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The Impact of Renewable Energy Supply on Economic Growth and Productivity

Kamil Makieła [1,*], Błażej Mazur [2] and Jakub Głowacki [3]

[1] Department of Econometrics and Operational Research, Cracow University of Economics, Rakowicka 27, 31-510 Krakow, Poland
[2] Department of Empirical Analyses of Economic Stability, Cracow University of Economics, Rakowicka 27, 31-510 Krakow, Poland; blazej.mazur@uek.krakow.pl
[3] Department of Public Economics, Cracow University of Economics, Rakowicka 27, 31-510 Krakow, Poland; jakub.glowacki@uek.krakow.pl
* Correspondence: kamil.makiela@uek.krakow.pl

Abstract: The threat of the negative consequences of global warming makes the discussion about the relationship between economic growth, productivity, and increasing renewable energy involvement an important topic. Hence, the aim of this study is to analyze the impact of renewable energy and energy supply on economic growth and productivity at the national level using stochastic frontier analysis and the aggregate production function framework. In doing so, we analyzed a panel of annual data from 133 countries from 2008 to 2014. We apply a generalized stochastic frontier model, which allows us to differentiate between persistent and transient inefficiency, as well as individual effects. Our results indicate a threshold level in terms of a country's development that needs to be obtained to benefit from increasing renewable energy involvement over time. However, if this threshold level is obtained, productivity gains are evident. We also found that the role of the energy supply in aggregate production is nontrivial. That is, its inclusion changes the relationship between key input factors (capital and labor) by decreasing their overall elasticities and increasing the observed economies of scale.

Keywords: renewables energy; economic growth; productivity

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1. Introduction

The problem between economic growth and the consumption of energy, including the one coming from renewable energy sources (RE hereafter), is complex and has many aspects related to climate change, national security, etc. Consequently, analyses that include just one of these aspects may provide a limited understanding of the overall motivation for investing in RE. This study considers the role of the primary energy supply, as well as the production of energy from renewable sources, in cross-country comparisons of productivity, which focuses on the interplay between economic growth (including productivity) and energy consumption (including the role of RE).

The incentives to invest in RE sources likely have a positive impact on climate change and overall energy security. These incentives are rather intangible and difficult to quantify. The big question, however, is about related economic incentives. In particular, to what degree does caring for climate change and energy security come at the cost of economic development. The authors of [1] identified three streams of literature in this regard. The first found no causality between RE and economic growth. The second one finds a positive link, which would mean that investing in RE provides a much more decentralized and stable source of energy, which in turn can further boost economic growth and productivity [2–4]. The third stream finds that increased RE consumption has a negative impact on economic growth, e.g., due to high costs. There is concern that using more renewable energy impedes productivity and, thus, the overall potential for economic growth [5,6]. Hence, although there are many studies about RE and its impact on economic development, a significant research gap remains, as the empirical literature is still inconclusive.

The goal of this research is to revisit the "renewable energy vs. economic development" nexus. In doing so, we propose a novel approach that (i) considers the impact of RE on economic development within the context of formal productive efficiency analysis via advanced forms of stochastic frontier models, and that (ii) is embedded within a cross-country panel data context. This should provide less biased and more general results than existing studies, which are often at the level of firm, industry, or country, and do not account for (in) efficiency of the underlying process or the scope of its cross-country variation. In doing so, our contribution to the literature is twofold. First, using advanced stochastic frontier methods (i), we evaluate the impact of RE supply on productivity and productive efficiency over time, and thus whether it contributes positively to economic growth (as measured by real GDP growth). This allows us to test the hypothesis if (H1) renewable energy is connected to economic growth indirectly via productive efficiency and if (H2) there is a threshold in terms of economic development that needs to be obtained for a country to achieve surplus development from renewable energy sources. Second, we recognize the primary energy supply as a key determinant of production's variation across countries and time. This allows us to evaluate (ii) how this indicator contributes to economic growth and (iii) how it interplays with other relevant input factors (i.e., capital and labor) in the aggregate production process. This allows us to evaluate the hypothesis, which states that (H3) energy supply is a significant factor influencing economic growth on par with input factors traditionally assumed in the economic growth literature.

