Energy Economics 125 (2023) 106795

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

The impact of energy, renewable and CO_2 emissions efficiency on countries' productivity

Oreste Napolitano [a], Pasquale Foresti [b,g], Konstantinos Kounetas [c,a,*], Nicola Spagnolo [d,e,f]

[a] University of Naples Parthenope, Italy
[b] The London School of Economics and Political Science, UK
[c] University of Patras, Greece
[d] Centre for Applied Macroeconomic Analysis (CAMA), Canberra, Australia
[e] Economics and Finance, Brunel University London, UK
[f] Economics, Universita' degli Studi della Campania, Italy
[g] University of Roehampton, UK

ARTICLE INFO

JEL classification:
D24
O13
O47
Q40

Keywords:
Technological heterogeneity
Metafrontier
Energy efficiency
Hansen threshold methodology

ABSTRACT

In this article, we investigate the combined impact of energy, renewable and CO_2 efficiency on countries' overall productive performance. To this aim, we employ a global-level dataset of 127 countries for more than two decades. The main takeaways of our research are the following. Overall, our analysis supports the idea that incentivizing energy efficient practices should result in more efficient productive processes and economic growth. However, thanks to the combined use of Directional Distance Function, Cluster analysis and Hansen threshold techniques, we evidence strong heterogeneity across different groups of countries. As a consequence, we argue that the international environmental reforms agenda should not follow a one-size-fits-all approach and, especially in relation to less developed economies, it should go hand in hand with other kinds of reforms.

1. Introduction

The world has witnessed a significant economic development over the last three decades. However, the extensive growth model – associated with high investments, high energy consumption, increasing greenhouse gas emissions (GHGs) and pollution – has not been fundamentally changed, impacting on global climate. As a result, increasing concerns about climate change have re-positioned the issues of energy and renewable efficiency. As such efficiencies have impact also on productivity (Hogan and Jorgenson, 1991), there is an increasing attention towards linking countries' productive performance and economic growth with the effects of climate change.

This has also implied an increasing institutional attention towards the development and diffusion of renewable sources and green technologies (Sun et al., 2019; Comin and Hobijn, 2010), as well as the implementation of energy efficiency measures (Worrell et al., 2022), based on the assumption that they can: reduce pollution (Wirl, 2004) by mitigating anthropogenic greenhouse gases (Akram et al., 2020); alter countries' energy mix by enhancing their energy security and dependence (Stergiou and Kounetas, 2021); evolve into a valuable asset for reducing GHGs and fulfilling the Paris Agreement objectives (IPCC, 2021); enhance competitiveness and promote economic growth via innovation (Jaffe et al., 2002; Popp et al., 2010).

However, although there is strong theoretical consensus on the relations between total factor productivity and energy consumption (Schurr, 1982; Jorgenson, 1984), the effects of energy efficiency, renewable efficiency and CO_2 emissions on total factor productivity have not been fully clarified yet. This lack of understanding is reflected in the contradictory results obtained by the countries that have followed the Kyoto protocol (Almer and Winkler, 2017; Trianni et al., 2013; European Commission, 2019). At the same time, the Paris Agreement, the Climate Action Conference (2018) in Seoul, the Katowice Summit (2018) and the New Green Deal launched by the European Commission (European Commission, 2019) are the proof of the increasing focus on energy efficiency, renewable sources diffusion and CO_2 abatement.

However, despite governmental encouragement and significant pressures to develop renewable technologies, implement energy efficiency measures and mitigate GHGs, further and stronger empirical evidence on the impact of such practices on countries' overall productive performance is needed (see Anwar et al., 2019). In this context, globalization may hinder energy efficiency exploitation (Liu et al., 2023) while

* Corresponding author.
E-mail address: kounetas@upatras.gr (K. Kounetas).

https://doi.org/10.1016/j.eneco.2023.106795
Received 23 February 2022; Received in revised form 1 June 2023; Accepted 9 June 2023
Available online 29 June 2023

institutions' quality play a crucial role (Sun et al., 2019). Hence, in order to contribute to the existing literature, in this paper we perform the following research.

First, we take a fully non-parametric approach to perform benchmarking on total factor energy efficiency, renewable efficiency, CO_2 emissions and productive performance across 127 countries using a Directional Distance Function (DDF). The incorporation of a meta-technology (global) production function and the creation of distinct production structures allow us to reveal any relevant countries' heterogeneity. Hence, in the second step of our investigation we perform a cluster analysis in order to group countries according to their economic situations and according to their potentials to enhance the impact of energy efficiency. Third, the impact of the employed measures of efficiency on countries' productive performance is investigated in a non-linear fashion by using the panel version of the Hansen methodology.

The main results of our study are the following. First, we document how increasing energy, renewable and CO_2 efficiency positively impacts on country's productivity and economic growth. Second, once we segment the countries in our dataset, we show that the impact of efficiency on countries' productivity is substantially stronger in more advanced economies and tends to diminish in less developed ones. Finally, when we differentiate the impact of the adopted measures of efficiency on countries' productivity, based on estimated thresholds of energy efficiency, we find the following. Advanced economies benefit of a multiplier effect, as levels of energy efficiency above the threshold imply a very strong increase in the magnitude of the impact of efficiency on productivity. Although this is true for large part of our sample, very high degrees of energy efficiency can negatively affect country's productivity and growth in less developed economies.

Based on these results, we provide evidence that countries' productivity can be boosted by improving efficiency in energy, renewable and CO_2 emissions but we also show that the international environmental reforms agenda should not follow a one-size-fits-all approach and, especially in relation to less developed economies, it should go hand in hand with other kinds of reforms.

The remainder of the article is organized as follows. Section 2 provides some backgrounds to our research and surveys relevant contributions in the literature. Section 3 presents the methodology adopted in our study. Section 4 describes the employed dataset, while Section 5 discusses our results. Section 6 concludes the study and presents some policy implications.

2. Related literature

Although we have seen an increasing governmental encouragement and pressure to develop renewable and energy efficient technologies, as highlighted in Anwar et al. (2019), so far the scientific literature has not been able to provide clear-cut empirical evidence on the impact of renewable, emissions and energy efficiency on countries' overall productive performance.[1]

In relation to the impact of energy efficiency on economic growth, part of the existing empirical analyses look at specific industries to explore the productivity benefits of energy efficiency measures. Among these, Worrell et al. (2003) review over 70 case studies in the iron and steel industry, Boyd and Pang (2000) focus on the glass industry, while other sectors like transport, residential and public services are studied in Costantini and Martini (2010). Similarly, Montalbano et al. (2022) explore the relationship between energy efficiency and productivity using firm-level data and show a positive relationship between the two variables. Despite the ample sample of industries and countries covered in this study, the estimated positive sign of the relationship holds quite consistently across them. The same conclusion is reached in Cantore et al. (2016) based on a sample of 26 developing countries. Another part of this literature looks at the problem from a more macroeconomic perspective by investigating the causal relationship between measures of energy efficiency and countries' economic growth. Among these, Zakari et al. (2022) provide evidence of a positive relation between sustainable economic development and energy efficiency based on a sample of 20 Asian and Pacific countries using Data Envelopment Analysis (DEA) from 2000 to 2018. Similarly, Pehlivanoglu et al. (2021) show the existence of a positive impact of energy efficiency on economic growth in 21 EU member countries over the 1995–2016 period. Santos et al. (2021), based on data for Portugal spanning the period 1960–2014, conclude that energy efficiency is unit elastic driver of total factor productivity and growth. Using a broader set of 85 countries, Stern (2012) estimates energy efficiency trends over a 37-year period showing that energy efficiency is higher in countries with higher total factor productivity.

Despite this large body of work supporting the idea that energy efficiency facilitates economic growth, another part of the literature suggests that we still need a deeper understanding of this relation. Akram et al. (2021) provide evidence of a positive impact of energy efficiency on economic growth in BRICS countries for the period 1990–2014 but their results are heterogeneous across different quantiles. Sun (2003) compares different paths of energy intensity and GDP per capita in 7 developing countries over the period 1973–1995 and finds that GDP increases have an ambiguous correlation with energy intensity depending on the adopted dataset. Stronger heterogeneity is shown in Rajbhandari and Zhang (2018). The authors use a panel VAR, based on data for 56 economies (classified as high income, upper-middle income and lower-middle income) from 1978 to 2012 and find evidence of long-run causality from energy efficiency to GDP growth only for lower-middle-income economies. On the contrary, in the short run they find bidirectional causality between energy efficiency and economic growth in high-income economies but no causality in both of the middle-income groups. Using energy waste as a proxy of energy efficiency, Oztruk and Acaravci (2010) cannot find any relation between energy efficiency and growth in Albania, Bulgaria and Romania over the period 1980–2006. Lee and Chang (2008) look at energy consumption and GDP and find that more energy consumption caused GDP to grow in 16 Asian countries during the period 1971–2002.

A similar picture seems to emerge from the literature regarding the effects of renewable energy on economic growth and productivity. Polat (2021), based on a dataset covering both developing and developed countries for the period 2002–2014, finds that renewable energy consumption is not a predictor of economic growth in developing countries. Similarly, the panel cointegration analysis in Bayar and Gavriletea (2019) reports short-run positive relation for a group of emerging economies in the period 1992–2014 but no significant long-run effects. In Akram et al. (2021), the empirical results unveil that renewable energy significantly decreases economic growth in BRICS countries and that the negative influence is more robust at the upper quantiles of economic growth. Another study that suggests that renewable energy may be counterproductive to economic growth is Menegaki (2013). Contrary to these studies, Inglesi-Lotz (2016) provides clear evidence of a positive impact of renewable energy on economic growth for a sample of 34 OECD countries over the period 1990–2010. Similar conclusion can be found in Apergis and Payne (2010), Sohag et al. (2021) and Sadorsky (2009). Furthermore, based on a sample of 25 European countries in the period 2007–2016, Ntanos et al. (2018) show that the long-run relationship between consumption of renewable energy and economic growth is stronger in countries with higher GDP. Tugcu et al. (2012) show that renewable energy is a relevant factor to generate economic growth and that such a link can be effectively represented with a production function. Following the same logic, Chien and Hu

[1] Given the copious amount of articles investigating these relationships, it is not possible to cover all the main streams and contributions in the literature in this section. For a more complete coverage, please see Oztruk (2010) and Anwar et al. (2019).

(2007) use the DEA method to estimate the technical efficiency for 45 economies in the years 2001 and 2002. In their production function, the three inputs are labor, capital stock, and energy, while real GDP is the single output. They found that increasing the share of renewable energy among total energy supply will significantly improve technical efficiency.

As suggested by Costantini and Martini (2010) and Rajbhandari and Zhang (2018), the reasons for the mixed findings in both streams of the literature can be due to several factors: the different employed econometric methods, the diverse definitions of variables and proxies and, most importantly, in the countries' specific characteristics and heterogeneities. In our understanding, the main contribution of the present paper is related to the latter. We provide further evidence on the impact of energy and renewable (as well as CO_2 emissions) efficiency on total factor productivity by using a wide sample of 127 countries. We take a fully non-parametric approach to perform benchmarking on these variables by using a DDF. Combining a global technology production function with distinct production functions for each country provides us the opportunity to reveal any relevant countries' heterogeneity. Hence, we also perform a cluster analysis in order to group countries according to their economic situations and according to their potentials to enhance the impact of energy efficiency. Finally, another peculiar feature of this paper is that the impact of the employed measures of efficiency on countries' productive performance is investigated in a non-linear fashion by using the panel version of the Hansen methodology. This allows us to investigate also whether the impact of energy, CO_2 emissions and renewable efficiency on countries' productivity changes according to the degree of energy efficiency.

3. Methodological underpinnings

We employ a two-stage methodological framework. In Sections 3.1 and 3.2, we first present the theoretical and methodological approaches regarding the estimation of energy, renewable and CO_2 efficiency scores. We also discuss an expansion in a meta-frontier framework highlighting the role of heterogeneity in the estimated results.

In the second stage (Section 3.3), we introduce a threshold model, with possible multiple equilibria, in which the sample splitting is based on a continuously-distributed variable. Specifically, since the interconnection between productive performance and energy efficiency may not be adequately captured by a linear specification, we estimate the model via the Hansen methodology. The implementation of the Hansen methodology is also complemented by a cluster analysis.

3.1. Directional distance function under cluster technology and meta-technology framework

The first stage of our research methodology can be presented by relying on the works of Chambers et al. (1996) and Färe and Grosskopf (2000), Färe et al. (2005).

Assume that a country employs a vector of inputs $x \in R_+^N$ to produce a vector of outputs $y^* \in R_+^M$. There are two kinds of outputs, namely the good (desirable) and the bad (undesirable) output that form two subvectors of the $y^* \in R_+^M$ output set. The good/desirable output is Gross Domestic Product, $y = (y_1, y_2, \dots, y_k) \in R_+^K$, while the bad/undesirable output is Carbon Dioxide Emissions (CO_2), $b = (b_1, b_2, \dots, b_k) \in R_+^L$. Let us now define $P(x)$ as the feasible output for the given vector $x \in R_+^N$ and $L(y, b)$ as the input requirement set for a given output vector y^* or (y, b). The following technology set denotes the relationship between the input and the output and can be defined as $T(x) = \{(y, b) : x$ can produce $(y, b)\}$. It is a bounded, non-empty and closed set used to represent the environmental production technology (Chambers et al., 1996). Moreover, the technology set satisfies that if $(x, y) \in T$, $x' \geq x$ and $y' \leq y$, then $(x', y') \in T$ (free disposability). This implies that if an observed output vector is feasible, then any output vector smaller than that is also feasible. The good and the bad outputs are null-joint, so that if $(x, y) \in T$, and $x = 0 \Rightarrow y = 0$ (no free lunch) and finally $(0, 0) \in T$ (Kumar, 2006; Mayer and Zelenyuk, 2014). There are two additional assumptions that are crucial for the determination of the DDF: weak and strong disposability. The assumption of weak disposability implies that it is not possible to reduce undesirable output without reducing the desirable one and thus if $(y, b) \in P(x)$ and $0 \leq \theta \leq 1$, then $\theta(y, b) \in P(x)$. The strong disposability assumption considers $(y, b) \in P(x)$ and $y^* \leq y$, then $(y^*, b) \in P(x)$, and it suggests that it is possible to reduce desirable output without reducing the undesirable one.

