradual downward trend in energy use efficiency from 2009 to 2010, dropping to below 0.62 in 2010. We think the reason for the lower efficiency might be the effects of the 2008 global financial crisis, resulting in a slightly downward trend of energy use efficiency in the 10 Baltic Sea countries in 2009. Additionally, previous research suggested that this crisis caused subsequent energy price volatility [40], which might be another possible reason for the decrease in energy use efficiency. From the results after the 2008 global financial crisis, we observe that the governments of the Baltic countries accelerated their respective economic recovery. Since the economic condition of a country is closely connected to energy efficiency [5], the average energy use efficiency scores from 2004 to 2014 in the 10 Baltic countries exhibit a gradual upward trend except in 2009. This implies that the economic condition in the Baltic Sea countries gradually improved in these years, except during the 2008 global financial crisis.

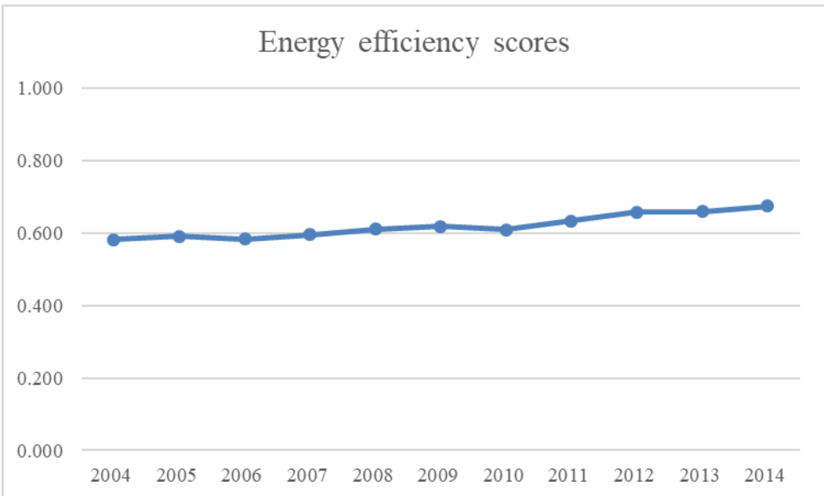

Figure 2. Average efficiency scores for the Baltic states 2004–2014.

Previous research also suggested that Lithuania experienced a drop in energy efficiency during the global financial crisis [5]. Other academic studies presented a similar perspective on this issue [4], suggesting that this severe crisis significantly influenced reductions in energy use. However, in our research, a possible explanation for the energy efficiency of the Baltic Sea countries showing a rising trend after the curve drops may lie in the trade-off between these countries to ensure the EU meets its climate and energy targets for the year 2020 strategy.

4. Discussion

The current study primarily analyzes the energy use efficiency of 10 countries in the Baltic Sea Region. We estimate energy efficiency by adopting a stochastic frontier model with environmental variables.

The Baltic Sea Region Energy Cooperation (BASREC) was founded in 1998 by the ministers for energy of the region and of the European Commission. The Baltic Sea Region Energy Cooperation (BASREC) was founded in 1998 by the ministers for energy of the region and of the European Commission. The BASREC consists of eleven-member states in the Baltic Sea region, including Denmark, Estonia, Finland, Germany, Iceland, Latvia, Lithuania, Norway, Poland, Russia, Sweden, and the European Commission [41]. Among these countries, only three countries are not member states in the EU (e.g., Iceland, Norway, and Russia). In order to enhance energy efficiency and facilitate European energy market operation, the BASREC tries to develop and adopt advanced energy-related technologies. In sum, the main objective of the BASREC is to make a contribution to continued growth and sustainable development of the Baltic Sea region.

First, our study results indicate that Finland, Latvia, Norway, and Sweden are four countries among the 10 in the region (in order) with above average energy use efficiency scores during the data period. We attribute this phenomenon to the fact that Denmark, Finland, and Norway are developed countries and have successfully promoted environmental policies characterized by low pollution. The research findings for the better performances in Denmark, Finland, and Norway correspond with the study of Graus et al. [42], who suggested that Nordic countries have higher efficiency scores in terms of traditional energy consumption (e.g., fossil-fired power generation). Although Latvia is a developing country, it follows the EU climate and energy policy. In addition to this, Roos et al. [43] further pointed out that the Baltic Sea countries adhere to the EU climate and energy policy, including increasing the share of renewable energy and improving energy efficiency to meet energy targets. Bengtsson [44] also indicated that Estonia, with the highest share of shale oil in its fuel consumption, needs financial support in order to develop renewable energy. Klevas et al. [45] noted that Lithuania uses EU Structural Funds for local sustainable energy development. Although the energy use efficiency of these Baltic Sea countries (e.g., Lithuania and Estonia) is lower than that of other European countries in the current study, it ranges from 0.450 to 0.500, indicating that there is still about 50% room for energy-saving improvement.