The paper is structured as follows. Section 2 discusses the relevant literature that gives context to the aforementioned hypotheses. Section 3 provides a methodology overview and discusses the data used in the empirical study. Section 4 provides the findings, while Section 5 concludes with a discussion and guidelines for further research.

2. Literature Review

The field of renewable energy observes rapid development [7]. From an economics perspective, there are two predominant research threads of RE research, which cover either the development of the RE industry [8,9] or the analysis of the relationship between RE and economic development. The latter is sometimes referred to as research on the renewable energy vs. economic development nexus, and it is the main focus of this study. Analyses of the topic have been performed at various levels of aggregation (firm, industry, country), and they have earned some significant attention in recent years [10].

As mentioned in Section 1, there are three streams of literature concerned with the nature of the relationship between RE and economic growth. The first one argues that increased RE involvement has a zero net effect on economic growth [11,12]. As [12] states, there is no causal link between RE and GDP, or—if any—it is a very weakly positive relationship at best. Sectoral-level analysis of the US industry conducted by [6] found no causality between RE consumption and GDP. A similar result, though for the entire economy, was found by [13]. The second stream argues that higher energy consumption coming from RE sources has a positive impact on economic growth [14–16]. A positive relationship between RE and growth is also found in [2], although the underlying causality remains unclear. Additionally, the analysis of 51 African countries by [4] indicates that, e.g., an increase in biomass energy sources increases GDP. The third stream indicates that investing in renewable energy comes at a cost to economic development [3,5,17]. As suggested by [5], the cost of supporting renewables may be too high. That is, the negative effects of RE may outweigh the positive effects it may have on generating income or at least cancel them out.

Empirical studies focused on verification of the above-mentioned hypotheses often arrive at ambiguous, or even contradictory conclusions depending on how a research sample is divided. For example, [3] analyzed 38 countries and distinguished three groups. In the first group (Austria, Bulgaria, Canada, Chile, China, the Czech Republic, Denmark, Finland, France, Germany, Greece, Italy, Kenya, Republic of Korea, Morocco, the Netherlands, Norway, Peru, Poland, Portugal, Romania, Spain, and the United Kingdom), RE is an important factor of economic growth; in the second group (India, Ukraine, the United States, and Israel), it has a negative effect on economic growth, while in the third group, it is difficult to establish the impact. Additionally, [16] noted that their results "on the whole" sample may change substantially if, e.g., different income groups are considered. They concluded that RE positively affects economic growth in OECD countries, but it has no significant effect on developed countries. A similarly ambiguous outcome can be found in numerous empirical studies that analyze the relationship between RE and economic growth [10].

One of the reasons why empirical studies fail to deliver consistent results may be that the inefficiency of the underlying aggregate production process (GDP creation) is not formally accounted for in the literature. Because failure to account for differences in productive efficiency may produce inaccurate results, efficiency modeling techniques take precedence in this study. Formal analyses of productive efficiency and productivity growth have a long history [18]. The primary methods used usually fall within two categories: Stochastic Frontier Analysis (SFA) and Data Envelopment Analysis (DEA). Since we use panel data and wish to analyze the characteristics of the aggregate production function, it is natural to consider the parametric approach, which is SFA. In doing so, we utilize recent advances in this field, which allow us to account for transient and persistent inefficiency, as well as individual effects, which are traditional in panel data models.

Given the above-mentioned background literature, we developed the following hypotheses within the stochastic frontier framework. First, we argue that the impact of RE on economic growth is indirect, i.e., RE interacts with economic growth by increasing (or decreasing) its productive efficiency component. Hence, the first hypothesis states that (H1) renewable energy contributes to economic growth indirectly via the productive efficiency component. Second, the direction of this dependency is not uniform; i.e., (H2) there is a threshold in terms of economic development that needs to be obtained for a country to achieve surplus development from renewable energy. We find that the threshold concept, which provides justification for some contradictory results of the empirical research, is only marginally explored in the literature [1,16].