It turns out that the DDF is a representation of a multiple-output, multiple-input distance function. Following Chambers et al. (1996), Picazo-Tadeo et al. (2005), we can define the DDF on the technology T as:

$$\overline{D_T}(x, y, b; g_y, g_b) = max\{\beta^* : (x, y + \beta^* g_y, b - \beta^* g_b) \in T(x, y, b)\} \tag{1}$$

which allows to proportionally increase desirable outputs, while undesirable outputs are proportionally decreased using the non-zero direction vector $g = (g_y, g_b)$.[2] This vector determines the output-input variables to be scaled and corresponds to the desirable and undesirable outputs determining the direction towards which efficiency is measured. This function is an implicit representation of an M-output and N-input production technology where an input–output vector is feasible if and only if $\overline{D_T}(x, y, b; g_y, g_b) \geq 0$.[3] The directional vector specifies in which direction an output vector is scaled so as to reach the boundary of the output set. This implies that a country becomes more efficient by increasing good outputs and decreasing bad outputs simultaneously. The solution β^* gives the maximum expansion and contraction amount of good and bad outputs, respectively, or the distance between an observation in a country in our study and a point on the production frontier (Watanabe and Tanaka, 2007).

In a global scale with L countries, where each of them has a specific state of technology S that belongs to a specific cluster with different characteristics (i.e OECD), a meta-frontier is defined as the boundary of the unrestricted technology set. In this case, if technology is freely interchangeable (Casu et al., 2016) and the L countries have potential access to the same technology, we can apply the same DDF in a meta-frontier framework (Hayami, 1969; Hayami and Ruttan, 1970). The basic thinking behind the meta-production is to emphasize the heterogeneity of production technology within different countries to reflect regional, economic, scale and other inherent attributes. All countries can be potentially divided into clusters according to the different sources of technological and other relevant heterogeneity. The notion of the meta-frontier comes into play at this stage as it provides a benchmark for all the participating countries irrespective of the frontier to which each of them belongs. Hence, given F technologies $T^1, T^2, \dots, T^F$, the meta-technology set (denoted as T^M) can be defined as the convex hull of the jointure of all technology sets (O'Donnell et al., 2008) and it can therefore be considered as a "basket" of the available technologies for all countries. Hence, the meta-technology set is defined as $T^M(x) = \{(y, b)$: x can produce $(y, b)\}$ in at least one of $T^1, T^2, \dots, T^F$ and the associated input-oriented meta-technical directional distance function is given by:

$$\begin{aligned}&\overline{D_T^M}(x, y, b; g_x, g_y)\\&\quad = \left\{max\beta^M : (x, y + \beta^M * g_x, b - \beta^M * g_y) \in T^M(x, y, b)\right\}\end{aligned} \tag{2}$$

The corresponding efficiency score is easily obtained by solving an analogous LP problem (see Eq. (4) in Section 3.2). Each productive efficiency score obtained from the estimation with respect to the individual technology (Eq. (1)) and common technology (Eq. (2)) can be used

[2] The choice of the appropriate directional vector depends on the research peculiarities and hypotheses under investigation.

[3] In this study we consider the simplest case in which the direction is assumed to be $\overline{D_T}(^*; g_y, g_b) = (^*; 1, -1)$.

to define the so-called meta-technology ratio. Such ratio is considered as a measure of proximity of the kth cluster individual frontier to its meta-frontier or, in other words, how close a system frontier is to the global meta-technology (meta-frontier). Thus, we can define the following meta-technology ratio (O'Donnell et al., 2008; Kounetas and Napolitano, 2018; Tsekouras et al., 2017; Kounetas and Zervopoulos, 2019) as the fraction of country meta-technical efficiency to technical efficiency:

$$MTR(x,y,b) = \frac{MTE(x,y,b)}{TE(x,y,b)} = \frac{1-\beta^M}{1-\beta^F} \tag{3}$$

together with the associated technology gap, (Kontolaimou et al., 2012; Kounetas et al., 2009).

3.2. Non parametric specification DEA and input-oriented slack based model

The use of the DDF is an alternative approach to the measurement of performance that can increase desirable outputs and simultaneously reduce undesirable ones. The formulation used in the literature for the estimation of environmental efficiency scores refers, on the one hand, to the non-parametric DEA model while, on the other hand, to the parametric frontier specification output (Kounetas et al., 2021). In this study, the non-parametric DEA model is employed on the basis that each year embraces different technology possibilities for the countries participating in the sample. The output distance function for the ith country is obtained by solving the following maximization problem (see Picazo-Tadeo et al., 2005; Watanabe and Tanaka, 2007):

$$\begin{aligned}
&\overline{D_T}(x^{k^*}, y^{k^*}, b^{k^*}; g_y, g_b) = min\beta^{k^*} \\
&S.t \quad \sum_{k=1}^{K} z_k y_{km} \geq y_{k^*_m} + \beta^{k^*} g_{y_m}, \quad m = 1,2,\dots,M \\
&\sum_{k=1}^{K} z_k y_{ki} = b_{k^*_i} - \beta^{k^*} g_{b_i}, \quad i = 1,2,\dots,I \\
&\sum_{k=1}^{K} z_k x_{km} \leq x_{k^*n}, \quad i = 1,2,\dots,N \\
&\sum_{k=1}^{K} z_k = 1 \\
&z_k \geq 0, \quad k = 1,2,\dots,K
\end{aligned} \tag{4}$$

where z_k is the weight of the kth country.

However, the current study also focuses on the estimation and evaluation of energy and renewable efficiency as well as of CO_2 emissions efficiency. It is well known that the DEA methodology provides additional information on the features of inputs–outputs such as the input slacks, as well as the radial and non-radial adjustments for the inputs considered in the production possibility set. This allows for the calculation of the Total Factor Energy Efficiency (TFEEF) measure as formulated by Hu and Wang (2006). TFEEF is opposed to single factor energy efficiency measures, i.e. the energy intensity, since it captures energy input efficiency in a total factor framework (Hu and Wang, 2006; Hu and Kao, 2007; Honma and Hu, 2008; Zhou et al. 2011; Stergiou et al., 2023) and thus incorporates all the interrelationships within the production technology (Zhang et al., 2013).[4] Further developments including the calculation of the TFEEF taking into account the presence of undesirable output can be found in works by Zhou et al. (2017),[5] Li and Hu (2012) and Bi et al. (2014). Thus, total factor energy, renewable energy and CO_2 emissions efficiency can be defined, with respect to the universal technology, as follows:

$$TFEEF_{it} = \frac{Target\ Energy\ Input_{i,t}}{Actual\ Energy\ Input_{i,t}} = 1 - \frac{(Energy\ Input\ Slack_{i,t} + Radial\ Adjustment_{i,t})}{Actual\ Energy\ Input_{i,t}} \tag{5}$$

$$TREEF_{it} = \frac{Target\ Renewable\ Input_{i,t}}{Actual\ Renewable\ Input_{i,t}} = 1 - \frac{(Renewable\ Energy\ Input\ Slack_{i,t} + Radial\ Adjustment_{i,t})}{Actual\ Renewable\ Energy\ Input_{i,t}} \tag{6}$$

$$\mathrm{TCO_2EF_{it}} = \frac{(TargetCarbonDioxideOutput)_{i,t}}{ActualCarbonDioxideOutput_{i,t}} = 1 - \frac{(CarbonDioxideOutputSlack + RadialAdjustment)_{i,t}}{ActualCarbonDioxideOutput_{i,t}} \tag{7}$$

As it can be seen from Eq. (5), (6) and (7), all the measures are established based on total factor productive performance and sustainable development process under the existence of undesirable output. However, it must be noted that the estimations of the above-mentioned efficiencies are based on using a Slacks-Based Measure (SBM) model that is taking into account a DEA environment technology (Zhou et al., 2008). Thus, the introduction and calculation of each specific efficiency is made using an input-oriented SBM model as follows:

$$\begin{aligned}
&min\rho = 1 - \frac{1}{L}\sum_{i=1}^{L}\frac{s_l^{e-}}{e_{l0}} \\
&S.t \sum_{j=1}^{J} z_j y_{ij} + s_i^{x-} = x_{i0}, \quad i = 1,2,\dots,M \\
&\sum_{j=1}^{J} z_j e_{lj} + s_l^{e-} = e_{l0}, \quad l = 1,2,\dots,L \\
&\sum_{j=1}^{J} z_j y_{rj} - s_r^{y+} = y_{r0}, \quad r = 1,2,\dots,R \\
&s_i^{x-}, s_l^{e-}, z_j \geq 0, \forall i,j,l,r
\end{aligned} \tag{8}$$

In Eq. (8), subscript 0 represents the country to be evaluated, the vectors s_i^{x-}, s_l^{e-} indicate the non-specific and specific input excess (energy, renewable energy, CO_2 emissions) while s_r^{y+} represents the desirable output shortfall.

3.3. A non-linear approach

The aim of our analysis is to investigate a possible non-linear functional form between productive performance and energy efficiency. The dependent variable used in our empirical analysis is the productive performance, retrieved as explained in Section 3.1. The same applies to the main independent variable (energy efficiency) and to the control variables (renewable efficiency and CO_2 efficiency).

The empirical investigation presented in this paper consists of a panel data analysis in which we argue that the linear relationship may hold only up to a certain threshold. In other words, the estimated coefficient of interest in a linear regression setting would only represent a weighted average of the same coefficient estimated in specific subsamples, which compose the sample in full. Neglecting the potential non-linearity dynamics would lead to a misleading interpretation of the causality effect and can cast doubts on the real magnitude of such an effect.

[4] This work considers that weak disposability in outputs implies that reducing the undesirable outputs (emissions in our case) is rather costly in terms of proportional reductions in good output.

[5] In this study, the imposition of weak disposability in outputs implies that reducing the undesirable outputs is rather costly in terms of proportional reductions in good output referring to congested production technology set.

Hence, we employ the Hansen (1999, 2000) threshold test procedure.[6] The threshold regression model can be described as follows:

$$TE_{i,t} = \alpha_i + \beta_1 TFEEF_{i,t} \cdot I(TFEEF_{i,t} \leq \gamma) + \beta_2 TFEEF_{i,t} \cdot I(TFEEF_{i,t} > \gamma) + \phi TREEF_{i,t} + \theta T\mathrm{CO_2EF}_{i,t} + \varepsilon_{i,t} \tag{9}$$

Where $TE_{i,t}$ is the technical efficiency score for country i at time t; α_i is the country specific effect and where $I(.)$ is the indicator function used to sort the data; $TFEEF_{i,t}$, is energy efficiency, $TREEF_{i,t}$ is renewable efficiency and $TCO_2EF_{i,t}$ is CO_2 efficiency; γ is the threshold value and ε_{it} the error term. Eq (9) can also be rewritten as:

$$TE_{i,t} = \begin{cases} \alpha_i + \beta_1 TFEEF_{i,t} + \phi_1 TREEF_{i,t} + \theta_1 \mathrm{TCO_2EF_{i,t}} \\ \quad + \varepsilon_{i,t}, TFEEF_{i,t} \leq \gamma \\ \alpha_i + \beta_2 TFEEF_{i,t} + \phi_2 TREEF_{i,t} + \theta_2 TCO_2EF_{i,t} \\ \quad + \varepsilon_{i,t}, TFEEF_{i,t} > \gamma \end{cases} \tag{10}$$

We test whether there is statistically significant evidence of a threshold in energy efficiency $TFEEF_{i,t}$ to productive performance depending on the parameter γ considering that the regimes have different slopes. We also assume that the threshold variable is non time-invariant and that the errors follows an iid.

4. Data

Regarding the composition of the dataset, our main objective was to create a wide sample over a sufficiently long and representative period of time. Since variables were retrieved from different sources (see Table 1), we have experienced a trade-off between data availability in the time domain and in the cross-section dimension. For some countries, available data were long-standing and up to date (like CO_2 emissions), while for other countries the reliable data were of more recent origin. As a result, for our analysis we have employed a balanced panel dataset including 127 countries[7] and spanning the period 1990–2014.

4.1. Variables measurement

The measurement of most of the variables used in this paper is relatively straightforward. We approximate the desirable output by using GDP in million dollars (in 2010 current prices), while we use CO_2 emissions (in metric tons) as the measure of undesirable output.[8] On the input side, we use Capital Stock, Labor Force, Energy Consumption and Renewable Energy Consumption. Capital stock is appertained to Gross Fixed Capital Formation in millions of constant 2010 U.S. dollars. Labor consists of Total Labor Force measured as the number of people (in thousands) aged 15 and over who are employed or looking for a job.[9] In addition, for the energy consumption variable we used Total Primary Energy Supply. This is provided by the International Energy Agency (IEA, 2000) and is expressed in units of tons of oil equivalent per thousand year-2000 purchasing price parity US dollars. This measure accounts for all energy consumed within a country (Liddle, 2012) and is made up of production imports, international marine bunkers and international aviation bunkers. It adjusts for the energy consumed in producing electricity and it is different from the delivered energy (Liddle, 2012; Kounetas, 2018). Finally, renewable energy consumption is measured as the Share of Renewable Energy in Total Final Energy Consumption (See Table 1). Table 2 provides the descriptive statistics of all the variables, while Table 3 presents the associated percentiles for our input and output specification.

4.2. Clustering and countries heterogeneity

The use of the meta-frontier, by itself, does not allow to identify homogeneous groups of countries. Hence, we perform a cluster analysis in order to group countries with similar economic situations. The clustering of the 127 countries has been carried out on the basis of the Economics and Competitiveness Index provided by the Heritage Foundation.