Second, we find that Sweden has relatively high energy use efficiency. The reason for this might be that its government has made a clearer and better energy-saving policy (e.g., its energy taxation system). Moreover, homeowners in Sweden have spontaneously adopted various ways to save energy at home [46]. Therefore, its energy use efficiency is higher than other sample countries.

Third, for the inefficiency estimates, a higher renewable energy consumption rate and urban population rate correspond to lower TFEE scores. This research finding is consistent with previous evidence that increasing the share of renewable energy among the total energy supply will significantly improve TFEE [35]. The research findings also suggest that traditional and renewable energies should be used together appropriately. By substituting traditional energy with renewable energy, an economy's technical efficiency can significantly improve, implying that countries should find an optimal policy that consumes renewable and traditional energy efficiently. This might be a possible explanation for greater renewable energy consumption corresponding to less energy use, which denotes an import substitution effect. Chien and Hu [38] presented that the relationship between renewables and energy imports is significantly positive. Therefore, a possible explanation is that when an economy has great demand for energy, it not only exploits more renewable energy, but also imports more energy, thus increasing energy efficiency.

Fourth, this study finds that the higher the urban population rate is, the greater are the TFEE scores, which is consistent with previous research on western countries, whereby energy efficiency in an urban area is relatively higher than that in a rural area due to the use of public transportation [47]. These research findings suggest that Baltic Sea countries' development can increase the efficiency of energy use by creating an optimal policy for using traditional and renewable energies and simultaneously enhancing energy efficiency in urban areas.

5. Conclusions

This study employs SFA to estimate the TFEE scores for 10 Baltic Sea regions and the determinants of their inefficiency for the period 2004–2014. Herein, we utilize the cross-section input-oriented SFA approach by Honma and Hu [11], who extended the cross-sectional model in Zhou et al. [20] to a panel data model for measuring Japan's regional energy efficiency.

Our SFA model includes real capital, labor, energy use, and CO_2 as regressors and renewable energy consumption and urban population as environmental variables. Empirical results indicate that the Baltic Sea countries demonstrate a gradual upward trend during the data period. This study thus suggests that technology transfer or financial fund support, industrial innovation and regulation, and energy supply and demand management are available energy policy instruments for Baltic Sea countries to enhance their energy efficiency.

Regarding the environmental variables, higher renewable energy consumption and urban population significantly bring higher TFEE scores. The Baltic Sea countries have abundant natural resources, such as hydro-electrical power in Norway, Finland, and Sweden and crude oil and natural gas in Norway. Therefore, in order to develop new renewable energy, these countries should reduce the use of non-renewable energy, create sustainable energy development, and support energy cooperation.

Our empirical findings suggest that the Baltic Sea countries can increase their energy use efficiency by creating an optimal policy for using traditional and renewable energies and simultaneously enhancing energy efficiency in urban areas. Many Baltic Sea countries such as Norway have already set up feasible renewable energy objectives for themselves. The countries around the Baltic Sea region can use different policy tools to enhance renewable energy usage; for example, providing funding for research restitutions to conduct research of enhancing renewable energy utilization and enacting the law on replacing traditional energy by renewable energy. We recommend improving energy efficiency in the future by starting with enhancing energy substitution, such as replacing energy use with capital or labor as well as developing renewable energy to replace the use of fossil fuels.

The limitations of the current study are as follows. First, the data period only covers 2004–2014, which does not allow us to gain a deeper understanding of energy efficiency trends and the impact of environmental variables on energy efficiency in recent years. Future research should collect more comprehensive data to conduct a longitudinal investigation of energy efficiency in the Baltic region. Second, we only employ two environmental variables, yet other variables might influence energy efficiency in the Baltic region. Future research should take other environmental variables into account to better and more deeply understand the critical factors influencing energy efficiency in this region.

Author Contributions: The work is the results o a collaborative research work by National Chiao Tung and Kainan University with the following details: Conceptualization, J.-L.H. and W.-L.H.; Methodology, J.-L.H.; Software, J.-L.H. and W.-L.H.; Validation, J.-L.H., M.-C.C. and W.-L.H.; Formal Analysis, W.-L.H. and J.-L.H.; Investigation, W.-L.H. and J.-L.H.; Data Curation, M.-C.C.; Writing-Original Draft Preparation, C.H. and W.-L.H.; Writing-Review & Editing, W.-L.H., J.-L.H., C.H. and M.-C.C.; Visualization, W.-L.H. and J.-L.H.; Supervision, J.-L.H. and C.H.; Project Administration, J.-L.H. and C.H.; Funding Acquisition, J.-L.H.

Funding: The work was funded by Taiwan's Ministry of Science and Technology (MOST106-2410-H-009-047).

Conflicts of Interest: The authors declare no conflict of interest.

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