Compared to the topic of "renewable energy vs. growth," the role of (total) energy supply, as well as consumption, in spurring economic growth is relatively well researched. The role of energy input in aggregate production analysis is discussed by, e.g., [19]. Moreover, [20] provides a critical re-evaluation of the neo-classical approach to studying the effects of climate change, including the relationship between energy use and GDP. However, although the positive role of energy supply in economic growth is currently a stylized fact in the literature, empirical studies tend to produce conflicting results in this regard [21]. That is, while some studies point out its leading role in GDP creation [22], others find no causal link, or argue that causality may simply depend on the (sub)group being analyzed [23,24]. Hence, although the positive impact of energy supply on economic growth is generally agreed upon, there remains a question of how significant it actually is, e.g., compared to other factors in the aggregate production process, such as capital and labor. Hence, the third hypothesis to be verified in this study states that (H3) energy supply is a significant factor influencing economic growth on par with the input factors traditionally assumed in the economic growth literature. This is somewhat similar to the main hypothesis proposed in [25], although our methodology is different. First and foremost, this study considers production inefficiency in two dimensions: transient and persistent. This is because disregarding process inefficiency may produce inaccurate results. Second, [25] considered panel cointegration techniques with traditional Cobb–Douglas production (as opposed to a more general translog form, used in this study). Since the panel cointegration technique for processes with latent variables (inefficiencies) is still in its infancy [26], we take a different route and consider a static panel approach. That is, we consider a relatively "short" panel (7 years) with a large number of countries (133).

3. Materials and Methods

3.1. Preliminary Assumptions

We start by considering a simple measure to describe the contribution of RE as a percentage of the primary energy supply in each country.

$$OZE_{it} = \frac{TRES_{it}}{TPES_{it}} \tag{1}$$

where *TRES* is total renewable energy supply, *TPES* is total primary energy supply, and i (i = 1, . . . , n) and t (t = 1, . . . , T) are country and time indices, respectively. This ratio (*OZE*) allows us to describe the involvement of renewables in the energy supply in an economy; thus, it is a "going green" indicator.

To reiterate, we wish to analyze (i) whether an increasing share in renewable energy supply leads to gains in productivity over time and, thus, if it contributes positively to economic growth (as measured by real GDP growth). Furthermore, we recognize the primary energy supply as a key determinant of production's variation across countries and time. In this regard, the question is (ii) how this indicator contributes to economic growth and (iii) how it interplays with other relevant input factors (i.e., capital and labor) in the aggregate production process. Given this, the methodology for this investigation is rooted in the theory of aggregate production function, as well as the related concepts of the world technology frontier, productivity, and economic growth [18]. We start with the following general form of an aggregate production process:

$$Y_{it} = F(K_{it}, L_{it}; \beta) \exp(\varepsilon_{it}) \tag{2}$$

where Y is GDP, K is capital stock, L is labor, $F(.)$ is the aggregate production function (i.e., the World Technology Frontier; WTF hereafter), and ε is the stochastic component. For further consideration, we rewrite the above equation as follows:

$$y_{it} = f(k_{it}, l_{it}; \beta) + \varepsilon_{it} \tag{3}$$

where lower case letters are natural logs of the original variables and $f(.)$ is the log of the WTF.

3.2. The Parametric Part of the Model

On the one hand, we want $F(.)$ to be flexible (e.g., nonlinear) to capture complex, nonlinear interactions between the dependent (production output) and the explanatory variables (key input factors, which are relevant in explaining the variation of output). On the other hand, we want $F(.)$ to be intuitive and not too cumbersome in estimation. That is why we consider a class of nonlinear functions in $F(.)$, which are, however, linear in $f(.)$. Two popular types of WTF parametrizations meet these requirements—Cobb–Douglass and translog. Since translog is a generalization of the Cobb–Douglas form, we chose the latter one (translog). Furthermore, we used the data translation technique described in [27]. In this way, translog parameters that relate to the first-order approximation of the unknown WTF report results for sample geometric means, as in simple Cobb–Douglass. All in all, we can rewrite Equation (3) as

$$y_{it} = x_{it}\beta + \varepsilon_{it} \tag{4}$$

where $x_{it} = \left[1\ k_{it}\ l_{it}\ k_{it}^2\ l_{it}^2\ k_{it} \cdot l_{it}\ t\right]$. Neutral technical changes are captured via parameter t, which should be sufficient in a short panel, such as the one in this study. We refer to this specification as Model 1.