The index is based on 12 sub-pillars (property rights, government integrity, judicial effectiveness, tax burden, government spending, fiscal health, business freedom, labor freedom, monetary freedom, trade freedom, investment freedom and financial freedom). Our clustering has been based on these 12 sub-pillars as, although not exhaustive, they can be useful to group countries based on principles that are very pertinent to our research. This is due to the fact that grouping countries on the basis these 12-pillars criteria can provide insights on their capabilities to exploit the benefits of energy efficiency. Good performance in terms of property rights protection, government integrity and healthy finances, general economic freedom with weak market distortions, as well as trade and financial openness, could foster investments in sectors with low competitiveness in the efficient use of energy. This should then trigger synergies able to boost the development and impact of energy efficiency (Chatzistamoulou et al., 2019; Kounetas, 2015; Samoilenko and Osei-Bryson, 2008, 2010).

Then, to check if it is possible to derive from this set of criteria different clusters for the countries in our dataset, we have applied a principal component analysis (PCA) to evaluate the degree of correlation between the different parameters of the twelve selected indicators. If the data exhibits clustering, this will be generally revealed with the PCA analysis: by retaining only the components with the highest variance, the clusters will be likely more visible (as they are most spread out). In this step, we find the optimal number of components that capture the greatest amount of variance in the data. This method defines the clusters taking into account the differences from each other (heterogeneity between clusters) but also emphasizing the same distinguishing features (homogeneity within the cluster).

We identify three clusters by covering 95% of the variance. Since the first three components explain the majority of the variance in our data, we can set K=3 and apply K-means algorithm to perform a classification of our dataset. The composition of the three clusters is reported in Table 1 (see also Fig. 1) for a geographical representation of the three clusters. The first cluster, called A, includes 40 countries. Most of them are economies that in the last 10 years have experienced incomes that are more than twice the average level in all other countries of cluster B and more than five times higher than the one of the countries in cluster C. In this cluster, economic freedom is closely related to openness and limited government economic intervention, both of which encourage entrepreneurial activity. Theoretically, the idea of economic freedom and growth nexus in the presence of energy use entails that the economies with more freedom are assumed to be more energy efficient (Gillingham and Palmer, 2020). Moreover, these countries are characterized by path dependence, that is, the complex processes that are 'unable to shake free of their history' (David, 2001). For most of them, the adoption of environmentally friendly technologies is based on past decisions and behavior signifying the role of past-accumulated knowledge and technical capabilities (Aklin and Urpelainen, 2013; Ćetković and Buzogány, 2020).

The second cluster, called B, is formed by 56 countries. Most of them are defined as developing countries with upper and low middle-income

[6] The above methodology does not require any prior about the value of the threshold as it allows testing for the presence of a threshold, if any, endogenously.

[7] For the full list of countries in the dataset, see Table 6.

[8] We are aware that these are presented in line with $UNFCCC$ accounting rules and $IPCC$ reporting guidelines. This implies that these do not often readily capture changes in fuel and that the sectoral mix of energy uses both upstream and downstream.

[9] It has to be noted that some countries do not incorporate members of the armed forces.

Table 1
Description of variables (inputs–outputs).
Source: All variables data, except energy consumption (IEA), were retrieved from the World Bank Database.

Variable	Measurement
GDP	Millions of constant 2010 US dollars
CO_2 Emissions	Metric tons
Gross Fixed Capital Formation	Millions of constant 2010 US
Labor Force, Total	Thousands of people
Energy Consumption	Kilograms of oil equivalent
Renewable Energy Consumption	(%) Share of renewable energy in total final energy consumption

Table 2
Descriptive statistics of inputs–outputs.

Variable	Obs	Mean	St. Dev.	Min	Max
GDP (millions of US dollars)	3048	13404.9	18120.5	160.3	110001.1
CO_2 Emissions (metric tons)	3048	5.1	5.6	0.05	38.3
Capital (millions of US dollars)	3048	91400	294000	0.001824	3530000
Labor (thousands of people)	3048	21600	76600	142	802000
Energy Consumption (kg of oil equivalent)	3048	2213.6	2377.7	102.2	18177.3
Renewable Energy Consumption (% of total energy use)	3048	30.1	29.2	0.002	98.3

Table 3
Percentiles of inputs–outputs.

	GDP	Capital Stock	Labor Force	En. Cons.	Ren. En. Cons.	CO_2 Emissions
10%	726.58	3.77	983174	363.26	1.15	0.25
25%	1616.21	22.2	1.96	561.68	5.08	0.94
50%	4934.13	94.9	4.63	1346.38	18.57	3.512
75%	17201.65	521	14.4	3067.86	51.1	7.582
90%	41120.41	2220	470	11094.97	78.83	11.11

and with standard of living, income, economic and industrial development that remain more or less below average of the countries in cluster A. For this second group, instead of having a path dependence we have to consider a sort of path creation. For them, although the initial conditions seem to be very weak, once a path has been selected, various mechanisms can lead to its self-reinforcement, such as positive network externalities or increasing returns (e.g. to scale, to scope, to learning). In order to implement these specific steps, the interconnection with more developed economies (cluster A) could play a crucial role in speeding up this process. Hence, the connection between economy and environment is a reflection of structural changes. They reveal a transition from an agricultural society to an industrial economy and then to a service-oriented economy.

The third cluster, called C, includes 28 countries. These countries are characterized by economies that showed very low growth within the last three-four decades. For these countries, avoiding dangerous climate change will make it necessary to reduce (or slow the increase of) their emissions. To date, however, in many cases emission-intensive fossil fuels constitute the least expensive source of energy, being significantly cheaper than low-carbon alternatives like renewable energy. These countries are facing low productivity, inefficient use of energy, and a low level of knowledge and technical capabilities. Furthermore, for many countries in this cluster, when we look at the measures of judicial effectiveness, property rights, governmental integrity and overall economic freedom, their performance is below average.

To gain a better understanding of the dynamics of such groups of countries, we have also split our sample and have applied the cluster analysis to four different sub-periods. Then, we have checked for switches of counties from one cluster to another over time. Over the first three sub-periods, 32 countries were involved in these switches. All of them had upgrade switching (i.e. from cluster C to cluster B or from cluster B to cluster A) except for Bangladesh, Ethiopia and Ukraine. Then, in the last sub-period the clusters' composition has not substantially changed, since only three countries (Armenia, Libya and Saudi Arabia) moved from cluster B to cluster C. These shifts highlight worsened economic conditions in these three countries, in comparison to the others. Instead, the countries previously in cluster A and C did not move.

5. Results and discussion

The discussion of the empirical results follows the two-stage structure of the methodology section. The estimated countries' specific efficiency measures (energy, renewable and CO_2) are first presented and discussed. Then, these measures are linked with the composition of the three clusters. Finally, we discuss the estimated impact of countries' energy, renewable and CO_2 efficiency on their productive performance (both at individual and cluster level).

5.1. Countries' energy, renewable and CO_2 efficiency

The main results under the condition that all countries have access to the common technology, known as global meta-technology, are presented in Table 7. Overall, energy and renewable efficiency report average high scores with values 0.886 and 0.847, respectively. In particular, for the energy efficiency case a club of countries (Australia, Belarus, Belgium, Canada, Croatia, Cyprus, Czech Republic, Denmark, Finland, France, Germany, Hong Kong, Hungary, Iceland, Iran, Italy, Israel, Jordan, Latvia, Luxembourg, The Netherlands, New Zealand, Norway, Poland, Portugal, Russia, Slovak Republic, Slovenia, Spain, Sweden Switzerland, United Arab Emirates, UK and USA) performs on the frontier regarding the specific inputs. These findings are in accordance with Halkos and Tzeremes (2010), for EU countries (i.e Finland, Norway, Spain, etc.), and Chien and Hu (2007), for OECD countries (i.e., Luxembourg, UK, Finland, Norway and Ireland). A more illustrative representation of our energy efficiency results is depicted in Fig. 2.[10] With regards to total factor energy efficiency, countries' performance was high on average. Countries like Mexico, Nepal, Mongolia, Sri Lanka, Kenya, Cambodia, Sudan and Malaysia defined the lowest average efficiency levels regarding the use of energy. In general, countries within North America showed high average total factor energy efficiency, while in South America, countries indicated moderate

[10] We distinguish three categories: low with values < 0.5, moderate with values in the [0.5, 0.8] interval and high with values > 0.8.

performance, on average. Conversely, Asia demonstrated low average total factor energy efficiency.

Regarding renewable efficiency, again Ireland, Luxembourg, The Netherlands, Saudi Arabia, Singapore, Switzerland, Ukraine, UAE and UK performed best, followed by mainly Scandinavian countries, denoting a significant smaller number of leading countries (see Table 7). Also in this case, Fig. 3 provides a spatial distribution of the average total factor renewable efficiency scores.[11] Indeed, the specific results regarding renewable efficiency are not surprising, as all these countries have heavily restructured their energy mix over the period under investigation. Countries that hold big scarcities of resources might develop straighter and more considerable policy and management of the production process leading to better energy and renewable energy scores than countries living in prosperity. Regarding CO_2 emissions efficiency, the mean is 0.907. The countries that appertain to the left tail of the distribution and form the outliers are Albania, Cambodia, Congo, Nigeria and Kenya. As for energy and renewable energy, also for CO_2 emissions efficiency Table 7 reports values for all countries in the dataset, while Fig. 4 shows the geographical distribution of this score. Another relevant result is that all countries delineate high and constant levels of efficiency from the middle of the 2000's.[12] Finally, at this point, it is worth mentioning that these discrepancies in energy and renewable efficiency scores could also be due to the differences in the input–output mix used, the different sample of countries, the time period and the methodology adopted.

Apart from the findings concerning efficiency estimates at the global scale, it is also interesting to compare the individual countries' scores with respect to their respective cluster. Table 8 presents our estimates, at average level, for the three clusters. It is clear the cluster A appears to have a better performance in terms of different types of efficiency. The basic assumption is that the strong relationship between energy, water, materials and waste makes it possible to obtain strategic multiplicative effects on productivity performance and economic growth. It also encourages policy makers and firms to reconsider industrial production with significant potential impacts on competitiveness. The same picture holds for the case of cluster B compared to cluster C. Thus, the apparent contradiction of the results obtained for cluster B can be explained considering that the energy situation in developing countries is highly variable. Per capita electricity consumption is significantly lower than that of industrialized countries while the annual growth rate of energy consumption in developing countries is three to four times higher than that of industrialized countries.

In terms of differences, we can denote that regarding productive performance, renewable and energy efficiency there is a significant variation between the three clusters. The variation diminishes in the case of CO_2 efficiency. Looking at each cluster, we can observe the same performance regarding individual countries. For example, countries in cluster A as UK, USA, Sweden, Finland, The Netherlands, etc. perform best. On the other hand, for cluster B countries that are top performers are Belarus, Brazil, Greece, Iceland, Kuwait, Russian Federation and United Arab Emirates. Regarding cluster C, only few of its countries can be characterized as the best performers (i.e Argentina, Chile, China, Gabon, Jordan, Mexico and Panama).[13]

Finally, in Fig. 6 we plot the retrieved measures of energy, renewable and CO_2 efficiency against the estimated measure of countries' productivity (technical efficiency). First of all, the three scatter plots suggest the possibility of a positive link between the variables. Furthermore, they also show how, especially in relation to energy and CO_2 efficiency, many countries in cluster A tend to associate high technical efficiency with good performance in the energy measures. On the contrary, many countries in cluster C have low scores in both dimensions of the scatter plots, while a more mixed picture emerges for countries in cluster B.

5.2. The impact of energy, renewable and CO_2 efficiency on countries' productivity

Having retrieved the productivity and efficiency measures, we can now apply our regression model as specified in Eqs. (9) and (10) to the meta-technology and to the three specific technologies (belonging to clusters A, B and C, respectively). The analysis has been carried out with the Hansen threshold methodology through a fixed effect panel model.[14] Tables 4 and 5 summarize the results.

We first look at the results of the estimations obtained without differentiating between regimes. The estimation related to the metafrontier shows that, overall, there is a positive impact of all three efficiency variables on countries' productivity. The strongest impact is attributed to energy efficiency (0.31). CO_2 estimated coefficient is 0.21, while the estimated coefficient for renewable efficiency is 0.12. All the estimated coefficients are statistically significant. The same analysis conducted on the three separate clusters confirms the fact that all the three variables have a positive impact on countries' productivity performance. Nevertheless, in relation to the magnitude of these effects, there are some differences between the clusters. Energy efficiency has a strong impact in cluster A (0.67) and a weaker impact in cluster B (0.02) and C (0.14). In cluster B, CO_2 has the strongest impact (0.36), while the impact of all the three variables is quite weak in cluster C with the impact of energy efficiency (0.14) being the strongest.[15]

These differences in terms of the impact of the measures of efficiency seem to be in line with what implied by our clustering. Overall, the impact of efficiency is strong in countries that have the best performance in terms of the 12-pillars classification adopted to generate the clusters. As we stated in Section 4.2, the 12 pillars are related to the capability of creating good grounds and environments for a positive impact of energy efficiency. Hence, as the performance in terms of the 12 pillars becomes progressively weaker in cluster B and then in C, it implies that the capability of energy, renewable and CO_2 efficiency to boost countries' productive performance becomes weaker and weaker as well.

Given the broad picture provided by the linear (no-regime) estimation of Eq. (9), we can then provide further insights by looking at the results of the Hansen method. With the Hansen estimations at the individual clusters level (Table 4), we find thresholds in clusters A and C with high levels (above 0.93), whereas in cluster B the threshold is substantially lower (0.73). The likelihood ratio clearly highlights the presence of one threshold only in the cases of cluster A and C, whereas for cluster B the presence of a second threshold cannot be disregarded.

More specifically, for countries in cluster A, energy efficiency positively and significantly affects their productive performance. The magnitude of such effect is more than 10 times larger (9.406) for countries with an efficiency exceeding the threshold (equal to 0.94) compared to the one (0.829) of countries with energy efficiency below the threshold.

[11] Morocco, India and Gabon indicated the lowest mean values, while Russian Federation, United States, Netherlands, Switzerland, Luxembourg and United Kingdom displayed the high average levels. Moreover, fluctuations across the countries within North and South America are observed. Regarding the use of the renewables, countries within North America indicated high and very low efficiency, while within South America, countries displayed very low, low and moderate efficiency.