The literature often considers a third factor of production, usually the so-called human capital. Unfortunately, good-quality estimates of human capital levels are available only for a handful of countries, mostly highly developed, which would severely limit our sample size. This is why we did not consider this variable in our study. We do, however, recognize energy input, which, apart from capital and labor inputs, may be considered one of the key determinants explaining GDP variation across countries and time. The inclusion of the energy input factor may also dramatically change the interaction between capital and labor inputs in the production process. To analyze this, we consider an extended WTF specification:

$$y_{it} = x^*_{it}\beta + \varepsilon_{it} \tag{5}$$

where $x^*_{it} = \left[1 \; k_{it} \; l_{it} \; e_{it} \; k^2_{it} \; l^2_{it} \; e^2_{it} \; k_{it} \cdot l_{it} \; k_{it} \cdot e_{it} \; e_{it} \cdot l_{it} \; t \right]$ and "e_{it}" is the total primary energy supply (*TPES*, in natural log) in vector x^*_{it}. We refer to this specification as Model 2. In the empirical section, we compare the results from Model 1 (Equation (4)) and Model 2 (Equation (5)).

3.3. The Stochastic Part of the Model

Our research strategy in this aspect is rooted within the productivity and technical efficiency literature, and thus we use Stochastic Frontier Analysis (SFA hereafter); see [28] and [29]. It is usually very challenging to consider all relevant determinants of economic growth and productivity, as the potential list may be quite long [30]. That is why, within the SFA framework, we take advantage of a relatively new modeling approach known as generalized true random effects—GTRE; see, e.g., [27,31–35]. The stochastic structure of the model allows us to capture several sources of disturbances, which can be due to: (i) country-specific effects, systematic time-invariant differences in WTF between countries (a sort of variation in the intercept), (ii) persistent efficiency, time-invariant differences in efficiency between countries, (iii) transient efficiency, temporal changes in efficiency (aka short-run efficiency), and (iv) standard symmetric random disturbance customary to econometric analyses. In essence, we treat other potential determinants not considered explicitly in the model as disturbances to be captured by the abovementioned effects (i)–(iii). This allowed us to focus on the factors relevant to our investigation. Given GTRE specifications, the stochastic component ε takes the following form:

$$\varepsilon_{it} = \alpha_i + v_{it} - \eta_i - u_{it} \tag{6}$$

in which the compound error ε_{it} is made up of two symmetrically distributed stochastic terms and two nonnegative terms: $\alpha_i \sim N(0, \sigma_\alpha)$ is the country-specific individual effect common in panel data models; $v_{it} \sim N(0, \sigma_v)$ is the standard error component of an econometric model; $\eta_i \sim \left|N(0, \sigma_\eta)\right|$ is to capture long-term, persistent differences in technical efficiency and productivity; $u_{it} \sim Exp(\lambda_{it})$ is to trace transient technical efficiency and thus productivity change over time.

Components η and u are referred to as persistent and transient inefficiency, respectively. They capture nonnegative deviations from the frontier, which can only decrease the observed output. Inefficiency in SFA is not directly observable but is treated as a latent variable derived based on the asymmetry of ε—which is observable. A simple transformation exp (-inefficiency)—which can also be viewed as reverting the model from Equation (3) back to (2)—produces a technical efficiency measure, which, given the nonnegative nature of η and u, is defined on the interval (0,1). Thus, from the perspective of Equation (2), technical efficiency is an observation (or object) specific factor that scales the production frontier.

To analyze *OZE*'s impact on efficiency (and thus productivity) over time, we parametrize component u, i.e., transient inefficiency. We consider the following equation, which parametrizes the mean and standard deviation parameter (λ) of the transient inefficiency distribution:

$$\ln \lambda_{it} = g_0 + g_1 OZE_{it} + g_2(d * OZE_{it}) \tag{7}$$

where *OZE* is the variable of interest, d is a dummy variable that indicates highly developed countries (i.e., top 20% countries in the sample as measured by GDP per capita; see countries with "hd" label in the Appendix A) and g_0, g_1, g_2 are the parameters to be estimated. This convolution extends a simple GTRE specification proposed by [31] and is known in the literature as Varying Efficiency Distribution; see, e.g., [36] and [37]. Parameter g_1 is used to identify the overall impact of *OZE* on technical efficiency and productivity over time. The second parameter g_2 is to capture the impact of *OZE* specifically on highly developed countries. This may be particularly important because the increasing involvement of *OZE* may have a different impact on highly developed countries than for the entire sample.