[12] We distinguish five categories: very low with values < 0.5, low with values in the [0.5, 0.6] interval, moderate with values at the [0.6,0.7] interval, high with values between 0.8 and 0.9 and very high with values greater that 0.9.

[13] Fig. 5 presents all measures for each of the participated countries. We owe this to an anonymous reviewer.

[14] This decision has been taken after testing for fixed vs random effects. The results of the test, not reported due to space constraints and available from the authors upon request, suggested a fixed effect specification.

[15] All the estimated coefficients are statistically significant except for CO_2 in cluster A and Renewable Efficiency in Cluster B.

Table 4
Clusters threshold regression estimates.

Countries Cluster A			
	No regimes	With regimes	
Estimated thresholds		Regime 1	Regime 2
		>0.94	≤ 0.94
$TFEEF$	0.67446***	9.40687***	0.82932***
	(0.08080)	(−0.106122)	(0.15626)
$TREEF$	0.24698***	0.22495***	−0.31593***
	(0.03837)	(0.03633)	(0.11563)
TCO_2EF	0.06531	0.06835	0.11112
	(0.063665)	(0.06189)	(0.47529)
Constant	−0.19471	−8.89352***	0.17046
	(0.11174)	(−0.10493)	(0.53475)
Observations	864	810	50
R-squared	0.12	0.14	0.39
LM-test for no threshold		37.922	
Bootstrap (p-value)		0.000	
Countries Cluster B			
	No regimes	With regimes	
Estimated thresholds		Regime 1	Regime 2
		>0.73	≤0.73
$TFEEF$	0.025714	0.102483	−0.6093***
	(.052191)	(.17621)	(.099002)
$TREEF$	0.220464***	0.241931***	−0.060293
	(0.049747)	(0.055087)	(0.079406)
TCO_2EF	0.366821***	0.387835***	0.20020***
	(0.057331)	(0.080799)	(0.063682)
Constant	−0.085503	−0.194151	0.60453***
	(0.083451)	(0.19792)	(0.113959)
Observations	816	707	109
R-squared	0.05	0.05	0.29
LM-test for no threshold		25.435	
Bootstrap (p-value)		0.000	
Countries Cluster C			
	No regimes	With regimes	
Estimated thresholds		Regime 1	Regime 2
		>0.93	≤ 0.93
$TFEEF$	0.147288***	−2.4705***	0.139824***
	(0.024349)	(0.564766)	(0.035721)
$TREEF$	0.065844***	0.048003	0.123638***
	(0.029486)	(0.035232)	(0.045229)
TCO_2EF	0.097183***	−0.024665	0.198133***
	(0.029301)	(0.0494515)	(0.034415)
Constant	0.148348***	2.8752***	0.014069
	(0.044622)	(0.558983)	(0.058211)
Observations	1584	811	773
R-squared	0.04	0.03	0.06
LM-test for no threshold		43.956	
Bootstrap (p-value)		0.000	

Table 5
All countries threshold regression estimates.

Estimated thresholds	No regimes	With regimes	
		Regime 1	Regime 2
		>0.92	≤0.92
$TFEEF$	0.314023***	−0.050787	0.0716188*
	(0.438769)	(0.023359)	(0.035845)
$TREEF$	0.125035***	0.13181***	0.13308***
	(0.024038)	(0.028159)	(0.040971)
TCO_2EF	0.217788***	0.19381***	0.20267***
	(0.042120)	(0.026704)	(0.031259)
Constant	−0.08227**	0.312789	0.050684
	(.038214)	(.434854)	(.053483)
Observations	3024	2029	985
R-squared	0.08	0.02	0.05
LM-test for no threshold		58.873	
Bootstrap (p-value)		0.000	

This implies a sort of multiplier effect for countries that have invested a lot in energy efficiency. These issues are closely connected with the approach to the efficient use of resources on which the developed countries tend to focus a lot. Renewable energy shows a positive effect (0.224) only once the threshold has been reached, while the estimated effect of CO_2 – although positive and quite stable across regimes – is not statistically significant (Amri, 2017). The basic intuition is that the strong performance of these countries, in terms of the 12-pillars criteria, creates a breeding ground for the impact of energy investment on countries' growth. However, as suggested from our results, strong investments in energy are required in order to magnify such impact. Possible explanations arise due to countries' different technological trajectories (Stern, 2012), exploitation of technological opportunities related to energy efficient and RES innovations (Rexhäuser and Löschel, 2015) and the role of each country absorptive capacity related to these technologies (Chatzistamoulou et al., 2019).

Results for cluster B show at first that the threshold is substantially lower compared to the other two clusters (0.75). As a result, we see that energy and renewable efficiency negatively affect productive performance for values below that threshold. At the same time, for countries performing above the threshold there is evidence of positive (although non-statistically significant for energy efficiency) effect. These results are strongly affected by the quite low estimated threshold. Developing countries with low performance in energy efficiency are likely to have not enhanced any virtuous mechanism yet, meaning that investment in energy cannot impact positively on productivity due to the overall low level of efficiency. Furthermore, there is a great deal of evidence that lack of funding in the energy sector is a major problem for developing countries that cannot be solved solely with public budgets or development aid. It is therefore necessary to attract private investments but these are limited by the absence – or unsatisfactory definition – of energy policy and the lack of institutional power. There is also a lack of a regulatory and financial legislative framework, which is essential for attracting private funding and ensuring the smooth functioning of the market. A possible explanation concerns the different market and environmental regulations imposed by governments and authorities (Bigerna et al., 2019). The regulation framework differentials inside the clusters under examination, although the "homogeneity" in terms of several characteristics accrue the difference in total factor energy efficiency, renewable efficiency and CO_2. Again, one can easily note how these elements are strictly related to the 12-criteria classification used for generating the clusters and with respect to which countries in cluster B require substantial improvements.

Lastly, looking at cluster C, the effect of energy efficiency is significant in both regimes although it is negative (−2.471) above the threshold and positive (0.139) below the threshold. Renewable efficiency and CO_2 efficiency show a positive and significant effect only when the observations are below the threshold. Again, these results can be explained by combining the level of the estimated threshold and the cluster's features in terms of the criteria used to construct it. Given the low performance of these countries in terms of the 12-pillars, they may not have established the necessary environment to enhance the impact of efficiency on countries' productivity. As a consequence, we have a limited impact of efficiency on productivity below the threshold. Following the same logic, investing in efficiency above the – high – threshold will negatively impact on productivity as the high costs cannot be covered due to the lack of the right environment to boost such impact. Country-related concepts heavily influenced by the structure of each economy (Chatzistamoulou et al., 2019), alterations in the composition of each one economy, and by changes in the energy mix (Turner and Hanley, 2011; Chien and Hu, 2007); (Rath et al., 2019), path dependence phenomena (David, 2001; Bleakley and Lin, 2012; Fouquet, 2016) and lock-in for specific energy-inefficient technologies (Aghion et al., 2005) can be considered as possible explanations.

6. Conclusion

In recent years, increasing concerns about climate change have repositioned the issues of energy, emissions, renewable efficiency and productive performance. This article has provided further understanding of the combined impact of energy, renewable and CO_2 efficiency on countries' overall productive performance. To this aim, we have used a global-level data-set consisting of 127 countries to estimate countries' productive performance but also energy, renewable and CO_2 efficiency and their potential links.

Our analysis has identified three clusters of countries showing substantial difference in terms of energy and renewable efficiency, while such difference diminishes in the case of CO_2 efficiency. A panel analysis applied to the entire set of countries has shown how increasing energy, renewable and CO_2 efficiency has a positive impact on country's productivity. However, when we have looked at the effects differentiating between different clusters, the estimated impact of efficiency on countries' productivity has resulted to be substantially stronger in more advanced economies and to diminish in less developed ones. Further insights regarding these results have been provided by the application of the Hansen methodology, where we have segmented the impact of efficiency on productivity based on estimated thresholds of energy efficiency. The results of this analysis have shown that advanced economies benefit from a multiplier effect as levels of energy efficiency above the threshold imply a very strong increase in the magnitude of the impact of efficiency on productivity. It is important to note that while our results have been backed up by the literature with regard to developed economies, results are inconclusive for what concerns developing economies. For the latter, entry barriers may play a detrimental role to the adoption and effectiveness of very high degrees of energy efficiency (see Fowlie and Meeks, 2021, among others).

Overall, our analysis supports the idea that incentivizing energy efficient practices should result in more efficient productive processes and, as a consequence, in further economic growth. Nevertheless, the clusters' heterogeneity that we have found suggests that the international reforms agenda and the related policy recommendations should not follow a one-size-fits-all approach. According to our results, more developed economies will benefit from strong incentives and policies aiming at improving energy efficiency as this should trigger a multiplicative effect magnifying the positive impact of energy efficiency on country's productivity. For less developed economies, our results suggest a more cautious approach as too much investment in energy efficiency may turn into a reduction in productivity. Our analysis suggests that in order to avoid such perverse effect and preserve a steady positive impact of energy efficiency investments on productivity, such countries should also implement reforms aiming at improve their performance in terms of government integrity, judicial effectiveness, fiscal health and general economic freedom and openness.

As this is the first study that quantitatively investigates the nonlinear impact of energy efficiency on productive performance, it presents some limitations that could suggest future research directions. It is noteworthy that this study has an empirical focus at country level. Therefore, the follow-up studies could investigate the problem at firm level or try to develop further its theoretical groundings. Moreover, the utilization of additional variables examining energy mix, innovation activities and technological and regulation aspects would enhance the explanatory power of the relationship.

CRediT authorship contribution statement

Oreste Napolitano: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Visualization, Writing – review & editing. **Pasquale Foresti:** Conceptualization, Writing – review & editing. **Konstantinos Kounetas:** Conceptualization, Methodology, Data curation, Software, Formal analysis, Writing – original draft, Visualization, Writing – review & editing. **Nicola Spagnolo:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

To the memory of our beloved friend and colleague, Oreste Napolitano, who sadly passed away on Saturday 13 August 2022. We would like to thank the Editor Richard Tol and three anonimous referees for very helpul comments and suggestions.

Appendix A. Clusters

See Tables 6–8.

Table 6
List of countries by cluster.

Cluster A							
Australia	Austria	Belgium	Canada	Chile	Croatia	Cyprus	Czech Republic
Denmark	Estonia	Finland	France	Georgia	Germany	Greece	Hong Kong
Hungary	Iceland	Ireland	Israel	Italy	Japan	Latvia	Lithuania
Luxembourg	Malta	New Zealand	Norway	Poland	Portugal	Singapore	Slovakia
Slovenia	Spain	Sweden	Switzerland	The Netherlands	United Kingdom	United States	Uruguay
Cluster B							
Albania	Argentina	Armenia	Azerbaijan	Benin	Bosnia and Herze	Botswana	Brazil
Bulgaria	Cambodia	China	Colombia	Costa Rica	Cote d'Ivoire	Dominican Rep	Egypt
El Salvador	Gabon	Ghana	Guatemala	Honduras	Indonesia	Jamaica	Jordan
Kazakhstan	Korea, Rep	Kuwait	Kyrgyz Republic	Lebanon	Macedonia	Maylasia	Mauritius
Mexico	Moldova	Mongolia	Morocco	Namibia	Nicaragua	Pakistan	Panama
Paraguay	Peru	Philippines	Romania	Russian Fed	Saudi Arabia	Senegal	South Africa
Sri Lanka	Tanzania	Thailand	Togo	Trinidad & Tob	Turkey	Un Arab Em	Zambia
Cluster C							
Algeria	Angola	Bangladesh	Belarus	Bolivia	Cameroon	Cuba	Congo, Dem Rep
Congo, Rep	Ecuador	Eritrea	Ethiopia	Haiti	India	Iran	Libya
Mozambique	Nepal	Niger	Nigeria	Sudan	Tajikistan	Tunisia	Ukraine
		Uzbekistan	Venezuela	Vietnam	Zimbabwe		

Table 7
Countries means of the estimated efficiencies (entire sample).

Country Name	TE	TFEEF	TREEF	TCO2EFF
Albania	0.504	0.715	0.873	0.776
	(0.122)	(0.122)	(0.131)	(0.234)
Algeria	0.818	0.94	0.769	0.923
	(0.06)	(0.026)	(0.271)	(0.104)
Angola	0.299	0.723	0.822	0.886
	(0.054)	(0.1)	(0.187)	0.161)
Argentina	0.306	0.992	0.816	0.893
	(0.048)	(0.008)	(0.125)	(0.116)
Armenia	0.645	0.974	0.873	0.643
	(0.31)	(0.026)	(0.236)	(0.29)
Australia	0.868	1.000	0.898	0.96
	(0.148)	(0.0002)	(0.217)	(0.11)
Austria	0.812	0.99	0.617	0.992
	(0.145)	(0.018)	(0.187)	(0.026)
Azerbaijan	0.225	0.94	0.958	0.964
	(0.173)	(0.095)	(0.143)	(0.064)
Bangladesh	0.671	0.885	0.998	0.808
	(0.138)	(0.145)	(0.005)	(0.289)
Belarus	0.177	1.000	0.882	0.996
	(0.241)	(0.000)	(0.212)	(0.007)
Belgium	(0.792	1.000	0.994	0.895
	(0.13)	(0.000)	(0.026)	(0.255)
Benin	0.211	0.715	0.973	0.546
	(0.049)	(0.272)	(0.058)	(0.331)
Bolivia	0.275	0.604	0.963	0.979
	(0.069)	(0.167)	(0.108)	(0.058)
Bosnia and Herze	0.734	0.815	0.985	0.978
	(0.246)	(0.302)	(0.072)	(0.072)
Botswana	0.487	0.845	0.759	0.965
	(0.063)	(0.133)	(0.105)	(0.108)
Brazil	0.446	0.906	0.927	0.954
	(0.069)	(0.139)	(0.166)	(0.098)
Bulgaria	0.161	0.89	0.96	0.999
	(0.075)	(0.031)	(0.091)	(0.004)
Cambodia	0.197	0.453	0.901	0.553

(continued on next page)

Table 7 (*continued*).

Country Name	TE	TFEEF	TREEF	TCO2EFF
	(0.082)	(0.19)	(0.165)	(0.293)
Cameroon	0.236	0.583	0.94	0.696
	(0.045)	(0.079)	(0.078)	(0.268)
Canada	0.738	1.000	0.682	0.968
	(0.225)	(0.000)	(0.138)	(0.109)
Chile	0.39	0.973	0.554	0.954
	(0.064)	(0.016)	(0.142)	(0.156)
China	0.739	0.615	0.675	0.978
	(0.208)	(0.179)	(0.293)	(0.078)
Colombia	0.516	0.992	0.637	0.945
	(0.081)	(0.037)	(0.289)	(0.185)
Congo, Dem. Rep.	0.096	0.843	0.952	.447
	(0.023)	(0.059)	(0.064)	(0.226)
Congo, Rep.	0.619	0.998	0.981	0.821
	(0.179)	(0.007)	(0.042)	(0.283)
Costa Rica	0.649	0.748	0.983	0.851
	(0.144)	(0.107)	(0.082)	(0.209)
Cote d'Ivoire	0.62	0.604	0.99	0.65
	(0.238)	(0.16)	(0.023)	(0.362)
Croatia	0.444	1.000	0.964	0.962
	(0.05)	(0.000)	(0.137)	(0.087)
Cuba	0.293	0.997	0.823	0.993
	(0.075)	(0.0005)	(0.272)	(0.028)
Cyprus	1.000	1.000	1.000	1.000
	(0.0002)	(0.0002)	(0.000)	(0.0007)
Czech Republic	0.315	1.000	0.923	1.000
	(0.107)	(0.000)	(0.14)	(0.000)
Denmark	0.968	1.000	0.957	0.953
	(0.053)	(0.000)	(0.146)	(0.198)
Dominican Republic	0.441	0.778	0.918	0.965
	(0.082)	(0.079)	(0.199)	(0.08)
Ecuador	0.398	0.787	0.587	0.952
	(0.085)	(0.075)	(0.266)	(0.098)
Egypt, Arab Rep.	0.21	0.763	0.782	0.977
	(0.069)	(0.088)	(0.187)	(0.043)
El Salvador	0.385	0.924	0.987	0.788
	(0.046)	(0.058)	(0.026)	(0.233)
Eritrea	0.67	0.739	0.994	0.831
	(0.149)	(0.096)	(0.012)	(0.299)
Estonia	0.337	0.973	0.759	0.998
	(0.158)	(0.008)	(0.301)	(0.005)
Ethiopia	0.699	0.926	0.965	0.947
	(0.133)	(0.052)	(0.068)	(0.096)
Finland	0.907	1.000	0.671	0.962
	(0.139)	(0.000)	(0.203)	(0.129)
France	0.827	1.000	0.989	0.949
	(0.205)	(0.000)	0.041)	0.098)
Gabon	0.708	0.997	0.492	0.565
	0.218)	(0.013)	(0.398)	(0.336)
Georgia	0.801	0.87	0.971	0.976
	(0.157)	(0.061)	(0.049)	(0.094)
Germany	0.966	1.000	0.94	0.933
	(0.106)	(0.000)	(0.1)	(0.228)
Ghana	0.313	0.853	0.952	0.624
	(0.109)	(0.05)	(0.098)	(0.22)
Greece	0.588	0.986	0.664	0.943
	(0.068)	(0.012)	(0.261)	(0.183)
Guatemala	0.317	0.816	0.966	0.857
	(0.073)	(0.307)	(0.074)	(0.208)
Haiti	0.689	0.99	0.991	0.973
	(0.19)	(0.05)	(0.032)	(0.083)
Honduras	0.27	0.793	0.982	0.923
	(0.039)	(0.09)	(0.031)	(0.136)
Hong Kong SAR, C	0.944	1.000	0.985	0.98
	(0.114)	(0.000)	(0.045)	(0.052)
Hungary	0.301	1.000	0.976	0.951
	(0.048)	(0.000)	(0.097)	(0.137)
Iceland	0.991	1.000	0.92	0.956
	(0.03)	(0.000)	(0.271)	(0.151)
India	0.189	0.568	0.427	0.948
	(0.14)	(0.171)	(0.236)	(0.138)
Indonesia	0.202	0.999	0.592	0.961
	(0.034)	(0.003)	(0.154)	(0.098)
Iran, Islamic Re	0.201	1.000	1.000	0.998

(*continued on next page*)

Table 7 (*continued*).

Country Name	TE	TFEEF	TREEF	TCO2EFF
	(0.096)	(0.0004)	(0.000)	(0.011)
Iraq	0.774	0.99	1.000	0.992
	(0.119)	(0.018)	(0.000)	(0.034)
Ireland	0.926	0.999	1.000	0.966
	(0.136)	(0.003)	(0.000)	(0.115)
Israel	0.677	1.000	0.762	0.94
	(0.102)	(0.0001)	(0.249)	(0.204)
Italy	0.796	1.000	0.844	0.993
	0.103)	(0.000)	(0.231)	(0.015)
Jamaica	0.431	1.000	1.000	0.993
	(0.079)	(0.000)	(0.000)	(0.033)
Japan	0.833	0.994	0.935	0.965
	(0.118)	(0.004)	(0.124)	(0.069)
Jordan	0.69	1.000	0.998	0.976
	(0.191)	(0)	(0.003)	(0.089)
Kazakhstan	0.174	0.999	0.97	0.999
	(0.096)	(0.005)	(0.145)	(0.003)
Kenya	0.152	0.442	0.949	0.562
	(0.026)	(0.182)	(0.117)	(0.336)
Korea, Rep.	0.406	0.883	0.952	0.99
	(0.061)	(0.065)	(0.103)	(0.027)
Kuwait	0.927	0.904	1.000	1.000
	(0.099)	(0.116)	(0.0003)	(0.0002)
Kyrgyz Republic	0.377	1.000	0.954	0.939
	(0.324)	(0.000)	(0.139)	(0.106)
Latvia	0.482	1.000	0.886	0.998
	(0.241)	(0.000)	(0.118)	(0.007)
Lebanon	0.495	0.762	1.000	0.988
	(0.13)	(0.122)	(0.000)	(0.039)
Libya	0.78	0.856	0.989	1.000
	(0.114)	(0.052)	(0.054)	(0.000)
Lithuania	0.265	0.751	0.969	1.000
	(0.051)	(0.096)	(0.103)	(0.000)
Luxembourg	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)
Macedonia, FYR	0.329	0.544	0.922	1.000
	(0.116)	(0.172)	(0.171)	(0.000)
Malaysia	(0.213)	(0.544)	(0.965)	1.000
	(0.065)	(0.225)	(0.117)	(0.000)
Malta	0.978	1.000	0.999	1.000
	(0.055)	(0.001)	(0.006)	(0.000)
Mauritius	0.813	0.998	1.000	1.000
	(0.103)	(0.011)	(0.000)	(0.000)
Mexico	0.322	0.352	0.816	0.979
	(0.052)	(0.238)	(0.189)	(0.064)
Moldova	0.496	0.998	0.913	0.819
	(0.334)	(0.007)	(0.217)	(0.277)
Mongolia	0.562	0.387	0.998	0.994
	(0.265)	(0.24)	(0.011)	(0.032)
Morocco	0.483	1.000	0.423	0.98
	(0.088)	(0.000)	(0.347)	(0.068)
Mozambique	0.068	1.000	0.921	0.562
	(0.018)	0.000	0.152	0.2
Namibia	0.682	0.551	0.983	0.972
	(0.166)	(0.188)	(0.075)	(0.129)
Nepal	0.117	0.375	0.934	0.724
	(0.026)	(0.248)	0.12)	(0.126)
Netherlands	0.832	1.000	1.000	0.945
	(0.137)	(0.000)	(0.000)	(0.199)
New Zealand	0.55	1.000	0.565	0.977
	(0.078)	(0.000)	(0.077)	(0.063)
Nicaragua	0.234	1.000	0.998	0.921
	(0.035)	(0.000)	(0.008)	(0.146)
Niger	0.695	0.996	0.999	0.981
	(0.153)	(0.009)	(0.006)	(0.067)
Nigeria	0.158	1.000	0.953	0.702
	(0.137)	(0.000)	(0.064)	(0.345)
Norway	0.973	1.000	0.825	0.909
	(0.08)	(0.000)	(0.31)	(0.205)
Pakistan	0.141	1.000	0.71)	1.000
	(0.047)	(0.000)	(0.197)	(0.000)
Panama	0.614	0.99	1.000	0.982
	(0.065)	(0.02)	(0.000)	(0.054)
Paraguay	0.289	1.000	1.000	0.872

(*continued on next page*)

Table 7 (*continued*).

Country Name	TE	TFEEF	TREEF	TCO2EFF
	(0.053)	(0.000)	(0.000)	(0.12)
Peru	0.543	0.864	0.676	0.92
	(0.103)	(0.274)	(0.367)	(0.241)
Philippines	0.287	0.875	0.818	0.963
	(0.068)	(0.258)	(0.229)	(0.12)
Poland	0.24	1.000	0.912	0.999
	(0.1)	(0.000)	(0.188)	(0.003)
Portugal	0.528	1.000	0.602	0.998
	(0.058)	(0.000)	(0.301)	(0.005)
Romania	0.217	0.942	0.868	0.997
	(0.064)	(0.118)	(0.192)	(0.014)
Russian Federation	0.19	1.000	0.992	1.000
	(0.161)	(0.000)	(0.029)	(0.002)
Saudi Arabia	0.954	1.000	1.000	1.000
	(0.078)	(0.000)	(0.000)	(0.000)
Senegal	0.533	0.87	0.996	0.781
	(0.187)	(0.269)	(0.021)	(0.153)
Singapore	0.891	0.985	1.000	0.955
	(0.144)	(0.032)	(0.000)	(0.149)
Slovak Republic	0.272	1.000	0.976	1.000
	(0.043)	(0.000)	(0.102)	(0.000)
Slovenia	0.469	1.000	0.893	1.000
	(0.036)	(0.000)	(0.125)	(0.000)
South Africa	0.169	0.98	0.729	1.000
	(0.108)	(0.041)	(0.271)	(0.000)
Spain	0.598	1.000	0.727	0.999
	(0.113)	(0.000)	(0.25)	(0.004)
Sri Lanka	0.326	0.431	1.000	0.81
	(0.055)	(0.261)	(0.000)	(0.224)
Sudan	0.221	0.5	0.957	0.6
	(0.047)	(0.18)	(0.07)	(0.293)
Sweden	0.594	1.000	0.891	0.78
	(0.138)	(0.000)	(0.108)	(0.139)
Switzerland	0.998	1.000	1.000	1.000
	(0.007)	(0.000)	(0.000)	(0.000)
Tajikistan	0.2	0.767	0.983	0.712
	(0.086)	(0.071)	(0.039)	(0.221)
Tanzania	0.103	0.878	0.935	0.664
	(0.018)	(0.051)	(0.099)	(0.125)
Thailand	0.182	0.901	0.694	0.987
	(0.068)	(0.05)	(0.152)	(0.051)
Togo	0.24	0.611	0.952	0.604
	(0.129)	(0.152)	(0.06)	(0.331)
Trinidad and Tob	0.446	1.000	0.974	0.992
	(0.285)	(0.000)	(0.129)	(0.036)
Tunisia	0.333	0.996	0.983	0.993
	(0.058)	(0.018)	(0.065)	(0.022)
Turkey	0.382	0.871	0.578	.919
	(0.055)	(0.245)	(0.216)	(0.18)
Ukraine	0.292	0.705	1.000	0.956
	(0.314)	(0.117)	(0.000)	(0.107)
United Arab Emirates	0.196	1.000	1.000	1.000
	(0.288)	(0.000)	(0.000)	(0.000)
United Kingdom	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)
United States	0.993	1.000	0.987	0.967
	(0.035)	(0.000)	(0.044)	(0.093)
Uruguay	0.652	0.999	0.764	0.908
	(0.15)	(0.005)	(0.239)	(0.212)
Uzbekistan	0.685	0.851	0.996	0.76
	(0.241)	(0.063)	(0.016)	(0.256)
Venezuela, RB	0.132	0.979	0.986	0.996
	(0.188)	(0.038)	(0.07)	(0.021)
Vietnam	0.384	0.962	0.759	0.973
	(0.082)	(0.079)	(0.277)	(0.078)
Yemen, Rep.	0.426	0.885	0.526	0.92
	(0.245)	(0.252)	(0.29)	(0.222)
Zambia	0.681	0.994	0.951	0.966
	(0.221)	(0.027)	(0.143)	(0.074)
Zimbabwe	0.426	0.964	0.933	0.677
	(0.121)	(0.021)	(0.069)	(0.226)

Note: Standard Deviations in parentheses.

Table 8
Countries means of the estimated efficiencies (by cluster).