It is worth noting that it is possible to parametrize α as well as η in a similar way as u, and thus include several other factors to be investigated as drivers of productivity differences between countries. However, we wish to maintain a clear focus of the paper, and such investigation is beyond the scope of this study.

To estimate the model, we use the Bayesian approach to Generalized True Random Effects (GTRE) models. In principle, two key papers discuss the Bayesian approach to estimating GTRE models [27,32]. We use the prior structure proposed by [27], as it is more intuitive and less likely to produce numerical problems. The VED component in Equation (7) is estimated based on the methodology proposed by [36] and extended by [37].

To approximate the posterior distribution of the vector of parameters β, g and latent variables u, η, α, we use Markov Chain Monte Carlo simulation (MCMC). In most cases, we can use a rather simple form of the MCMC method known as Gibbs sampling, which relies on repetitive draws from conditional posterior distributions to approximate marginal posterior distributions of any model quantity (parameter or latent variable) of interest. The only requirement for Gibbs sampling is that the conditionals are straightforward to draw from. This is the case for all but one model quantity—parameter(s) of transient inefficiency (u). Although [38] discusses a case where the conditional for u can be easily drawn from, it requires discretization of variable *OZE* and thus a possible loss of information in the model (due to discretization). We wanted to keep the variable *OZE* continuous. Thus, when drawing u we perform a Metropolis-Hastings step, which is a generalization of Gibbs sampling, i.e., in Metropolis-Hastings does not require us to be able to directly draw from the conditional (and thus, the conditional can be complex).

3.4. Data

The dataset used in this study is a balanced panel that covers annual data from 133 countries in the period 2008–2014. The full list of countries is provided in the Appendix A. Data on the total primary energy supply (*TPES*, measured in million "toe"—ton of oil equivalent) and total renewable energy supply (*TRES*, measured in thousand toe) are from the OECD Renewable Energy database [39]. The primary economic indicators are from Penn World Table 9.0 [40]. These are output-side real GDP at current PPPs in millions 2011 US$ (cgdpo), capital stock at current PPPs in millions 2011 US$ (ck), and the number of persons engaged in millions (emp). The number of countries (133), as well as the timeframe (7 years), are the consequence of data availability in both of the abovementioned databases at the time of analysis.

4. Results

Tables 1 and 2 present the estimation results from Model 1 (Equation (4)) and Model 2 (Equation (5)) discussed in Section 3, i.e., the model without total primary energy supply, *TPES* hereafter (Model 1), and with *TPES* (Model 2). Regardless of the model used, we find that there is a small, yet statistically significant, neutral technical change within the analyzed period (see the estimate of β_t; Tables 1 and 2). Returns to Scale (RTS) are decreasing on average.

Table 1. Results based on the model without *TPES* (Equation (4)).

Parameter	P.Mean	P.Std	*t*
β_0	12.4269	0.0416	299.00
β_1	0.4769	0.0309	15.43
β_2	0.4174	0.0338	12.37
β_{11}	−0.0356	0.0073	4.87
β_{22}	−0.0140	0.0143	0.98
β_{12}	0.0841	0.0142	5.92
β_t	0.0002	0.0019	0.11
σ_α	0.3613	0.0468	7.71
σ_v	0.0300	0.0029	10.17
σ_η	0.4692	0.0579	8.10
λ_{it} (av.)	0.0765	0.0052	14.86
g_0	−2.5722	0.0670	38.38
g_1	0.0058	0.0014	4.24
g_2	−0.0525	0.0060	8.73

Notes: the "p.mean" is the posterior mean and "p.std" is the posterior standard deviation; "t" is the ratio of p.mean and p.std; the order of parameters in vector β corresponds to variables in vector x_{it}; the variables have been mean corrected and so parameters β_1, β_2 are average capital and labor elasticities of production, respectively; β_t is the parameter of neutral technical change; the remaining parameters relate to the second-order approximation in translog and do not have any particular interpretation.