Country-cluster A	TE	TFEEF	TFREE	TCO2EF
Australia	0.504	0.715	0.873	0.982
	(0.122)	(0.122)	(0.131)	(0.012)
Austria	0.818	0.94	0.769	1.000
	(0.082)	(0.002)	(0.131)	(0.000)
Belgium	(0.792	1.000	0.994	0.914
	(0.13)	(0)	(0.026)	(0.028)
Canada	0.738	1.000	0.682	1.000
	(0.225)	(0)	(0.138)	(0.000)
Chile	0.39	0.973	0.554	0.968
	(0.064)	(0.016)	(0.142)	(0.002)
Croatia	0.516	0.992	0.637	0.988
	(0.081)	(0.037)	(0.289)	(0.002)
Cyprus	0.096	0.843	0.952	1.000
	(0.023)	(0.059)	(0.064)	(0.000)
Czech Republic	0.619	0.998	0.981	1.000
	(0.179)	(0.007)	(0.042)	(0.000)
Denmark	0.649	0.748	0.983	0.997
	(0.144)	(0.107)	(0.082)	(0.001)
Estonia	0.62	0.604	0.99	1.000
	(0.238)	(0.16)	(0.023)	(0.000)
Finland	0.444	1.000	0.964	1.000
	(0.05)	(0)	(0.137)	(0.000)
France	0.293	0.997	0.823	0.983
	(0.075)	(0.0005)	(0.272)	(0.002)
Georgia	1.000	1.000	1.000	1.000
	(0.0002)	(0.0002)	(0.000)	(0.000)
Germany	0.315	1.000	0.923	1.000
	(0.107)	(0)	(0.14)	(0.000)
Greece	0.968	1.000	0.987	0.967
	(0.069)	(0.088)	(0.187)	(0.008)
Hong Kong SAR, C	0.985	1.000	1.000	1.000
	(0.114)	(0.004)	(0.000)	(0.000)
Hungary	0.301	1.000	0.976	0.965
	(0.048)	(0.000)	(0.097)	(0.011)
Iceland	0.991	1.000	0.92	1.000
	(0.03)	(0.000)	(0.271)	(0.000)
Ireland	0.926	0.999	1.000	0.971
	(0.136)	(0.003)	(0.000)	(0.012)
Israel	0.677	1.000	0.762	0.962
	(0.102)	(0.001)	(0.249)	(0.012)
Italy	0.796	1.000	0.844	1.000
	(0.136)	(0.000)	(0.104)	(0.000)
Japan	0.833	0.994	0.935	1.000
	(0.118)	(0.004)	(0.124)	(0.000)
Latvia	0.482	1.000	0.886	1.000
	(0.241)	(0.000)	(0.118)	(0.000)
Lithuania	0.265	0.751	0.969	1.000
	(0.051)	(0.096)	(0.103)	(0.000)
Luxembourg	1.000	1.000	1.000	1.000
	(0)	(0.000)	(0.000)	(0.000)
Malta	0.978	0.999	0.999	1.000
	(0.055)	(0.001)	(0.006)	(0.000)
New Zealand	0.554	1.000	0.565	0.981
	(0.078)	(0.000)	(0.077)	(0.011)
Norway	0.973	1.000	0.825	0.972
	(0.08)	(0.000)	(0.31)	(0.010)
Poland	0.24	1.000	0.912	1.000
	(0.1)	(0.000)	(0.188)	(0.000)
Portugal	0.528	1.000	0.602	1.000
	(0.058)	(0.000)	(0.301)	(0.000)
Singapore	0.891	0.985	1.000	0.978
	(0.144)	(0.032)	(0)	(0.012)
Slovak Republic	0.272	1.000	0.976	1.000
	(0.043)	(0)	(0.102)	(0.000)
Slovenia	0.469	1.000	0.893	1.000
	(0.036)	(0.000)	(0.125)	(0.000)
Spain	0.598	1.000	0.727	1.000
	(0.113)	(0.000)	(0.25)	(0.000)
Sweden	0.594	1.000	0.891	1.000
	(0.138)	(0.000)	(0.108)	(0.000)
Switzerland	0.998	1.000	1.000	1.000
	(0.007)	(0.00)	(0.000)	(0.000)
The Netherlands	0.988	1.000	1.000	1.000

(*continued on next page*)

Table 8 (*continued*).

Country-cluster A	TE	TFEEF	TFREE	TCO2EF
	(0.007)	(0.00)	(0.000)	(0.000)
United Kingdom	1.000	1.000	1.000	1.000
	(0)	(0.000)	(0.000)	(0.000)
United States	0.993	1.000	0.987	1.000
	(0.035)	(0.000)	(0.044)	(0.000)
Uruguay	0.652	0.999	0.764	0.918
	(0.15)	(0.005)	(0.239)	(0.032)

Country-cluster B	TE	TFEE	TFREE	TCO2EF
Albania	0.385	0.924	0.987	0.812
	(0.046)	(0.058)	(0.026)	(0.075)
Argentina	0.337	0.973	0.759	0.901
	(0.158)	(0.008)	(0.301)	(0.032)
Armenia	0.907	1.000	0.671	0.688
	(0.139)	(0.000)	(0.203)	(0.125)
Azerbaijan	0.827	1.000	0.989	1.000
	(0.205)	(0.000)	0.041)	(0.000)
Benin	0.708	0.997	0.492	0.611
	0.218)	(0.013)	(0.398)	(0.143)
Bosnia Herzegovina	0.801	0.87	0.971	0.989
	(0.157)	(0.061)	(0.049)	(0.009)
Botswana	0.966	1.000	0.94	0.998
	(0.106)	(0.000)	(0.101)	(0.000)
Brazil	0.313	0.853	0.952	0.987
	(0.109)	(0.05)	(0.098)	(0.002)
Bulgaria	0.588	0.986	0.664	1.000
	(0.068)	(0.012)	(0.261)	(0.000)
Cambodia	0.317	0.816	0.966	0.589
	(0.073)	(0.307)	(0.074)	(0.187)
China	0.27	0.793	0.982	1.000
	(0.039)	(0.09)	(0.031)	(0.000)
Colombia	0.202	0.999	0.592	0.978
	(0.034)	(0.003)	(0.154)	(0.001)
Costa Rica	0.774	0.991	0.984	0.898
	(0.119)	(0.018)	(0.008)	(0.063)
Cote d' Ivoire	0.431	0.928	0.954	0.721
	(0.079)	(0.014)	(0.031)	(0.201)
Dominican Republic	0.69	1.000	0.998	1.000
	(0.191)	(0.000)	(0.003)	(0.000)
Egypt	0.174	0.999	0.97	0.999
	(0.096)	(0.005)	(0.145)	(0.000)
El salvador	0.152	0.442	0.949	0.821
	(0.026)	(0.182)	(0.117)	(0.128)
Gabon	0.406	0.883	0.952	0.639
	(0.061)	(0.065)	(0.103)	(0.178)
Ghana	0.927	0.904	1.000	0.687
	(0.099)	(0.116)	(0.0003)	(0.218)
Guatemala	0.377	0.915	0.954	0.912
	(0.324)	(0.000)	(0.019)	(0.043)
Honduras	0.495	0.762	1.000	1.000
	(0.13)	(0.122)	(0.000)	(0.000)
Indonesia	0.329	0.544	0.922	1.000
	(0.116)	(0.172)	(0.171)	(0.000)
Jamaica	(0.213)	(0.544)	(0.965)	1.000
	(0.065)	(0.225)	(0.117)	(0.000)
Jordan	0.813	0.998	0.987	1.000
	(0.103)	(0.011)	(0.001)	(0.000)
Kazakhstan	0.322	0.352	0.816	1.000
	(0.052)	(0.238)	(0.189)	(0.000)
Korea, Rep.	0.406	0.883	0.952	1.000
	(0.061)	(0.065)	(0.103)	(0.000)
Kuwait	0.927	0.904	1.000	1.000
	(0.099)	(0.116)	(0.0003)	(0.000)
Kyrgyz Republic	0.377	0.915	0.954	0.987
	(0.324)	(0.000)	(0.019)	(0.001)
Lebanon	0.495	0.762	1.000	0.989
	(0.13)	(0.122)	(0.000)	(0.000)
Macedonia, FYR	0.329	0.544	0.922	1.000
	(0.116)	(0.172)	(0.171)	(0.000)
Malaysia	(0.213)	(0.544)	(0.965)	1.000
	(0.065)	(0.225)	(0.117)	(0.000)

(*continued on next page*)

Table 8 (*continued*).

Country-cluster B	TE	TFEE	TFREE	TCO2EF
Mauritius	0.813	0.998	0.987	1.000
	(0.103)	(0.011)	(0.001)	(0.000)
Mexico	0.322	0.352	0.816	0.999
	(0.052)	(0.238)	(0.189)	(0.000)
Moldova	0.496	0.998	0.913	0.879
	(0.334)	(0.007)	(0.217)	(0.089)
Mongolia	0.562	0.387	0.998	0.999
	(0.265)	(0.24)	(0.011)	(0.000)
Morocco	0.483	0.978	0.423	0.999
	(0.088)	(0.001)	(0.347)	(0.000)
Namibia	0.682	0.551	0.983	0.983
	(0.166)	(0.188)	(0.075)	(0.002)
Nicaragua	0.234	0.912	0.998	0.941
	(0.035)	(0.012)	(0.008)	(0.012)
Pakistan	0.141	0.943	0.71)	1.000
	(0.047)	(0.023)	(0.197)	(0.000)
Panama	0.614	0.994	0.978	0.999
	(0.065)	(0.02)	(0.001)	(0.000)
Paraguay	0.289	0.967	0.976	0.912
	(0.053)	(0.002)	(0.001)	(0.023)
Peru	0.543	0.864	0.676	0.938
	(0.103)	(0.274)	(0.367)	(0.032)
Philippines	0.287	0.875	0.818	0.991
	(0.068)	(0.258)	(0.229)	(0.004)
Romania	0.217	0.942	0.868	0.999
	(0.064)	(0.118)	(0.192)	(0.000)
Russian Federation	0.19	1.000	0.992	1.000
	(0.161)	(0.000)	(0.029)	(0.000)
Saudi Arabia	0.469	1.000	0.893	1.000
	(0.036)	(0.000)	(0.125)	(0.000)
Senegal	0.533	0.87	0.996	0.781
	(0.187)	(0.269)	(0.021)	(0.153)
South Africa	0.169	0.98	0.729	1.000
	(0.108)	(0.041)	(0.271)	(0.000)
Sri Lanka	0.326	0.431	1.000	0.81
	(0.055)	(0.261)	(0.000)	(0.224)
Tanzania	0.998	1.000	1.000	1.000
	(0.007)	(0.000)	(0.000)	(0.000)
Thailand	0.2	0.767	0.983	0.712
	(0.086)	(0.071)	(0.039)	(0.221)
Togo	0.103	0.878	0.935	0.664
	(0.018)	(0.051)	(0.099)	(0.125)
Turkey	0.182	0.901	0.694	0.987
	(0.068)	(0.05)	(0.152)	(0.051)
United Arab Emirates	0.24	0.611	0.952	0.604
	(0.129)	(0.152)	(0.06)	(0.331)
Zambia	0.446	1.000	0.974	0.992
	(0.285)	(0.000)	(0.129)	(0.036)

Country-cluster C	TE	TFEEF	TREEF	TCO2EF
Algeria	0.828	0.954	0.814	0.961
	(0.161)	(0.021)	(0.129)	(0.021)
Angola	0.349	0.817	0.872	0.898
	(0.261)	(0.120)	(0.129)	(0.087)
Bangladesh	0.719	0.902	0.992	0.904
	(0.161)	(0.054)	(0.029)	(0.032)
Belarus	0.321	1.000	0.992	0.914
	(0.201)	(0.000)	(0.002)	(0.021)
Bolivia	0.319	1.000	0.992	1.000
	(0.181)	(0.000)	(0.029)	(0.000)
Cameroon	0.409	0.623	0.974	0.712
	(0.201)	(0.103)	(0.009)	(0.087)
Ecuador	0.412	0.823	0.674	0.971
	(0.191)	(0.063)	(0.089)	(0.007)
Cuba	0.319	0.999	0.874	0.999
	(0.241)	(0.000)	(0.039)	(0.000)
Eritrea	0.784	0.819	0.999	0.912
	(0.089)	(0.086)	(0.000)	(0.021)
Ethiopia	0.819	0.972	0.987	0.987
	(0.083)	(0.012)	(0.008)	(0.001)
Haiti	0.809	0.999	0.993	0.999

(*continued on next page*)

Table 8 (*continued*).

Country-cluster C	TE	TFEEF	TREEF	TCO2EF
	(0.098)	(0.000)	(0.001)	(0.000)
India	0.389	0.681	0.527	0.961
	(0.176)	(0.101)	(0.136)	(0.009)
Iran, Islamic Re	0.398	1.000	0.977	1.000
	(0.076)	(0.000)	(0.003)	(0.000)
Libya	0.829	0.898	0.999	1.000
	(0.094)	(0.032)	(0.000)	(0.000)
Mozambique	0.209	0.964	0.976	0.689
	(0.038)	(0.011)	(0.007)	(0.151)
Nepal	0.331	0.451	0.964	0.872
	(0.126)	(0.108)	(0.009)	(0.054)
Niger	0.751	0.999	0.999	0.999
	(0.132)	(0.000)	(0.000)	(0.000)
Nigeria	0.358	0.999	0.983	0.852
	(0.127)	(0.000)	(0.004)	(0.053)
Republic of Congo	0.311	0.876	0.977	0.612
	(0.187)	(0.091)	(0.003)	(0.076)
Sudan	0.421	0.576	0.997	0.712
	(0.147)	(0.161)	(0.000)	(0.076)
Tajikistan	0.422	0.817	0.999	0.817
	(0.206)	(0.041)	(0.000)	(0.049)
Tunisia	0.452	0.999	1.000	1.000
	(0.108)	(0.000)	(0.000)	(0.000)
Ukraine	0.412	0.776	1.000	1.000
	(0.294)	(0.121)	(0.000)	(0.000)
Uzbekistan	0.718	0.882	1.000	1.000
	(0.121)	(0.083)	(0.000)	(0.000)
Venezuela, RB	0.312	0.981	0.991	1.000
	(0.218)	(0.008)	(0.002)	(0.000)
Vietnam	0.428	0.976	0.819	0.934
	(0.103)	(0.009)	(0.067)	(0.023)
Zimbabwe	0.512	0.984	0.950	0.843
	(0.201)	(0.001)	(0.019)	(0.075)

Note: Standard deviations in parentheses

Appendix B. Figures

See Figs. 1–6.

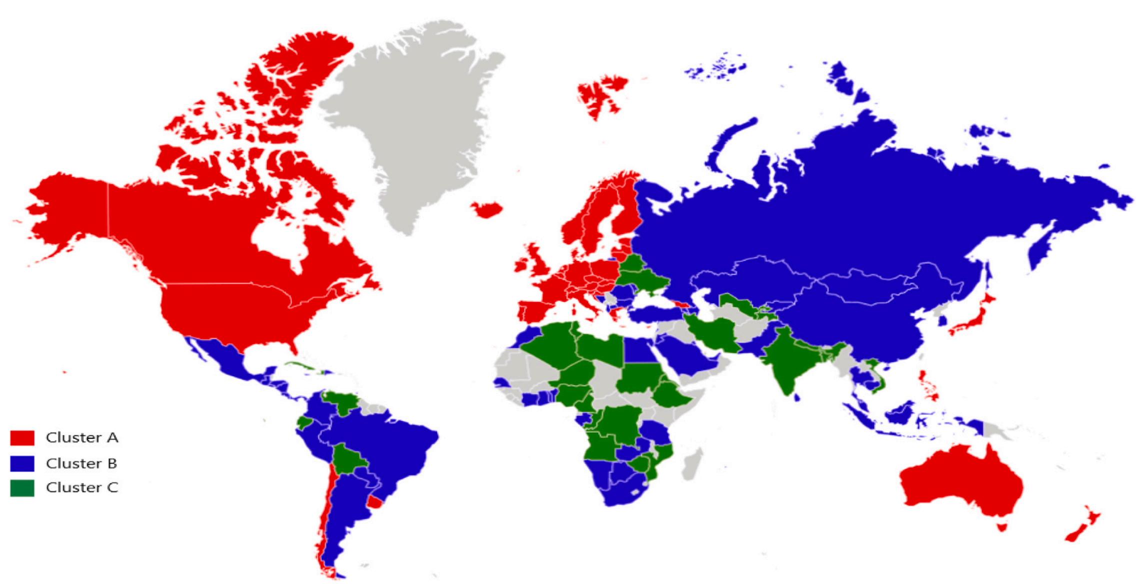


Fig. 1. Geographical distribution of the three clusters.

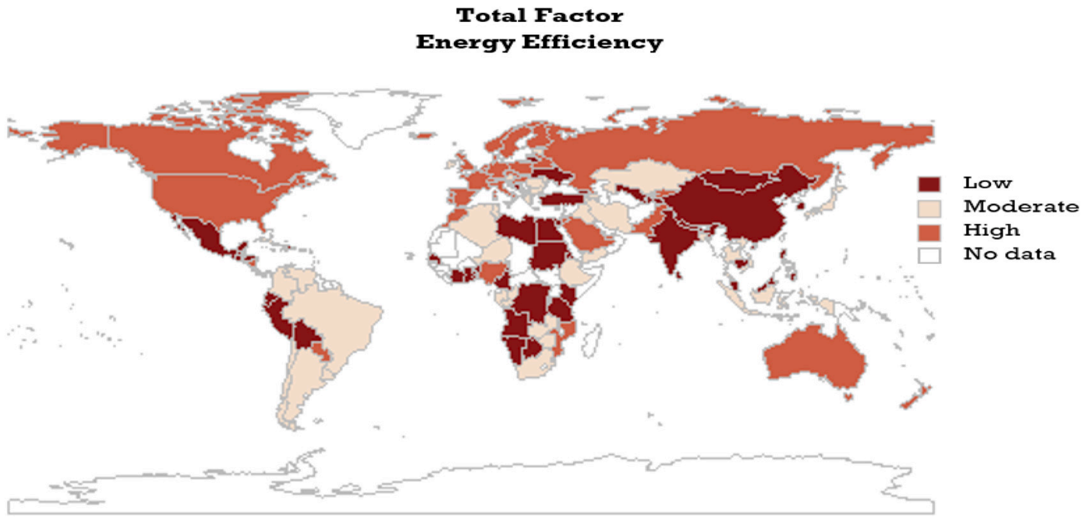


Fig. 2. Spatial distribution of average total factor energy efficiency (127 countries globally).

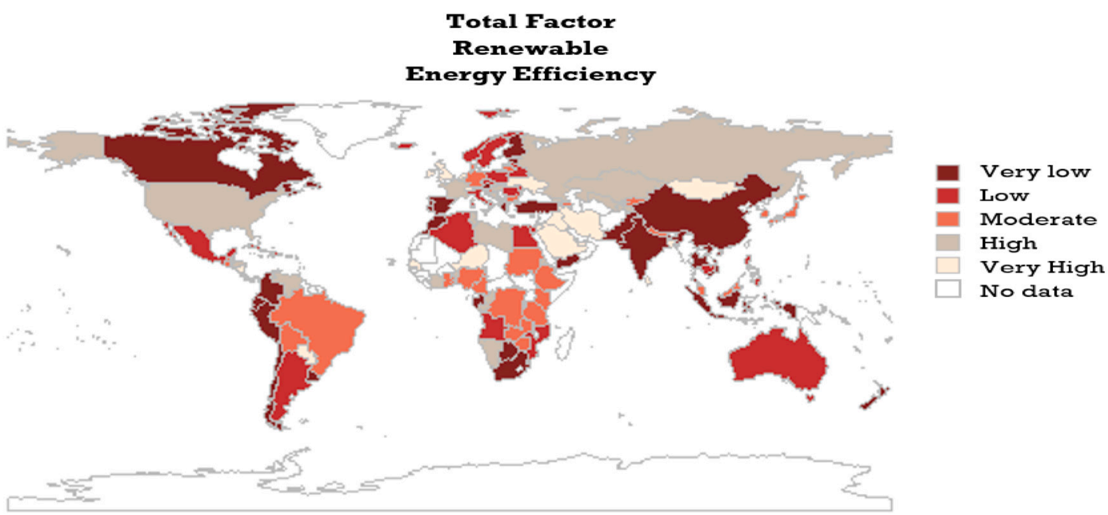


Fig. 3. Spatial distribution of average total factor renewable energy efficiency (127 countries globally).

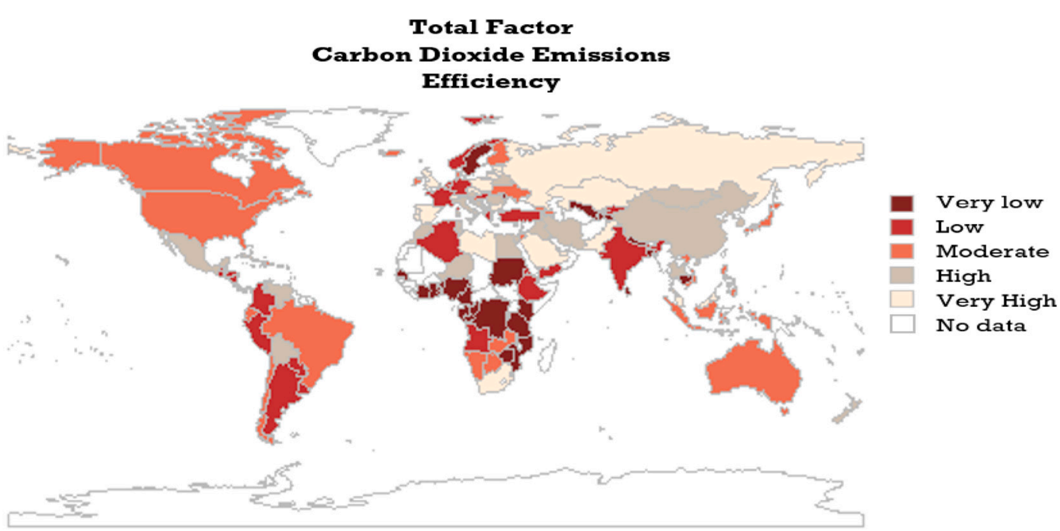


Fig. 4. Spatial distribution of average carbon dioxide emissions efficiency (127 countries globally).

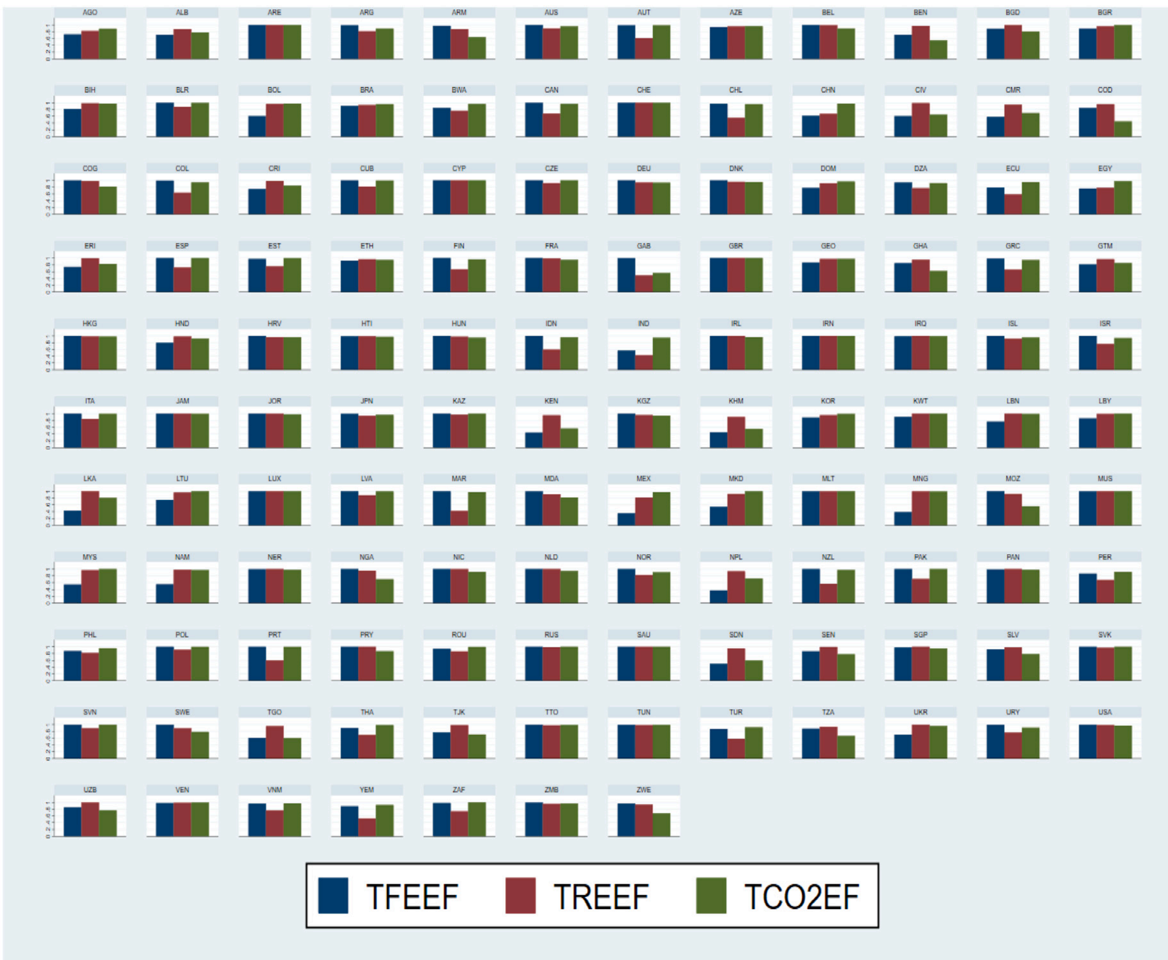
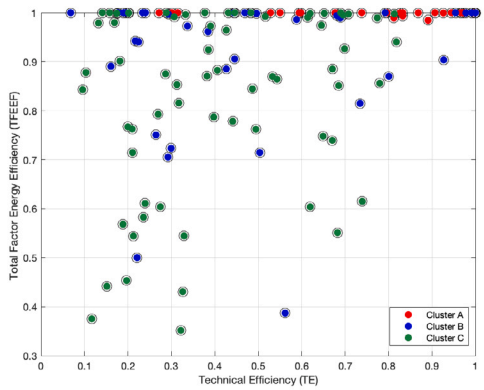
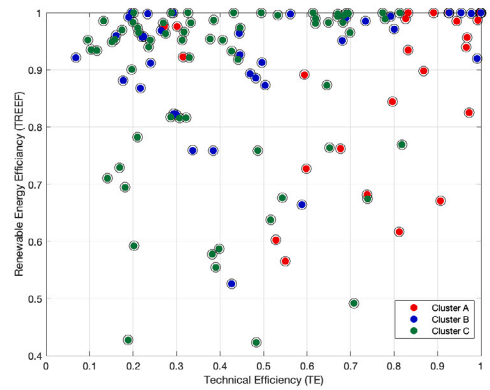


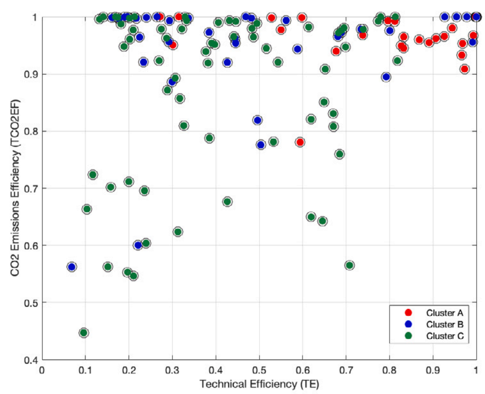
Fig. 5. Distribution, on average, of all measures per each country.



(a) TE and TFEEF



(b) TE and TREFF



(c) TE and TCO_2EF

Fig. 6. Scatter plots of estimated measures based on cluster type.

Appendix C. Data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eneco.2023.106795.

References

Aghion, P., Bloom, N., Blundell, R., Griffith, R., Howitt, P., 2005. Competition and innovation: An inverted-U relationship. Q. J. Econ. 120 (2), 701–728.

Aklin, M., Urpelainen, J., 2013. Political competition path dependence, and the strategy of sustainable energy transitions. Am. J. Polit. Sci. 57 (3), 643–658.

Akram, R., Chen, F., Khalid, F., Huang, G., Irfan, M., 2021. Heterogeneous effects of energy efficiency and renewable energy on economic growth of brics countries: a fixed effect panel quantile regression analysis. Energy 215 (B), 119122.

Akram, R., Chen, F., Khalid, F., Ye, Z., Majeed, M.T., 2020. Heterogeneous effects of energy efficiency and renewable energy on carbon emissions: evidence from developing countries. J. Clean. Prod. 247, 119122.

Almer, C., Winkler, R., 2017. Analyzing the effectiveness of international environmental policies: The case of the kyoto protocol. J. Environ. Econ. Manag. 82, 125–151.