Table 2. Results based on the model with *TPES* (Equation (5)).

Parameter	P.Mean	P.Std	*t*
β_0	12.3775	0.0429	288.74
β_1	0.3699	0.0220	16.83
β_2	0.1568	0.0247	6.35
β_3	0.4344	0.0274	15.85
β_{11}	0.0514	0.0111	4.65
β_{22}	−0.0052	0.0183	0.28
β_{33}	0.1200	0.0238	5.03
β_{12}	0.0848	0.0172	4.93
β_{13}	−0.1835	0.0291	6.30
β_{23}	−0.0607	0.0311	1.95
β_t	0.0049	0.0017	2.82
σ_α	0.1530	0.0329	4.65
σ_v	0.0373	0.0032	11.64
σ_η	0.4498	0.0494	9.11
λ_{it} (av.)	0.0600	0.0044	13.66
g_0	−2.8003	0.0858	32.65
g_1	0.0061	0.0016	3.93
g_2	−0.0352	0.0163	2.16

Notes: parameter β_3 is the sample average for the total primary energy supply (*TPES*) elasticity of production; see notes for Table 1 for the remaining label descriptions.

As far as the impact of RE involvement on productivity is concerned, we find that the estimate of parameter g_1, discussed in Equation (7), has a positive sign, and it is statistically significant regardless of the model. This indicates that, for the overall sample, increasing involvement of renewables comes with a decreasing effect on productive efficiency. This is small but statistically significant. However, the estimate of parameter g_2 (Equation (7)) has a negative sign, and it is also statistically significant. This means that, for highly developed countries, the increasing involvement of RE in the economy is associated with productivity growth. Importantly, as shown in Figure 1, the estimate of g_2 is several times larger than the estimate of g_1—so the positive net effect for highly developed countries is evident. This leads us to the following conclusions. First is the fact that both estimates (g_1, g_2) are highly statistically significant and provide evidence in favor of hypothesis H1, as the impact of RE on growth clearly appears to be indirect and contributes via the productive efficiency channel. Second, as noted above, we get different signs for the estimates of parameters g_1

and g_2, and the estimate of g_2 is several times larger than the estimate of g_1. This finding provides evidence in favor of hypothesis H2, as there is an obvious threshold level in terms of the state of development that a country needs to obtain to benefit from the increased involvement of RE. Alternatively, one may say that a certain level of development is required to obtain economies of scale from RE. It seems that this can primarily be achieved in highly developed countries. However, if the threshold level is obtained, the productivity gains from increasing RE involvement in total energy supply over time, as measured by the indicator *OZE*, are evident (i.e., high, and statistically significant).

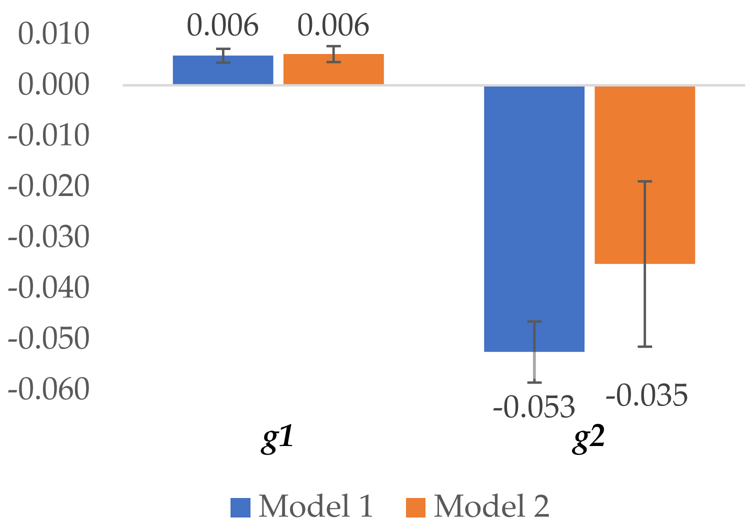

Figure 1. Impact of RE on productive inefficiency: the whole sample (g_1) vs. high-income countries (g_2).