Amri, F., 2017. Intercourse across economic growth trade and renewable energy consumption in developing and developed countries. Renew. Sustain. Energy Rev. 69 (C), 527–534.

Anwar, M.Z., Zhou, R., Asmi, F., Wang, D., Hammad, A., 2019. Mapping the evolution of energy-growth nexus: synergies and trade-offs. J. Econ. Surv. 33 (3), 698–998.

Apergis, N., Payne, J.E., 2010. Renewable energy consumption and economic growth: evidence from a panel of OECD countries. Energy Policy 38, 656–660.

Bayar, Y., Gavriletea, M.D., 2019. Energy efficiency renewable energy, economic growth: evidence from emerging market economies. Qual. Quant. 53, 2221–2234.

Bi, G.B., Song, W., Zhou, P., Liang, L., 2014. Does environmental regulation affect energy efficiency in China's thermal power generation? Empirical evidence from a slacks-based DEA model. Energy Policy 66, 537–546.

Bigerna, S., D'Errico, M.C., Polinori, P., 2019. Environmental and energy efficiency of eu electricity industry: An almost spatial two stages DEA approach. Energy J. 40, (The New Era of Energy Transition).

Bleakley, H., Lin, J., 2012. Portage and path dependence. Q. J. Econ. 127 (2), 587–644.

Boyd, G., Pang, J., 2000. Estimating the linkage between energy efficiency and productivity. Energy Policy 28 (5), 289–296.

Cantore, N., Calı, M., te Velde, D., 2016. Does energy efficiency improve technological change and economic growth in developing countries? Energy Policy 92, 279–285.

Casu, B., Ferrari, A., Girardone, C., Wilson, J.O., 2016. Integration productivity and technological spillovers: Evidence for Eurozone banking industries. Euro. J. Oper. Res. 255 (3), 971–983.

Ćetković, S., Buzogány, A., 2020. Between markets politics and path-dependence: explaining the growth of solar and wind power in six central and eastern European countries. Energy Policy 139, 111325.

Chambers, R.G., Chung, Y., Färe, R., 1996. Benefit and distance functions. J. Econom. Theory 70 (2), 407–419.

Chatzistamoulou, N., Kounetas, K., Tsekouras, K., 2019. Energy efficiency productive performance and heterogeneous competitiveness regimes. does the dichotomy matter? Energy Econ. 81, 687–697.

Chien, T., Hu, J.L., 2007. Renewable energy and macroeconomic efficiency of OECD and non-OECD economies. Energy Policy 35 (7), 3606–3615.

Comin, D., Hobijn, B., 2010. An exploration of technology diffusion. Amer. Econ. Rev. 100 (5), 2031–2059.

Costantini, V., Martini, V., 2010. The causality between energy consumption and economic growth: A multi-sectoral analysis using non-stationary cointegrated panel data. Energy Econ. 32 (3), 591–603.

David, P.A., 2001. Path dependence its critics and the quest for 'Historical economics'. Evolut. Path Dependence Econ. Ideas Past Present 15 (40).

European Commission, 2019. (Accessed 22 July 2021).

Färe, R., Grosskopf, S., 2000. Theory and application of directional distance functions. J. Product. Anal. 13 (2), 93–103.

Färe, R., Grosskopf, S., Noh, D.W., Weber, W., 2005. Characteristics of a polluting technology: theory and practice. J. Econometrics 126 (2), 469–492.

Fouquet, R., 2016. Path dependence in energy systems and economic development. Nat. Energy 1 (8), 1–5.

Gillingham, K., Palmer, K., 2020. Bridging the energy efficiency gap: Policy insights from economic theory and empirical evidence. Rev. Environ. Econ. Policy.

Halkos, G.E., Tzeremes, N.G., 2010. The effect of foreign ownership on SMEs performance: An efficiency analysis perspective. J. Product. Anal. 34 (2), 167–180.

Hansen, B.E., 1999. Threshold effects in non-dynamic panels: Estimation testing, and inference. J. Econometr. 93 (2), 345–368.
Hansen, B.E., 2000. Sample splitting and threshold estimation. Econometrica 68 (3), 575–603.
Hayami, Y., 1969. Sources of agricultural productivity gap among selected countries. Am. J. Agric. Econ. 51 (3), 564–575.
Hayami, Y., Ruttan, V.W., 1970. Agricultural productivity differences among countries. Am. Econ. Rev. 60 (5), 895–911.
Hogan, W.W., Jorgenson, D.W., 1991. Productivity trends and the cost of reducing CO2 emissions. Energy J. 12 (1).
Honma, S., Hu, J.L., 2008. Total-factor energy efficiency of regions in Japan. Energy Policy 36 (2), 821–833.
Hu, J.L., Kao, C.H., 2007. Efficient energy-saving targets for APEC economies. Energy Policy 35 (1), 373–382.
Hu, J.L., Wang, S.C., 2006. Total-factor energy efficiency of regions in China. Energy Policy 34 (17), 3206–3217.
Inglesi-Lotz, R., 2016. The impact of renewable energy consumption to economic growth: A panel data application. Energy Econ. 53, 58–63.
IPCC, 2021. Summary for policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I To the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, in press.
Jaffe, A.B., Newell, R.G., Stavins, R.N., 2002. Environmental policy and technological change. Environ. Resour. Econ. 22 (1–2), 41–70.
Jorgenson, D.W., 1984. The role of energy in productivity growth. Energy J. 5 (3).
Kontolaimou, A., Kounetas, K., Mourtos, I., Tsekouras, K., 2012. Technology gaps in European banking: Put the blame on inputs or outputs? Econ. Model. 29 (5), 1798–1808.
Kounetas, K., 2015. Heterogeneous technologies strategic groups and environmental efficiency technology gaps for european countries. Energy Policy 83, 277–287.
Kounetas, K.E., 2018. Energy consumption and CO2 emissions convergence in European union member countries A Tonneau Des Danaides?. Energy Econ. 69, 111–127.
Kounetas, K., Mourtos, I., Tsekouras, K., 2009. Efficiency decompositions for heterogeneous technologies. Eur. J. Oper. Res. 199 (2009), 209–218.
Kounetas, K., Napolitano, O., 2018. Modeling the incidence of international trade on Italian regional productive efficiency using a meta-frontier DEA approach. Econ. Model. 71, 45–58.
Kounetas, K.E., Polemis, M.L., Tzeremes, N.G., 2021. Measurement of eco-efficiency and convergence: Evidence from a non-parametric frontier analysis. European J. Oper. Res. 291 (1), 365–378.
Kounetas, K., Zervopoulos, P.D., 2019. A cross-country evaluation of environmental performance: Is there a convergence-divergence pattern in technology gaps? European J. Oper. Res. 273 (3), 1136–1148.
Kumar, S., 2006. Environmentally sensitive productivity growth: a global analysis using Malmquist–Luenberger index. Ecol. Econom. 56 (2), 280–293.
Lee, C.C., Chang, C.P., 2008. Energy consumption and economic growth in Asian economies: A more comprehensive analysis using panel data. Resour. Energy Econ. 30 (1), 50–65.
Li, L.B., Hu, J.L., 2012. Ecological total-factor energy efficiency of regions in China. Energy Policy 46, 216–224.
Liddle, B., 2012. The importance of energy quality in energy intensive manufacturing: Evidence from panel cointegration and panel FMOLS. Energy Econ. 34 (6), 1819–1825.
Liu, F., Sim, J.Y., Sun, H., Edziah, B.K., Adom, P.K., Song, S., 2023. Assessing the role of economic globalization on energy efficiency: Evidence from a global perspective. China Econ. Rev. 77, 101897.
Mayer, A., Zelenyuk, V., 2014. Aggregation of malmquist productivity indexes allowing for reallocation of resources. European J. Oper. Res. 238 (3), 774–785.
Menegaki, A.N., 2013. Growth and renewable energy in europe: Benchmarking with data envelopment analysis. Renew. Energy 60, 363–369.
Montalbano, P., Nenci, S., Vurchio, D., 2022. Energy efficiency and productivity: A worldwide firm-level analysis. Energy J. 43 (5).
Ntanos, S., Skordoulis, S., Kyriakopoulos, G., Arabatzis, G., Chalikias, M., Galatsidas, S., Batzios, A., Katsarou, A., 2018. Renewable energy and economic growth: Evidence from European countries. Sustainability 10 (8), 2626.
O'Donnell, C.J., Rao, D.P., Battese, G.E., 2008. Metafrontier frameworks for the study of firm-level efficiencies and technology ratios. Empir. Econ. 34 (2), 231–255.
Oztruk, I., 2010. A literature survey on energy–growth nexus. Energy Policy 38 (1), 340–349.
Oztruk, I., Acaravci, A., 2010. A the causal relationship between energy consumption and GDP in Albania Bulgaria, Hungary and Romania: Evidence from ARDL bound testing approach. Appl. Energy 87 (6), 1938–1943.
Pehlivanoglu, F., Kocbulut, O., Akdag, S., Alola, A., 2021. Toward a sustainable economic development in the EU member states: The role of energy efficiency-intensity and renewable energy. Int. J. Energy Res. 45 (15), 21219–21233.
Picazo-Tadeo, A.J., Reig-Martinez, E., Hernandez-Sancho, F., 2005. Directional distance functions and environmental regulation. Resour. Energy Econ. 27 (2), 131–142.
Polat, B., 2021. The impact of renewable and nonrenewable energy consumption on economic growth: a dynamic panel data approach. Asia-Pacific J. Account. Econ. 28 (5), 592–603.
Popp, D., Newell, R.G., Jaffe, A.B., 2010. Energy the environment, and technological change. In: Handbook of the Economics of Innovation, vol. 2. pp. 873–937.
Rajbhandari, A., Zhang, F., 2018. Does energy efficiency promote economic growth? Evidence from a multicountry and multisectoral panel dataset. Energy Econ. 69, 129–139.
Rath, B.N., Akram, V., Bal, D.P., Mahalik, M.K., 2019. Do fossil fuel and renewable energy consumption affect total factor productivity growth? Evidence from cross-country data with policy insights. Energy Policy 127, 186–199.
Rexhäuser, S., Löschel, A., 2015. Invention in energy technologies: Comparing energy efficiency and renewable energy inventions at the firm level. Energy Policy 83, 206–217.
Sadorsky, P., 2009. Renewable energy consumption and income in emerging economies. Energy Policy 37, 4021–4028.
Samoilenko, S., Osei-Bryson, K.M., 2008. Increasing the discriminatory power of DEA in the presence of the sample heterogeneity with cluster analysis and decision trees. Expert Syst. Appl. 34 (2), 1568–1581.
Samoilenko, S., Osei-Bryson, K.M., 2010. Determining sources of relative inefficiency in heterogeneous samples: Methodology using cluster analysis DEA and neural networks. Euro. J. Oper. Res. 206 (2), 479–487.
Santos, J., Borges, A.S., Domingos, T., 2021. Exploring the links between total factor productivity and energy efficiency: Portugal 1960–2014. Energy Econ. 101, 105407.
Schurr, S.H., 1982. Energy efficiency and productive efficiency: some thoughts based on American experience. Energy J. 3 (3).
Sohag, K., Chukavina, K., Samargandi, N., 2021. Renewable energy and total factor productivity in OECD member countries. J. Clean. Prod. 296, 126499.
Stergiou, E., Kounetas, K., 2021. European industries' energy efficiency under different technological regimes: the role of CO2 emissions, climate, path dependence and energy mix. The Energy Journal 42 (1).
Stergiou, E., Rigas, N., Zaroutieri, E., Kounetas, K., 2023. Energy, renewable and technical efficiency convergence: a global evidence. Econ. Change Restruct. 1–28.
Stern, D.I., 2012. Modeling international trends in energy efficiency. Energy Econ. 34 (6), 2200–2208.
Sun, J.W., 2003. Energy intensity versus per capita GDP in seven developing countries 1973-1995. Int. J. Glob. Energy Issues 20 (1), 95–114.
Sun, H., Edziah, B.K., Sun, C., Kporsu, A.K., 2019. Institutional quality green innovation and energy efficiency. Energy Policy 135, 111002.
Trianni, A., Cagno, E., Thollander, P., Backlund, S., 2013. Barriers to industrial energy efficiency in foundries: a European comparison. J. Clean. Prod. 40, 161–176.
Tsekouras, K., Chatzistamoulou, N., Kounetas, K. and, 2017. Productive performance technology heterogeneity and hierarchies: who to compare with whom. Int. J. Product. Econ. 193, 465–478.
Tugcu, C.T., Ozlturk, I., Aslain, A., 2012. Renewable and non-renewable energy consumption and eocnomic growth revisited: evidence from G7 countries. Energy Econ. 34, 1942–1950.
Turner, K., Hanley, N., 2011. Energy efficiency rebound effects and the environmental Kuznets curve. Energy Econ. 33 (5), 709–720.
Watanabe, M., Tanaka, K., 2007. Efficiency analysis of Chinese industry: a directional distance function approach. Energy Policy 35 (12), 6323–6331.
Wirl, F., 2004. Sustainable growth renewable resources and pollution: thresholds and cycles. J. Econ. Dyn. Control 28 (6), 1149–1157.
Worrell, E., Laitner, J., Ruth, M., Finman, H., 2022. Productivity benefits of industrial energy efficiency measures. Energy 28 (11), 1081–1098.
Zakari, A., Khan, I., Tan, D., Alvarado, R., Dagar, V., 2022. Energy efficiency and sustainable development goals (SDGs). Energy 239 (E), 122365.
Zhang, N., Zhou, P., Choi, Y., 2013. Energy efficiency CO2 emission performance and technology gaps in fossil fuel electricity generation in Korea: A meta-frontier non-radial directional distance function analysis. Energy Policy 56, 653–662.
Zhou, P., Ang, B.W., Poh, K.L., 2008. A survey of data envelopment analysis in energy and environmental studies. European J. Oper. Res. 189 (1), 1–18.
Zhou, P., Wu, F., Zhou, D.Q., 2017. Total-factor energy efficiency with congestion. Ann. Oper. Res. 255 (1), 241–256.