Furthermore, we find that including *TPES* increases returns to scale (Model 1: RTS is about 0.89; in Model 2, it is 0.96) and decreases elasticities of capital and labor. As Figure 2 clearly indicates, when *TPES* is present in the model, it is the most influential factor of GDP growth, i.e., 1 pp growth in *TPES* results in 0.41 pp growth in GDP, ceteris paribus. Moreover, if *TPES* is excluded from the model, as in Model 1, the elasticities of capital and labor are significantly negatively correlated (−0.662), which is to be expected, as their contribution to production is somewhat substitutional. However, when *TPES* is included (Model 2), capital and labor elasticities are almost uncorrelated (−0.087), and the elasticity of *TPES* is significantly negatively correlated with the other two factors (−0.567 and −0.546, respectively). This leads to the following conclusion in terms of hypothesis H3 mentioned in Sections 1 and 2: the energy supply is an important factor influencing economic growth because (i) it changes the contribution of the main input factors (capital and labor), which is substantially diminished by *TPES* (which now has the highest average elasticity), and (ii) it changes the interaction between capital and labor elasticities; their correlation in Model 2 is negligible, while they both correlate with *TPES*.

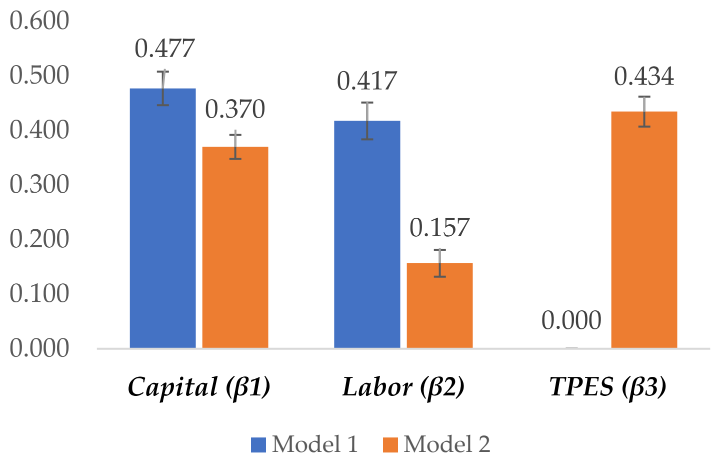

Figure 2. Factor elasticities of production in Models 1 and 2.

5. Conclusions

This paper demonstrates the importance of adequate model formulation for aggregate technology analyses by including energy inputs and the energy-related drivers of inefficiency variation in a cross-country, panel data SFA framework. We show that these relationships are likely to take the form of cross-variable dependencies, which are indicated by the relevance of (i) the product terms in the translog form and (ii) the inefficiency regressors in the VED component. The omission of these dependencies may result in a distorted inference.

The authors of [8] showed that GDP per capita is a relevant factor in boosting RE development. This study indicates that it is, in fact, a vital prerequisite for RE to contribute positively to economic growth. That is, our research indicates that transitioning to RE can lead to higher productivity, and thus, it can positively affect economic growth. However, this is evident only for countries with a high level of development as measured by GDP per capita. This finding is in line with more recent studies, such as [41] or [14], which note that RE is growth-enhancing in high-income economies. Additionally, it is similar to [16], who noted that RE generally stimulates economic growth, though this may depend on their subsample.

Consequently, our results indicate that low- and middle-developed countries may not find it beneficial to invest in RE due to possible adverse effects on economic growth. Hence, highly developed countries should boost their supporting policies for less-developed countries to help promote the development of the RE sector there. Given the findings in [42], foreign direct investments (FDI) seem to be the optimal solution, as they also boost economic development through the input accumulation channel [43].

This study also outlines and characterizes the role of energy supply as the third input in the aggregate production function. We show that this role is nontrivial because incorporating energy supply increases returns to scale, which is in line with the more recent literature, e.g., [25], who indicate that economic growth is related to energy supply, or [22], who emphasize that economic growth mainly depends on energy consumption. Furthermore, incorporating energy supply also changes the interaction between capital and labor elasticities of production from negatively correlated to almost uncorrelated. Estimates of output elasticities with respect to various inputs are often reported to be negatively correlated [44,45]. This indicates statistical uncertainty regarding the decomposition of the joint influence of the pair of inputs. Such an effect is therefore undesirable. Hence, our results from Model 2 (with the energy input) have an additional appeal, which reflects a more precise inference.

As with all research, this study has its limitations. First, as we discuss the interplay between economic growth and energy use, with the emphasis on RE, we assume that the technology is homogenous both in time and across countries, though this comes with some adjustments stemming from the so-called neutral technical change (via parameter β_t) and the panel structure of the model (i.e., country individual effects and persistent inefficiency). These assumptions are perhaps satisfactory for our dataset, which covers a relatively short period due to data availability limitations. Nonetheless, it would be beneficial to extend the timespan under consideration while introducing some form of structural change, e.g., to capture technological progress in renewable energy production and energy use, or to explicitly analyze possible technological heterogeneity across countries [46]. Second, we treat all renewable energy sources as one, which is a crude approximation. Perhaps the aggregate technology should explicitly account for "adverse products," i.e., carbon emissions. In addition, to consider policy trade-offs, one should take some measure of resilience or structural stability. This is because energy systems are often evaluated not only in terms of average performance but also by their reactions to shocks. Finally, our model takes a specific view of the causal structure. Our conclusion is that higher productivity coincides with a higher RE share for the developed countries, although there is little empirical evidence as to the direction of the causality. This issue would require further research.

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Appendix A

Table A1. Countries considered in the analysis; "hd" in brackets indicates highly developed countries.

1	Angola	46	Ghana	91	Norway (hd)
2	Albania	47	Greece (hd)	92	Nepal
3	United Arab Emir. (hd)	48	Guatemala	93	New Zealand
4	Argentina	49	China (hd)	94	Oman
5	Armenia	50	Honduras	95	Pakistan
6	Australia (hd)	51	Croatia	96	Panama
7	Austria (hd)	52	Haiti	97	Peru
8	Azerbaijan	53	Hungary	98	Philippines
9	Belgium (hd)	54	Indonesia	99	Poland
10	Benin	55	India	100	Portugal
11	Bangladesh	56	Ireland (hd)	101	Paraguay

Table A1. *Cont.*

12	Bulgaria	57	Iran	102	Qatar
13	Bahrain	58	Iraq	103	Romania
14	Bosnia and Herzegovina	59	Iceland (hd)	104	Russian Federation
15	Belarus	60	Israel	105	Saudi Arabia
16	Bolivia	61	Italy (hd)	106	Sudan (Former)
17	Brazil	62	Jamaica	107	Senegal
18	Brunei Darussalam	63	Jordan	108	Singapore (hd)
19	Botswana	64	Japan (hd)	109	El Salvador
20	Canada (hd)	65	Kazakhstan	110	Serbia
21	Switzerland (hd)	66	Kenya	111	Slovakia
22	Chile	67	Kyrgyzstan	112	Slovenia
23	China	68	Cambodia	113	Sweden (hd)
24	Côte dIvoire	69	Republic of Korea (hd)	114	Syrian Arab Republic
25	Cameroon	70	Kuwait	115	Togo
26	D.R. of the Congo	71	Lebanon	116	Thailand
27	Congo	72	Sri Lanka	117	Tajikistan
28	Colombia	73	Lithuania	118	Turkmenistan
29	Costa Rica	74	Luxembourg (hd)	119	Trinidad and Tobago
30	Cyprus (hd)	75	Latvia	120	Tunisia
31	Czech Republic	76	Morocco	121	Turkey
32	Germany (hd)	77	Republic of Moldova	122	Taiwan (hd)
33	Denmark (hd)	78	Mexico	123	U.R. of Tanzania
34	Dominican Republic	79	TFYR of Macedonia	124	Ukraine
35	Algeria	80	Malta	125	Uruguay
36	Ecuador	81	Myanmar	126	United States (hd)
37	Egypt	82	Montenegro	127	Uzbekistan
38	Spain (hd)	83	Mongolia	128	Venezuela
39	Estonia	84	Mozambique	129	Viet Nam
40	Ethiopia	85	Malaysia	130	Yemen
41	Finland (hd)	86	Namibia	131	South Africa
42	France (hd)	87	Niger	132	Zambia
43	Gabon	88	Nigeria	133	Zimbabwe
44	United Kingdom (hd)	89	Nicaragua		
45	Georgia	90	Netherlands (hd)		

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